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NextGEng

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NextGEng Project

WP3

International team-teaching pilot program

Deliverable 3.1b

Developed course modules C1…C4

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TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

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WP3	R3.1b - Developed course modules C1…C4
Authors	Ciprian Rad
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1. Introduction

This report presents the outcomes of the course upgrading and team-teaching development carried out within WP3 of the NextGEng project. The implementation process led to the creation of **24 new English-language course modules**, equally developed across the three partner universities—TUCN, JAMK, and UJA (eight modules each). These modules were designed using student-centered and collaborative teaching approaches, integrating blended and digital delivery methods, eco-friendly concepts, and real-life case studies to ensure a modern and practice-oriented learning experience.

The development process was highly collaborative, involving **32 coordination meetings** across the co-teaching teams of courses C1–C4, with the participation of **15 higher-education teachers** and **10 industry experts**. This joint effort ensured alignment of content, consistent implementation across institutions, and the integration of industry-relevant competencies.

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In the next Chapters the produced courses modules are presented.

2. Courses topics

C1 - Strength of materials

Module 1 – Bending of Beams

Module 2 – Torsion of Bars

Module 3 – Deflection of Beams

Module 4 – Combining Stresses

Module 5 – General Theory of Bending

Module 6 – Buckling

C2 - Industrial Automation

Module 1 – Industrial Control Systems. Industrial Programming Languages

Module 2 – Structured Programming. Sequential Function Chart (SFC). GRAFCET

Module 3 – DCS

Module 4 – Operating interfaces (SCADA/HMI)

Module 5 – Programmable Logic Controllers (PLCs). GRAFCET

Module 6 – Basics of the PID controllers

C3 - Design Projects

Module 1 – Applying ergonomics in companies – sustainability impact of ergonomics projects

Module 2 – Ergonomic principles and criteria for design

Module 3 – User experience UX and usability

Module 4 – General UI design principles

Module 5 – Economic and Financial Feasibility of Projects

Module 6 – Planning and Project Control Basis

C4 - Quality Assurance and Applied Methods

Module 1 – Errors in Measurement

Module 2 – Uncertainties in the Measurement

Module 3 – Development Techniques - FMEA

Module 4 – Development Techniques - LEAN

Module 5 – The evolution of Six sigma

Module 6 – Green Six Sigma

C1 – Strength of Materials

M1 – Bending of Beams

HEI name: Technical University of Cluj-Napoca (TUCN)

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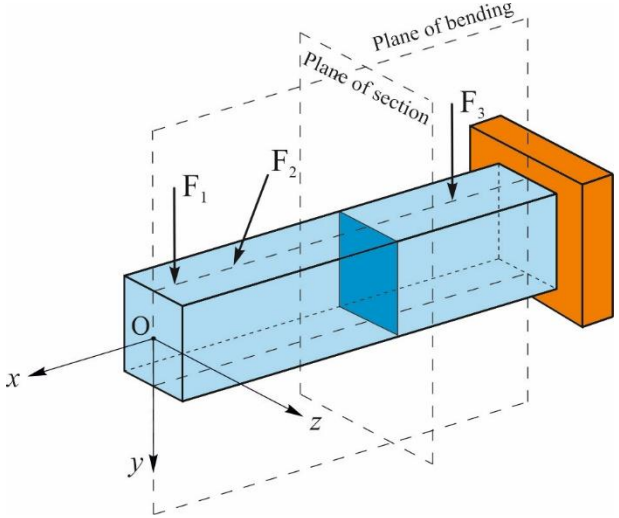
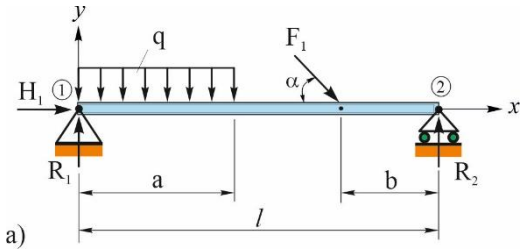
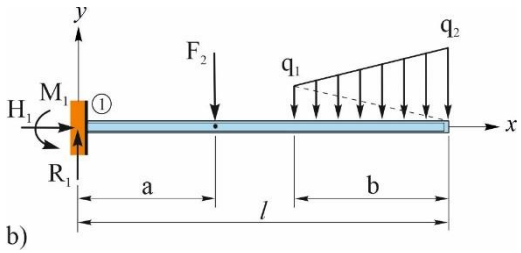
Module 1 - Bending of Beams



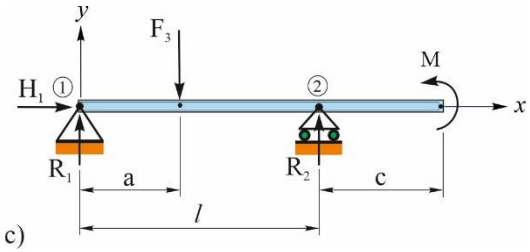
Beams and shafts are important structural and mechanical elements in engineering. In this chapter we will determine the stress in these members caused by bending. The chapter begins with a discussion of how to establish the shear and moment diagrams for a beam or shaft. Like the normal-force the shear and moment diagrams provide a useful means for determining the largest shear and moment in a member, and they specify where these maximums occur. Once the internal moment at a section is determined, the bending stress can then be calculated.
Members that are slender and support loadings that are applied perpendicular to their longitudinal axis are called beams.



Simply supported beam



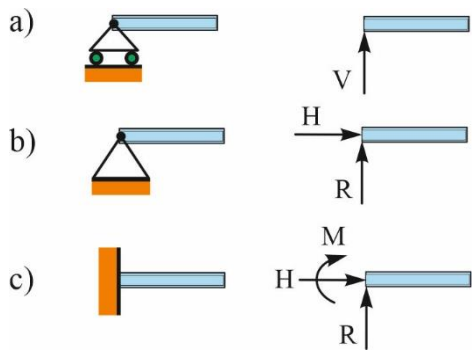
Cantilevered beam



Overhanging beam

Bending of Beams

Supports and reactions

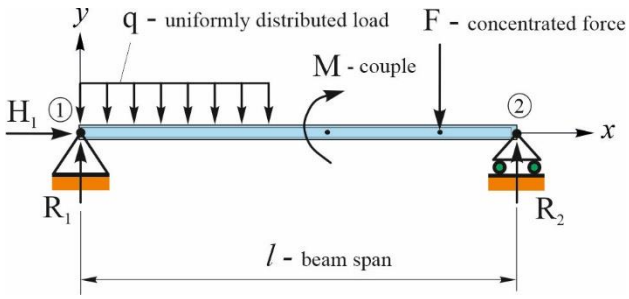


Roller support

Pin support

Fixed support (clamp)

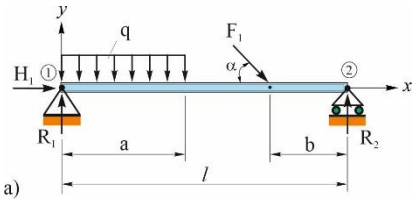
Types of forces



From the three equilibrium equations, the reactions in the supports of a statically determined beam can be calculated. A statically determined system has the number of reactions in the supports equal to the number of equilibrium equations.

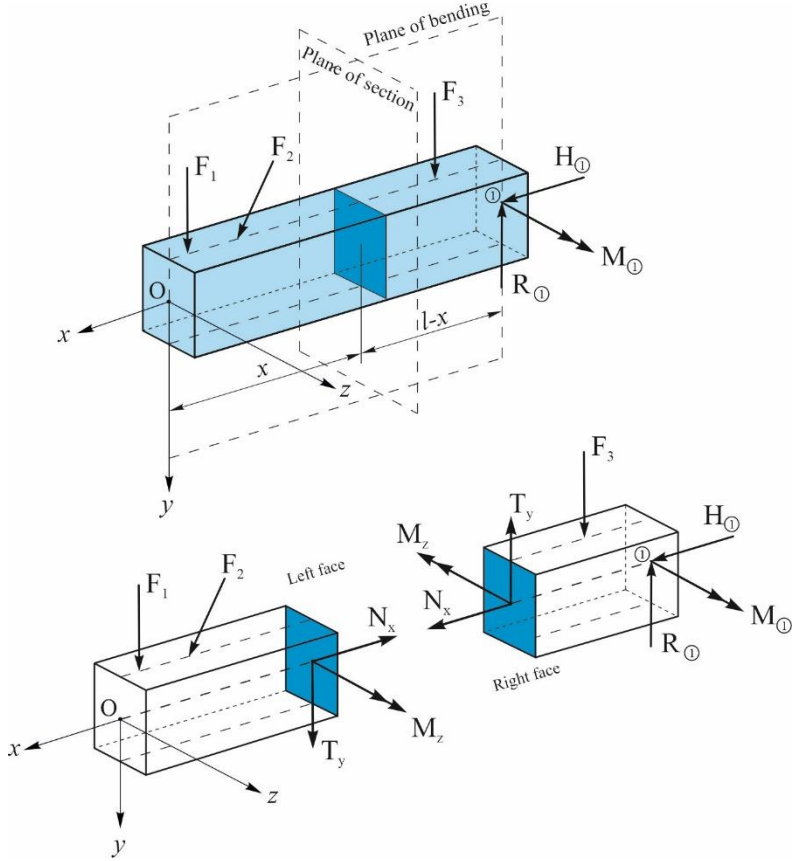
$$\sum_{i=1}^{n} F_{x_i} = 0; \qquad \sum_{i=1}^{n} F_{y_i} = 0; \qquad \sum_{i=1}^{n} \mathrm{M}_{(1)\mathrm{i}} = 0. \qquad \text{or} \qquad \sum_{i=1}^{n} F_{x_i} = 0; \qquad \sum_{i=1}^{n} M_{(1)i} = 0; \qquad \sum_{i=1}^{n} \mathrm{M}_{(2)\mathrm{i}} = 0.$$

Example:



Bending of Beams

INTERNAL FORCES IN BEAMS SUBJECTED TO BENDING



At a distance x from the left end of the beam we apply the method of sections, cutting the beam with an imaginary plane, normal on the axis of the beam. The values of internal forces can be calculated from equations of static equilibrium of the right-hand side or left-hand side of the sectioned beam.

- Normal force N_x

$$N_x(x) = \sum F_{iH\,left} \qquad \text{or} \qquad N_x(x) = -H_1 + \sum F_{iH\,right}.$$

- Shear force V_y

$$V_y(x) = \sum F_{iV\,l} \qquad \text{or} \qquad V_y(x) = -R_1 + \sum F_{iV\,r}.$$

- The bending moment in section x can be calculated as the sum of the moments of all forces on the left or right of that section

$$M_z(x) = \sum F_{iV\,l}(x - a_{il}) \qquad \text{sau} \qquad M_z(x) = R_1 x + M_1 + \sum F_{iV\,r}(x - a_{ir})$$

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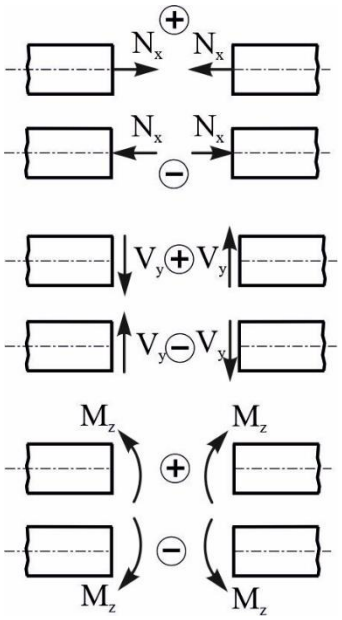
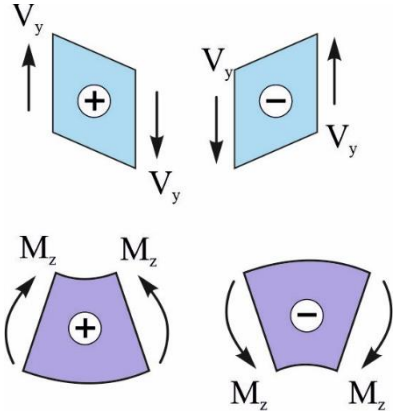
Bending of Beams

SIGN RULES



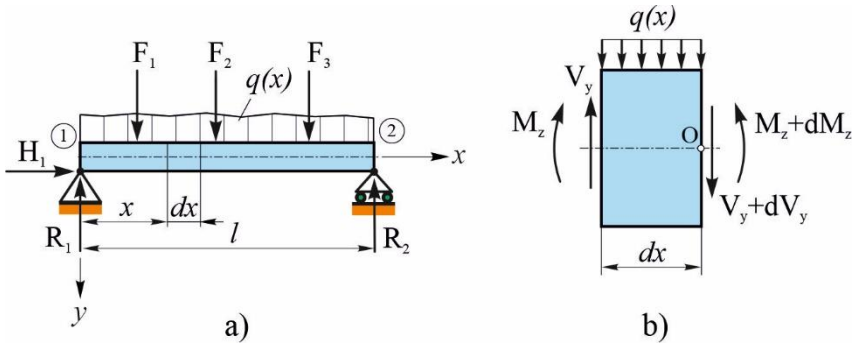
- Positive normal force N tends to elongate the element and a negative ones to compress it.
- A positive shear force V acts clockwise against the material and a negative shear force acts counterclockwise against the material. / Positive shear force tends to deform the element by causing the right-hand face to move downward with respect to the left-hand side.
- A positive bending moment M elongates the lower part of a beam and compresses the upper part.



Because the signs for shear force and B.M are related to the deformations of the material, these sign conventions are called deformation sign convention.
The deformations of an element caused by both positive and negative shear forces and bending moments are sketched in Figure.

Bending of Beams

DIFFERENTIAL RELATIONS BETWEEN SHEAR FORCE AND BENDING MOMENT



Let us consider an element of a beam cut out between two cross-sections d*x* apart. On the left-hand face of the element act shear force and bending moment in their positive directions. V&M on the right-hand face of the element are slightly different from their values on the left-hand face. If we denote the increments by dV and dM, respectively, then the corresponding resultant of internal forces are V+dV and M+dM.

The equilibrium of forces in the vertical direction leads to:

$$V_y - q(x)\cdot dx - (V_y + dV_y) = 0$$

Equation of the moments of point O:

$$M_z + V_y \cdot dx - q(x)\cdot dx \cdot \frac{dx}{2} - \left(M_z + dM_z\right) = 0$$

Relationships between Load, Shear Force and Bending Moment

$$\frac{dV_y}{dx} = -q(x);$$

$$\frac{dM_z}{dx} = V_y$$

$$\frac{d^2M_z}{dx^2} = \frac{dV_y}{dx} = -q(x)$$

- the rate of change of shear force V with respect to *x* is equal to –*q*.
- the rate of change of the bending moment M with respect to *x* is equal to the shear force

Bending of Beams

Consequences :

- When q=0, V=constant ⇒ dM/dx=constant ⇒bending moments varies linearly.
- When q = constant , V – varies linearly ⇒ M has parabolic variation.
- If force q is positive , shear force V decrease, and cavity of the bending moment are in the negative ordinates.
- Intensity q of the force is equal with the slope of tangent to shear force diagram.
- If shear force is positive the bending moment increases.
- If shear force is negative the bending moment decreases.
- Where V=0 ⇒ bending moment has an extreme value.
- At a point where concentrated load acts an abrupt change in the shear force occurs, the value of the jump is equal with the concentrated force F.
- At a point where concentrated couple acts an abrupt change in the bending moment occurs, the value of the jump is equal with the concentrated couple M.

$$\begin{cases} \dfrac{dT_y}{dx} = -q(x); \\ \dfrac{dM_z}{dx} = T_y \\ \dfrac{d^2M_z}{dx^2} = \dfrac{dT_y}{dx} = -q(x) \end{cases}$$

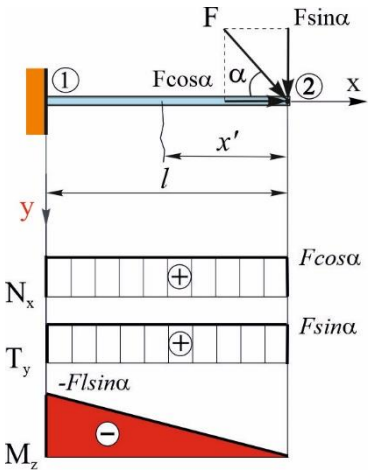
Bending of Beams

SHEAR FORCE & BENDING MOMENT DIAGRAMS

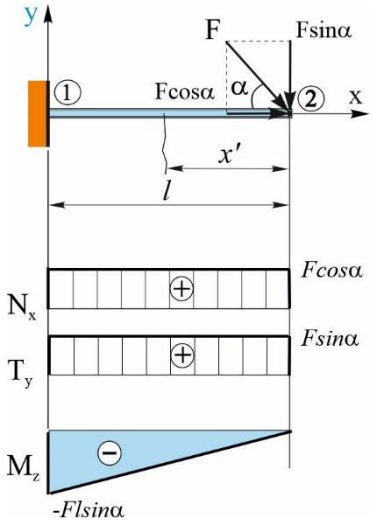
- The shear forces V and bending moments M in a beam are functions of the distance *x*, measured along the longitudinal axis.
- When designing a beam, it is desirable to know the values of V and M at all cross sections. A convenient way to provide this information is to draw graphs showing how V and M vary with *x*.
- To plot such a graph, we consider the abscissa as the position of the cross section (distance x) and we the ordinate as the corresponding value of either the shear force or the bending moment. These graphs are called **shear-force** and **bending moment diagrams**.

Plot conventions:

Romanian books

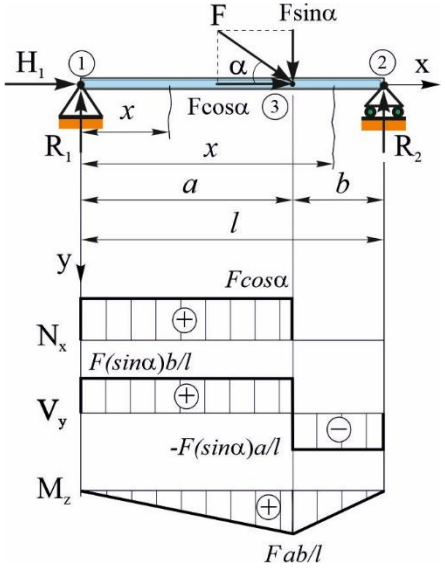


International books



Bending of Beams

SIMPLE SUPPORTED BEAM LOADED BY A CONCENTRATED FORCE



Reaction's calculus

$$H_1 + F\cos\alpha = 0 \qquad H_1 = -F\cos\alpha$$

$$R_1 l - F\sin\alpha \cdot b = 0 \qquad R_1 = F\sin\alpha\,\frac{b}{l} \qquad R_2 = F\sin\alpha\,\frac{a}{l}$$

$$-R_2 l + F\sin\alpha \cdot a = 0$$

Shear force & Bending moment diagrams

$x \in [0,\, a)$

$$N_x = -H_1 = F\cos\alpha$$

$$V_y = R_1 = F\sin\alpha \cdot \frac{b}{l}$$

$$M_z = R_1 \cdot x = F\sin\alpha \cdot \frac{b}{l} \begin{cases} x = 0 \Rightarrow M_z = 0 \\ x = a \Rightarrow M_z = F\sin\alpha \cdot \dfrac{b}{l} \end{cases}$$

$x \in [a,\, l)$

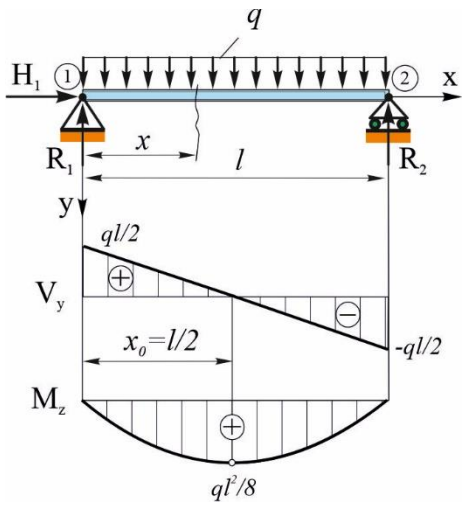
$$N_x = -H_1 - F\cos\alpha = F\cos\alpha - F\cos\alpha = 0$$

$$V_y = R_1 - F\sin\alpha = F\sin\alpha \cdot \frac{b}{l} - F\sin\alpha = F\sin\alpha \cdot \left(\frac{b-l}{l}\right) = -F\sin\alpha \cdot \frac{a}{l} = -R_2$$

$$M_z = R_1 \cdot x - F\sin\alpha \cdot (x-a) \begin{cases} x = a \Rightarrow M_z = F\sin\alpha \cdot \dfrac{a \cdot b}{l} \\ x = l \Rightarrow M_z = F\sin\alpha \cdot b - F\sin\alpha \cdot b = 0 \end{cases}$$

Bending of Beams

SIMPLE SUPPORTED BEAM LOADED BY A DISTRIBUTED FORCE



Reaction's calculus $R_1 = R_2 = \frac{q \cdot l}{2}$

Shear force & Bending moment diagrams

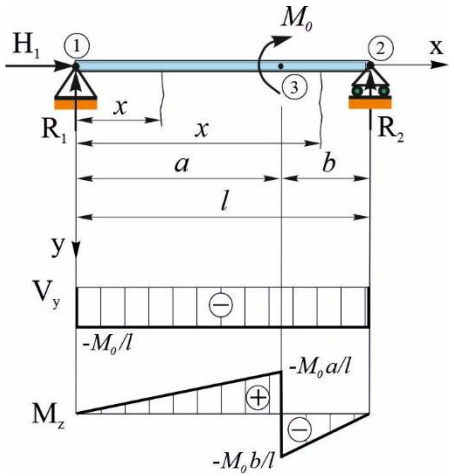
$x \in [0, l)$ $\quad V_y = R_1 - q \cdot x = \frac{q \cdot l}{2} - q \cdot x \begin{cases} x = 0 \Rightarrow V_y = \frac{q \cdot l}{2} \\ x = \frac{l}{2} \Rightarrow V_y = \frac{q \cdot l}{2} - q \cdot l = -\frac{q \cdot l}{2} = -R_2 \end{cases}$

$V_y = 0$ $\quad V_y = \frac{q \cdot l}{2} - q \cdot x_0 = 0 \Rightarrow x_0 = \frac{l}{2}$

$$M_z = R_1 \cdot x - \frac{q \cdot x^2}{2} \begin{cases} x = 0 \Rightarrow M_z = 0 \\ x = l \Rightarrow M_z = 0 \\ x = \frac{l}{2} \Rightarrow M_z = \frac{q \cdot l}{2} \cdot \frac{l}{2} - \frac{q \cdot l^2}{8} = \frac{q \cdot l^2}{8} \end{cases}$$

Bending of Beams

SIMPLE SUPPORTED BEAM LOADED BY A CONCENTRATED MOMENT



Reaction's calculus

$$R_1 l + M_0 = 0; \quad R_1 = -\frac{M_0}{l}$$

$$-R_2 l + M_0 = 0; \quad R_2 = \frac{M_0}{l}$$

Shear force & Bending moment diagrams

$x \in [0, a)$

$$V_y = R_1 = -\frac{M_0}{l}$$

$$M_z = R_1 \cdot x = -\frac{M_0}{l} x,$$

$$\rightarrow \begin{cases} x = 0 \Rightarrow M_z = 0 \\ x = a \Rightarrow M_z = -\dfrac{M_0 a}{l} \end{cases}$$

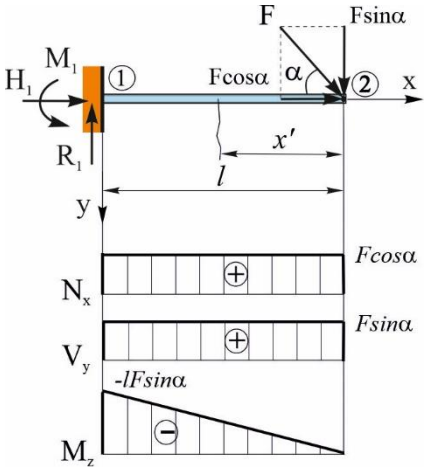
$x \in [0, l)$

$$V_y = R_1 = -\frac{M_0}{l}$$

$$M_z = R_1 x + M_0 = -\frac{M_0}{l} x + M_0 \quad \begin{cases} x = a \Rightarrow M_z = -\dfrac{M_0 b}{l} \\ x = l \Rightarrow M_z = 0 \end{cases}$$

Bending of Beams

CANTILEVER BEAM LOADED BY A CONCENTRATED FORCE



Reaction's calculus

Shear force & Bending moment diagrams

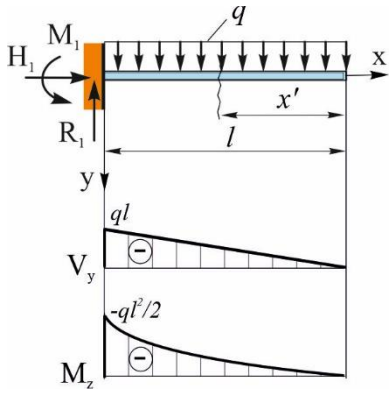
$$N_x = F\cos\alpha$$

$$V_y = F\sin\alpha$$

$$M_z = -F\sin\alpha\cdot x' \quad \Rightarrow \quad \begin{cases} x'=0 \Rightarrow V_y = 0 \\ x'=l \Rightarrow V_y = -F\sin\alpha\cdot l \end{cases}$$

Bending of Beams

CANTILEVER BEAM LOADED BY A DISTRIBUTED FORCE



Reaction's calculus

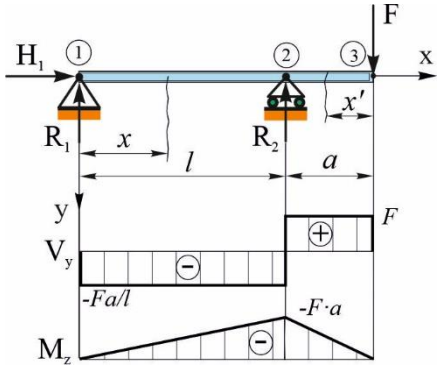
Shear force & Bending moment diagrams

$$x' \in [0, l) \qquad V_y = -qx' \quad \begin{cases} x'=0 \Rightarrow V_y = 0 \\ x'=l \Rightarrow V_y = -ql \end{cases}$$

$$M_z = -\frac{qx'^2}{2} \quad \begin{cases} x'=0 \Rightarrow M_z = 0 \\ x'=l \Rightarrow M_z = -\frac{ql^2}{2} \end{cases}$$

Bending of Beams

BEAM WITH AN OVERHANG LOADED BY A CONCENTRATED FORCE



Reaction's calculus

$$R_1 \cdot l + F \cdot a = 0 \quad \Rightarrow \quad R_1 = -F\frac{a}{l} \qquad\qquad -R_2 \cdot l + F \cdot (l+a) = 0 \quad \Rightarrow \quad R_2 = F\frac{l+a}{l}$$

Shear force & Bending moment diagrams

$x \in [0,\, l)$

$$V_y = R_1 = -F \cdot \frac{a}{l}$$

$$M_z = R_1 \cdot x = -F\frac{a}{l}x \quad \begin{cases} x = 0 \Rightarrow M_z = 0 \\ x = l \Rightarrow M_z = -Fa \end{cases}$$

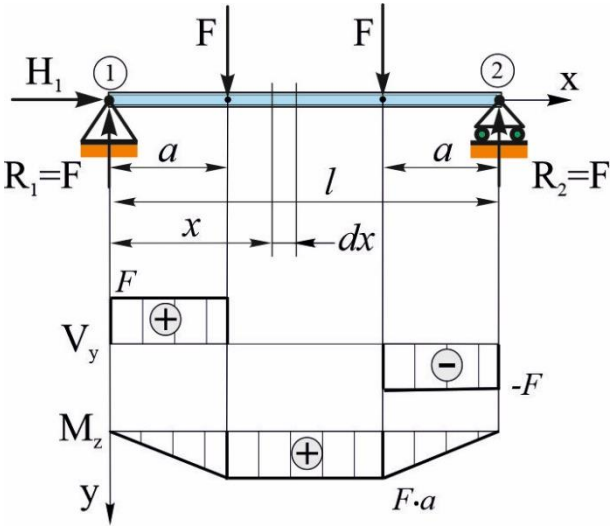
$x' \in [0,\, a)$

$$V_y = F$$

$$M_z = -F \cdot x' \quad \begin{cases} x' = 0 \Rightarrow M_z = 0 \\ x' = a \Rightarrow M_z = -Fa \end{cases}$$

Bending of Beams

NORMAL STRESSES IN BEAMS. FLEXURE FORMULA

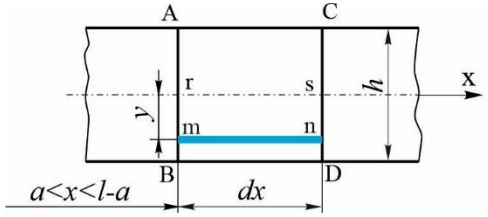


We will study a particular case of plane bending, namely the case of **pure bending**, when the only internal force in the section is the bending moment.

Between the elongated and the compressed fibers there is a surface, called the **neutral surface**, in which the fibers neither elongate nor shorten. The intersection of the neutral surface of the beam with its longitudinal plane of symmetry (xoy plane), which is also the plane of forces, is made after a fiber called **neutral fibre** of the beam.

We consider a volume element with length *dx*, separated from a beam in pure bending. The beam element will be analyzed before and after loading. According to Bernoulli's hypothesis, the plane and normal sections on the beam axis before deformation remain flat and normal on the axis and after deformation. After deformation, the two sections will make an angle $d\varphi$ between them, and the neutral fiber will have the radius of curvature ρ.

Bending of Beams



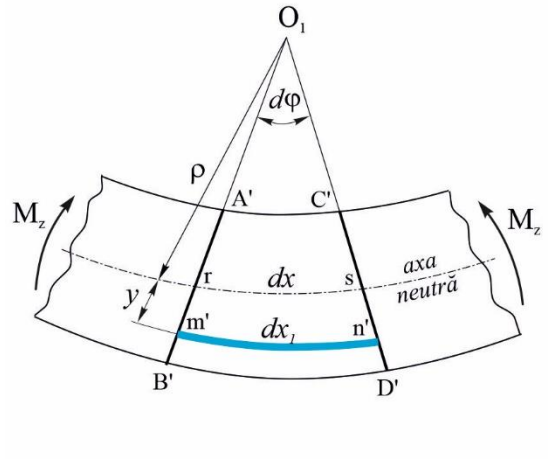
A fiber of length *dx* situated at distance *y* from the neutral fiber will have the same length before deformation as the neutral fiber.

$$dx = \rho\, d\varphi$$

After deformation, the fiber bends and lengthens $dx_1 = (\rho + y)\, d\varphi$

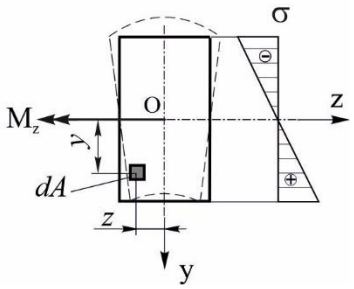
$$\Delta(dx) = dx_1 - dx = (\rho + y)\, d\varphi - \rho\, d\varphi = y\, d\varphi$$

The strain of this fiber is: $\varepsilon = \dfrac{\Delta(dx)}{dx} = \dfrac{y\, d\varphi}{\rho\, d\varphi} = \dfrac{y}{\rho} = \theta\, y,$



$$\theta = \frac{1}{\rho} = \frac{d\varphi}{dx},$$

Where θ represents the angle at which two cross sections on the beam rotate relative to each other.



There are a normal stress σ oriented along the fiber (x direction).

$$\sigma = E \cdot \varepsilon = E \cdot \frac{y}{\rho}; \quad \text{or} \quad \frac{1}{\rho} = \frac{\sigma}{E \cdot y}$$

The stress value is proportional to the distance *y* from the neutral axis. $\sigma_{max} = \dfrac{E \cdot y_{max}}{\rho}$

Bending of Beams

$$N_x = \int_A \sigma \, dA = 0; \quad M_y = \int_A \sigma \cdot z \, dA = 0; \quad M_z = \int_A \sigma \cdot y \, dA$$

$$\begin{cases} \int_A \sigma \, dA = \dfrac{E}{\rho} \int_A y \, dA = \dfrac{E}{\rho} S_z = 0; \\ \int_A \sigma \, z \, dA = \dfrac{E}{\rho} \int_A yz \, dA = \dfrac{E}{\rho} I_{zy} = 0; \\ \int_A \sigma \, y \, dA = \dfrac{E}{\rho} \int_A y^2 \, dA = \dfrac{E}{\rho} I_z = M_z. \end{cases}$$

From the first relation it results that the neutral axis of the section, the z axis, is the central axis (passes through centroid and the first moment of area is zero S_z=0). Thus, the origin O of the reference system coincides with the centroid of the cross section.

The second relation leads to the conclusion that I_{zy} must be zero, which assumes that the Oy axis is a principal axis of inertia.

$$M_z = \frac{E}{\rho} I_z \quad \text{sau} \quad \frac{1}{\rho} = \frac{M_z}{E I_z}$$

$$\frac{\sigma}{E \cdot y} = \frac{M_z}{E I_z} \Rightarrow \sigma = \frac{M_z \cdot y}{I_z},$$

where: I_z is the moment of inertia of the cross section about z axis; EI_z is the *stiffness modulus in bending*

Navier's formula

$$\sigma_{\max} = \frac{M \cdot y_{\max}}{I_z} = \frac{M_z}{W_z}$$

Flexure formula

$$W_z = \frac{I_z}{y_{\max}}$$

section modulus about the central axis Oz

Claude-Louis Navier (1785-1836)

https://en.wikipedia.org/wiki/Claude-Louis_Navier

Bending of Beams

Fundamental problems of strength of materials in bending*:

a) ***Design***. The maximum bending moment and the allowable stress of the materials are known, and is calculated the section modulus:

$$W_{z_{nec}} = \frac{M_{z_{\max}}}{\sigma_a}$$

b) ***Checking***. The beam's cross section and the maximum bending moment are known and is calculated the maximum normal stress and compared with the allowable stress of the material

$$\sigma_{ef} = \frac{M_{t_{\max}}}{W_{z_{ef}}} \leq \sigma_a$$

c) ***Allowable bending moment*** . The beam's cross section and the the allowable stress are known, the maximum bending moment that can be supported by the beam is:

$$M_{z_{\max}} = W_{z_{nec}} \cdot \sigma_a$$

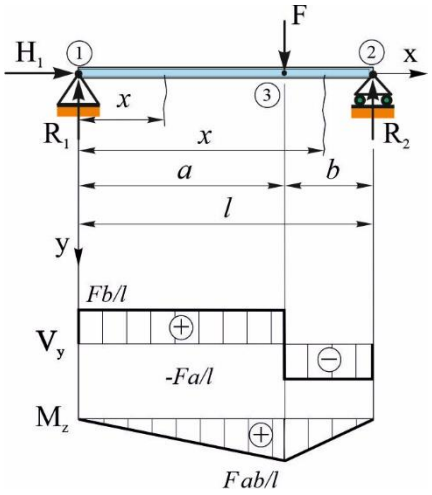
*The design (sizing) and checking of the beams is done for the dangerous/critical section, the section in which the bending moment, in absolute value, has its maximum.

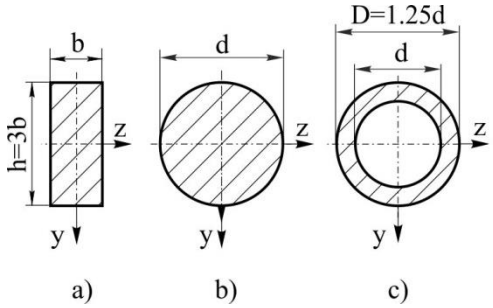
Bending of Beams

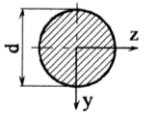
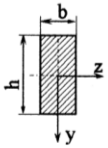
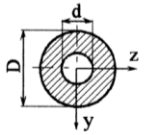
In bending, in order to achieve material savings, it is advisable to use sections with such shapes in which the distribution of material is predominant in the areas furthest from the centroid of the cross-section.

$$k = \frac{W_z}{A \cdot h}$$ *efficiency in bending*

Design the simple supported beam, loaded by a concentrated force, using the shapes of the cross section presented in figures a), b) and c).



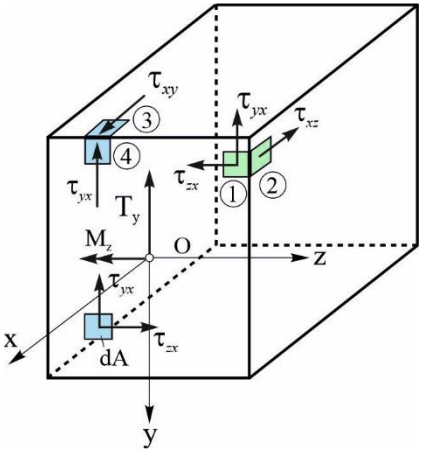


	I_z	y_{max}	W_z	k
	$\frac{\pi d^4}{64}$	$\frac{d}{2}$	$\frac{\pi d^3}{32}$	0,125
	$\frac{bh^3}{12}$	$\frac{h}{2}$	$\frac{bh^2}{6}$	0,167
	$\frac{\pi(D^4-d^4)}{64}$	$\frac{D}{2}$	$\frac{\pi(D^4-d^4)}{32D}$	$0{,}125\left(1+\frac{d^2}{D^2}\right)$
Profil laminat, I	Standardizat			0,29–0,32 Exp: **I 30** $k = 0{,}314$
Profil laminat, U	Standardizat			0,27-0,31 exp: **U 20** $k = 0{,}295$

Bending of Beams

SHEAR STRESSES IN BEAMS. SHEAR FORMULA

In addition to the bending moment, a shear force acts in the cross sections of the beams subjected to simple bending. This is the result of tangential stresses occurring in the beam section.



Shear stresses acting on an element separated from a beam subjected simple bending

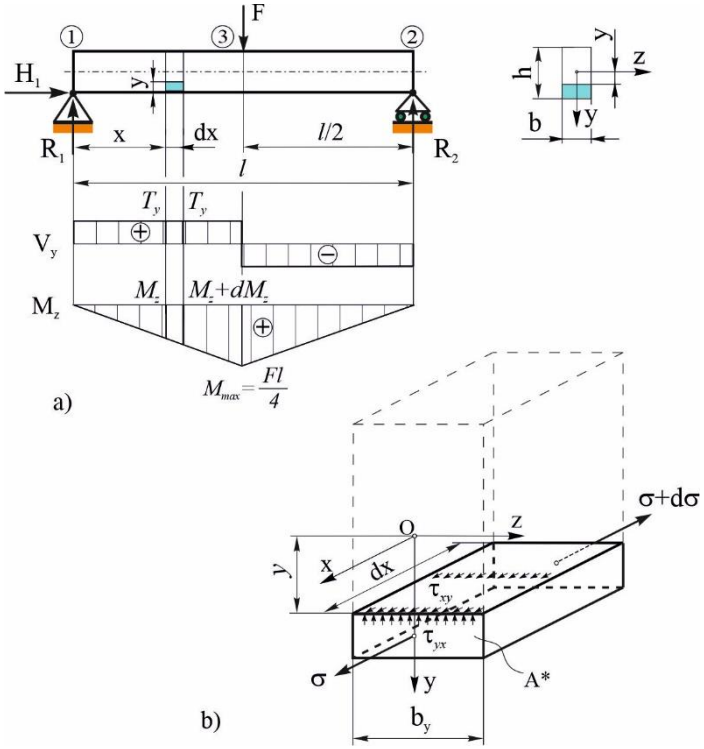
$$\int_A \tau_{yx}\, dA = T_y;$$

$$\int_A \tau_{zx}\, dA = T_z = 0$$

The second relation expresses the fact that the tangential stresses (shear stresses) τ_{zx} are zero, or of opposite signs, so that their resultant is zero.

At any point on the contour the shear stress τ is tangent to the contour.

Bending of Beams



$$\int_{A'} \sigma dA + \tau_{xy} \cdot b_y \cdot dx - \int_{A'} (\sigma + d\sigma) dA = 0$$

$$\sigma = \frac{M_z}{I_z} y \qquad \sigma + d\sigma = \frac{M_z + dM_z}{I_z} y$$

$$\int_{A^*} \sigma \, dA = \int_{A^*} \frac{M_z \cdot y}{I_z} dA = \frac{M_z}{I_z} \int_{A^*} y \, dA = \frac{M_z}{I_z} S_z^*;$$

$$\int_{A^*} (\sigma + d\sigma) \, dA = \int_{A^*} \frac{(M_z + dM_z)}{I_z} dA = \frac{M_z + dM_z}{I_z} \int_{A^*} y \, dA = \frac{M_z + dM_z}{I_z} S_z^*,$$

$$-\frac{M_z}{I_z} S_z^* - \tau_{xy} b_y \, dx + \frac{M_z + dM_z}{I_z} S_z^* = 0, \qquad \tau_{yx} = \tau_{xy} = \frac{dM_z}{dx} \cdot \frac{S_z^*}{b_y I_z}$$

$$\tau_{yx} = \tau_{xy} = \frac{T_y \cdot S_z^*}{b_y \cdot I_z}$$

Shear formula

- A^* – cross-sectional area of the beam member;

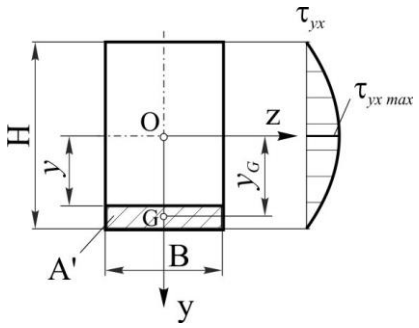
$$S_z^* = \int_{A^*} y \, dA$$

https://en.wikipedia.org/wiki/Dmitrii_Ivanovich_Zhuravskii

- S_z^*- first moment of area of the cross section of an element situated at distance y about the neutral axis or first moment of sliding area,
- I_z – moment of inertia of the entire cross-section about the neutral axis
- b_y width of the cross-section at ordinate y.

Bending of Beams

RECTANGLE



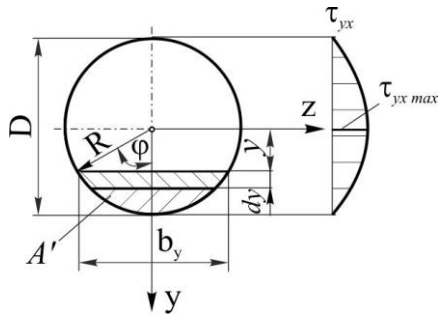
$$S_z^* = \int_{A'} y\,dA = y_G \cdot A^* = \left(y - \frac{\frac{H}{2} - y}{2} \right) \cdot B \cdot \left(\frac{H}{2} - y \right) = \frac{B}{2} \cdot \left(\frac{H^2}{4} - y^2 \right),$$

$$I_z = \frac{B \cdot H^3}{12}; \qquad b = B; \qquad B \cdot H = A;$$

$$\tau_{yx} = \frac{T_y \cdot \frac{B}{2} \left(\frac{H^2}{4} - y^2 \right)}{B \cdot \frac{B \cdot H^3}{12}} = \frac{6T_y \left(\frac{H^2}{4} - y^2 \right)}{B \cdot H^3}$$

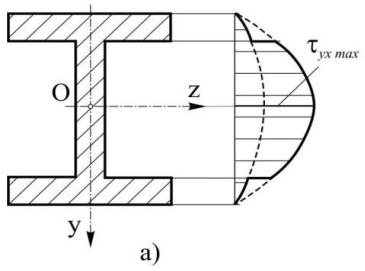
$$\tau_{yx\max} = \frac{6T_y \cdot H^2}{4B \cdot H^3} = \frac{3}{2} \cdot \frac{T_y}{A}$$

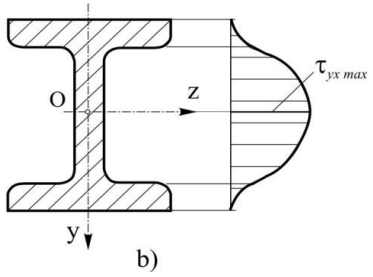
CIRCLE



$$\tau_{yx\max} = \frac{4}{3} \cdot \frac{T}{A}$$

I SHAPE



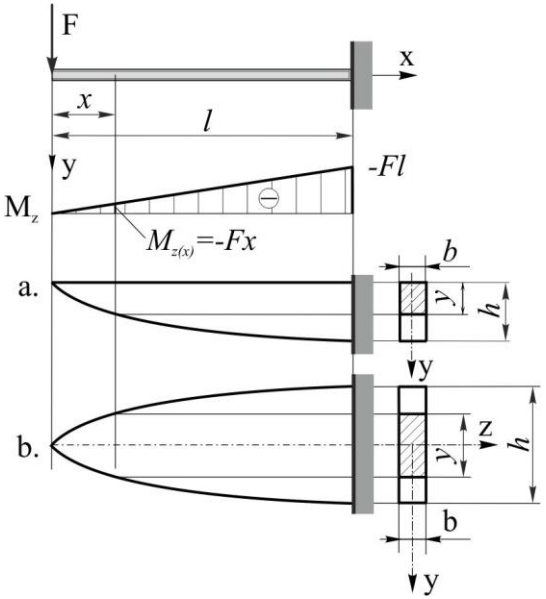


Bending of Beams

Fully Stressed beams

The beam in which the normal stress in each cross-section has the same value is called fully stressed beam.

Cantilever beam with rectangular cross-section and constant width loaded by a concentrated force at the free end



$$M_{z(x)} = -F \cdot x$$

$$W_{z(x)} = \frac{M_{z(x)}}{\sigma_a} = \frac{F \cdot x}{\sigma_a}$$

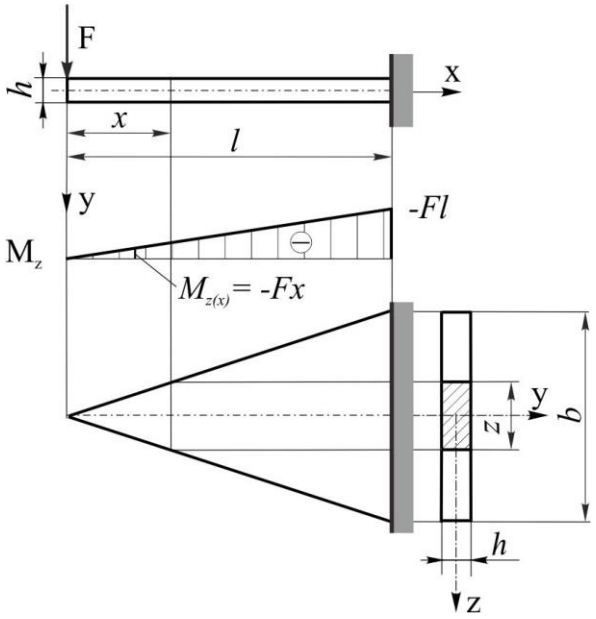
$$W_{z_{(x)}} = \frac{b \cdot y^2}{6}$$

$$\frac{b \cdot y^2}{6} = \frac{F \cdot x}{\sigma_a} \Rightarrow$$

$$y = \sqrt{\frac{6F \cdot x}{b \cdot \sigma_a}} \qquad y_{\max} = h = \sqrt{\frac{6F \cdot l}{b \cdot \sigma_a}}$$

Bending of Beams

CANTILEVER BEAM WITH RECTANGULAR CROSS-SECTION AND CONSTANT THICKNESS LOADED BY A CONCENTRATED FORCE AT THE FREE END



$$M_{z(x)} = -F \cdot x$$

$$W_{z(x)} = \frac{zh^2}{6}$$

$$\frac{z \cdot h^2}{6} = \frac{F \cdot x}{\sigma_a}$$

$$z = \frac{6 \cdot F \cdot x}{h^2 \cdot \sigma_a}$$

$$z_{\max} = b = \frac{6Fl}{h^2 \sigma_a}$$

Bending of Beams

On-line classes: **JAMK**

Direct bending theory: Suora taivutus (jamk.fi)

Example 1: Palkin taivutuksesta aiheutuvat normaali- ja leikkausjännitys esimerkki 1
Normal and shear stresses from bending example 1 (jamk.fi)

Example 2: Palkin taivutuksesta aiheutuvat normaali- ja leikkausjännitys esimerkki 2
Normal and shear stresses from bending example 2 (jamk.fi)

C1 – Strength of Materials

M1 - Bending of beams

Theoretical and Experimental Aplications

HEI name: Technical University of Cluj-Napoca (TUCN)

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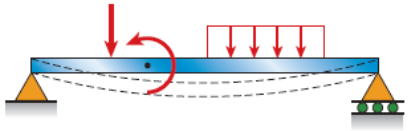
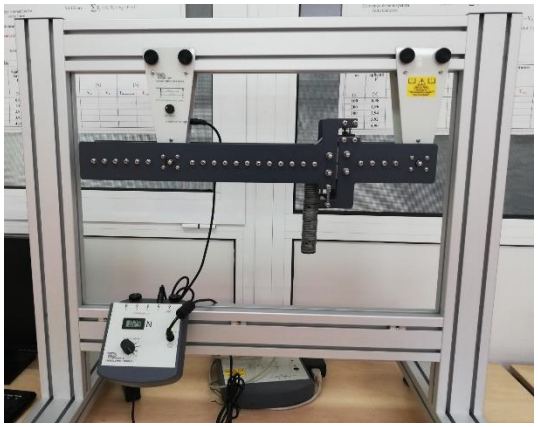
Module 1 - Bending of beams

Theoretical and Experimental Aplications





Module 1 - Bending of beams

Theoretical and Experimental Aplications

Upon completion of this module, the student will be able to:

1) Calculate the reactions for beams subjected to plane bending
2) Calculate and draw the diagrams for shear forces and bending moments
3) To perform experimental measurements of shear forces and bending moments.

Content

- Introduction - Theoretical backgrounds
- Topic 1: Beams subjected to plane bending (Theoretical Applications)

  Topic 1.1: Simple supported beam

  Topic 1.2: Cantilever beam
- Topic 2: Beams subjected to plane bending (Experimental Applications)

  Topic 2.1: Shear force in a beam subjected to plane bending

  Topic 2.2: Bending moment in a beam subjected to plane bending

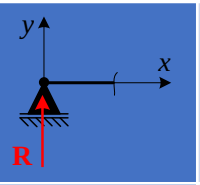
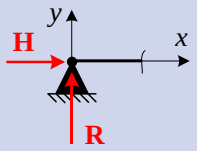
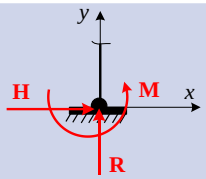
Introduction

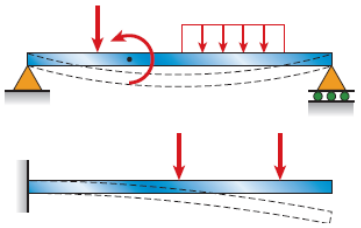
Introduction

Theoretical backgrounds

A beam is subjected to plane bending if external forces are applied perpendicular to the longitudinal axis of the beam, or bending moments are in the same plane as the longitudinal axis of the beam, and the deformation occurring in the plane of the forces.

▪ **Type of supports and reactions**

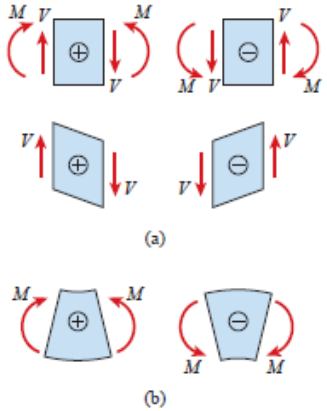
1. Simple support (roller)	2. Fixed or articulated support	3. Fixed support
		
Reaction: ▪ Vertical reaction (force), R	**Reactions:** ▪ Horizontal (H) and vertical forces (R)	**Reactions:** ▪ Horizontal (H) and vertical forces (R), bending moment (M)



Examples of beams subjected to plane bending:
(a) simple supported beam;
(b) fixed beam (cantilever beam)

▪ **Sign convention for efforts calculus**

When a beam is loaded by forces or couples, stresses and strains are created throughout the interior of the beam. To determine these stresses and strains, we first must find the internal forces and internal couples that act on cross sections of the beam. For the calculation of efforts, the sign convention presented below must be considered.



Sign conventions for shear force *V* and bending moment *M*

Deformations (highly exaggerated) of a beam element caused by (a) shear forces, and (b) bending moments

▪ Shear force and bending moments diagrams

When designing a beam, it is necessary to know how the shear forces and bending moments vary throughout the length of the beam. Of special importance are the maximum and minimum values of these quantities.

Information of this kind is usually provided by graphs in which the shear force and bending moment are plotted as ordinates and the distance *x* along the axis of the beam is plotted as the abscissa. Such graphs are called **shear-force and bending-moment diagrams**.

Shear force and bending moment diagrams – Steps

1. A direction of travel of the beam is established
2. Enter the plane reference system (xOy)
3. The supports are identified, and the reactions related to the type of support are introduced
4. The reactions in the supports are calculated by applying the static equilibrium equations:

$$\sum F_x = 0;\ \sum F_y = 0;\ \sum M_o = 0$$

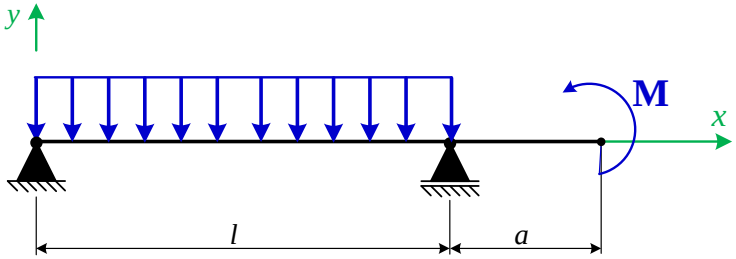
5. The relations of efforts (N, V, M) are written on each interval, considering the convention of the signs of the efforts
6. With the obtained values of the efforts, the shear force and bending moments diagrams are plotted
7. The maximum values of the efforts are noted.

Topic 1: Beams subjected to plane bending (Theoretical Applications)

Topic 1.1

Simple supported beam

For the given simple supported beam and loaded as in the figure, it is necessary to:

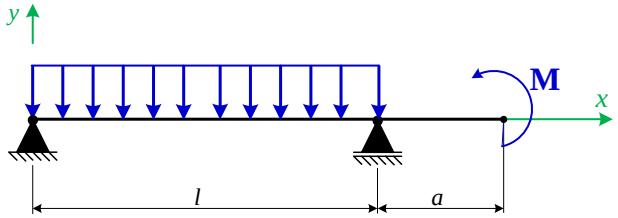


a) Calculate the reactions in the supports;

b) Calculate the internal forces and moments (T and Mi) in the cross section of the beam;

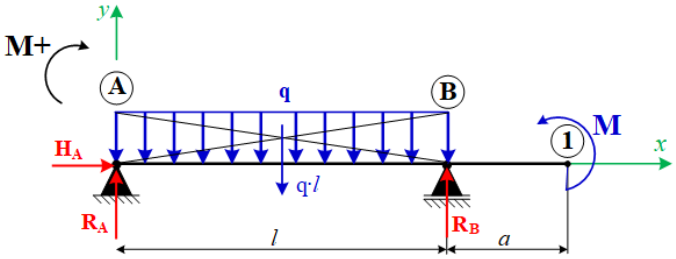
c) Draw the shear force and bending moment diagrams;

d) Write the maximum efforts.



Input data:
M = 4 kN·m; q = 10 kN/m; *a* = 0.5 m; *l* = 1 m.

a) Reactions calculus in the supports



$$\sum F_x = 0 \rightarrow H_A = 0$$

$$\sum M_A = 0; q \cdot l \cdot \frac{l}{2} - R_B \cdot l - M = 0 \rightarrow R_B = \frac{1}{l} \cdot \left(q \cdot l \cdot \frac{l}{2} - M \right)$$

$$\rightarrow R_B = \frac{1}{1} \cdot \left(10 \cdot 1 \cdot \frac{1}{2} - 4 \right) \rightarrow R_B = 1\ kN$$

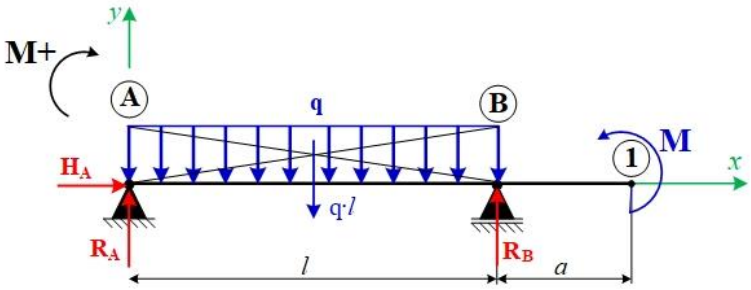
$$\sum M_B = 0; R_A \cdot l - q \cdot l \cdot \frac{l}{2} - M = 0 \rightarrow R_A = \frac{1}{l} \cdot \left(q \cdot l \cdot \frac{l}{2} + M \right)$$

$$\rightarrow R_A = \frac{1}{1} \cdot \left(10 \cdot 1 \cdot \frac{1}{2} + 4 \right) \rightarrow R_A = 9\ kN$$

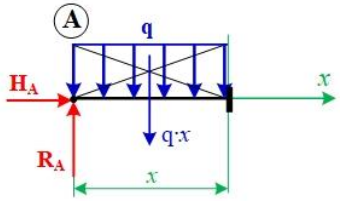
Check of the results: $\sum F_y = 0 \rightarrow R_A + R_B - q \cdot l = 0$

$9 + 1 - 10 \cdot 1 = 0 \rightarrow 0 = 0$

b) Shear forces (V) and bending moments (M) in the cross-section of the beam



Interval A – B: $x \in [0; l)$; $x \in [0; 1)$



Shear force $\boxed{V_{1-2} = R_A - q \cdot x}$

$$x = 0 \rightarrow R_A = R_A \rightarrow V_A = 9\ kN$$
$$x = l \rightarrow V_B = R_A - q \cdot l$$
$$x = 1 \rightarrow V_B = 9 - 10 \cdot 1$$
$$\rightarrow V_B = -1\ kN$$

The maximum moment occurs where the shear force equals zero. This point can be found by setting the shear force equal to zero and solving for the value of *x*, which is denoted by *x*0. The result is:

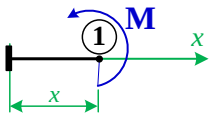
$V_{A\text{-}B} = 0 \rightarrow M_{max_A\text{-}B.}$

$$V_{A-B} = 0 \rightarrow R_A - q \cdot x_0 = 0 \rightarrow x_0 = \frac{R_A}{q} \rightarrow x_0 = \frac{9}{10} \rightarrow x_0 = 0.9\ m$$

Bending moment $\boxed{M_{A-V} = R_A \cdot x - q \cdot x \cdot \frac{x}{2}}$

$$x = 0 \rightarrow M_A = 0$$
$$x = l \rightarrow M_B = R_A \cdot l - q \cdot l \cdot \frac{l}{2}$$
$$x = 1 \rightarrow M_B = 9 \cdot 1 - 10 \cdot 1 \cdot \frac{1}{2} \rightarrow M_B = 4\ kN \cdot m$$
$$x = x_0 = 0.9 \rightarrow M_{maxA_B} = 9 \cdot 0.9 - 10 \cdot 0.9 \cdot \frac{0.9}{2}$$
$$\rightarrow M_{maxA_B} = 4.05\ kN \cdot m$$

Interval 1 – B: $x \in [0; l)$; $x \in [0; 0.5)$



Shear force

$$V_{1-B} = 0$$

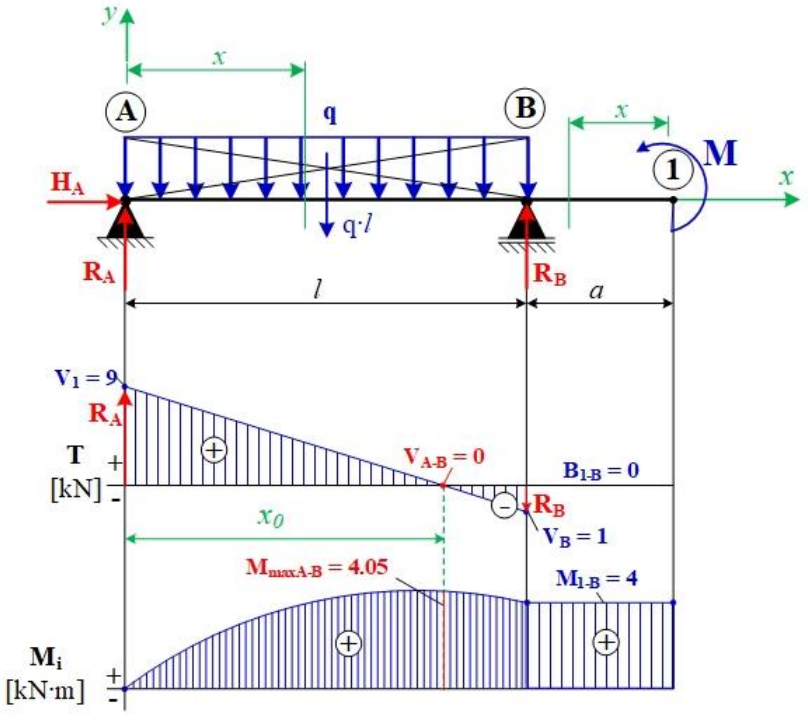
Bending moment

$$M_{1-B} = M$$

$$\rightarrow M_{1-B} = 4\ kN \cdot m$$

c) Shear forces and bending moments diagrams

The corresponding shear-force and bending-moment diagrams are shown in the following figure:



d) Write the maximum efforts.

The maximum shear force (V) and bending moment (M) are: $V_{max} = R_A = 9$ kN; $M_{max} = M_{maxA-B} = 4.05$ kN·m

Topic 1.2

Cantilever beam

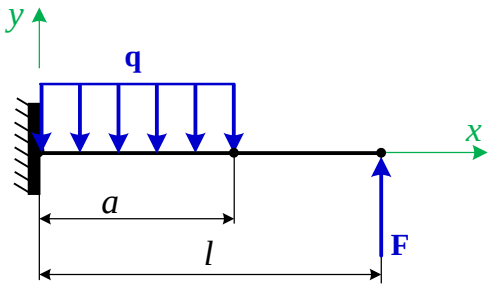
For the given cantilever beam and loaded as in the figure, it is necessary to:

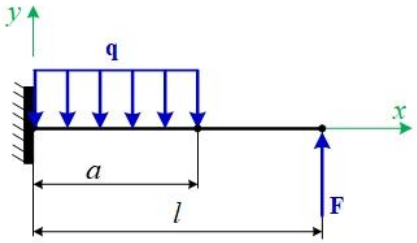
a) Calculate the reactions in the supports;

b) Calculate the internal forces and moments (T and Mi) in the cross section of the beam;

c) Draw the shear force and bending moment diagrams;

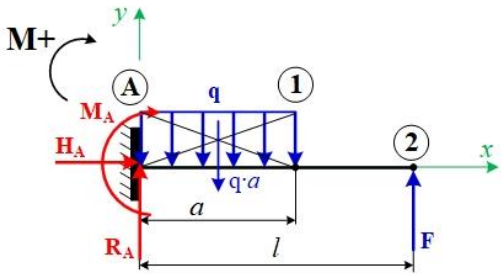
d) Write the maximum efforts.





Input data:
F = 8 kN; q = 12 kN/m; a = 0.5 m; l = 1.2 m.

a) Reactions calculus in the supports



$$\sum F_x = 0 \rightarrow H_A = 0$$

$$\sum F_y = 0 \rightarrow R_A - q \cdot a + F = 0 \rightarrow R_A = q \cdot a - F$$

$$\rightarrow R_A = 12 \cdot 0.5 - 8 \rightarrow R_A = -2\ kN$$

$$\sum M_A = 0;\ M_A + q \cdot a \cdot \frac{a}{2} - F \cdot l = 0 \rightarrow\ M_A = -q \cdot a \cdot \frac{a}{2} + F \cdot l$$

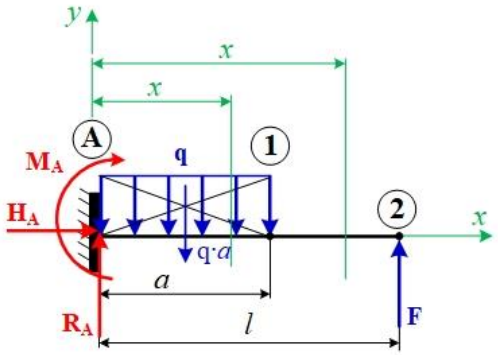
$$\rightarrow\ M_A = -12 \cdot 0.5 \cdot \frac{0.5}{2} + 8 \cdot 1.2 \rightarrow\ M_A = 8.1\ kN \cdot m$$

Check of the results: $\sum M_2 = 0;\ M_A + R_A \cdot l - q \cdot a \cdot \left(l - \frac{a}{2}\right) = 0$

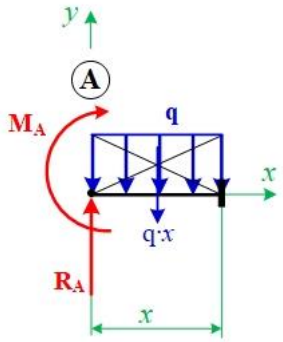
$$\rightarrow 8.1 - 2 \cdot 1.2 - 12 \cdot 0.5 \cdot \left(1.2 - \frac{0.5}{2}\right) = 0$$

$$\rightarrow 0 = 0$$

b) Shear forces (V) and bending moments (M) in the cross-section of the beam



Interval A – 1: $x \in [0; a)$; $x \in [0; 0.5)$



Shear force

$$\boxed{V_{A-1} = R_A - q \cdot x}$$

$$x = 0 \rightarrow V_A = R_A \rightarrow V_A = -2\ kN$$

$$x = a \rightarrow V_A = R_A - q \cdot a$$

$$x = 0{,}5 \rightarrow V_B = -2 - 12 \cdot 0.5$$

$$\rightarrow V_B = -8\ kN$$

Bending moment

$$\boxed{M_{A-1} = R_A \cdot x - q \cdot x \cdot \frac{x}{2} + M_A}$$

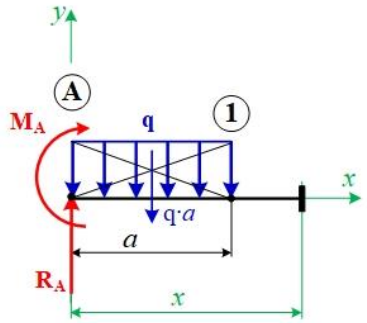
$$x = 0 \rightarrow M_A = M_A = 8.1\ kN \cdot m$$

$$x = a \rightarrow M_1 = R_A \cdot a - q \cdot a \cdot \frac{a}{2} + M_A$$

$$x = 0{,}5 \rightarrow M_1 = -2 \cdot 0.5 - 12 \cdot 0.5 \cdot \frac{0.5}{2} + 8.1$$

$$\rightarrow M_1 = 5.6\ kN \cdot m$$

Interval 1 – 2: $x \in [a; l)$; $x \in [0.5; 1.2)$



Shear force

$$\boxed{V_{1-2} = R_A - q \cdot a}$$

$$\rightarrow V_{1-2} = -2 - 12 \cdot 0.5 \rightarrow V_{1-2} = -8\ kN$$

Bending moment

$$\boxed{M_{1-2} = R_A \cdot x - q \cdot a \cdot \left(x - \frac{a}{2}\right) + M_A}$$

$$x = a \rightarrow M_1 = R_A \cdot a - q \cdot a \cdot \left(a - \frac{a}{2}\right) + M_A$$

$$x = 0.5 \rightarrow M_1 = -2 \cdot 0.5 - 12 \cdot 0.5 \cdot \left(0.5 - \frac{0.5}{2}\right) + 8.1$$

$$\rightarrow M_1 = 5.6\ kN \cdot m$$

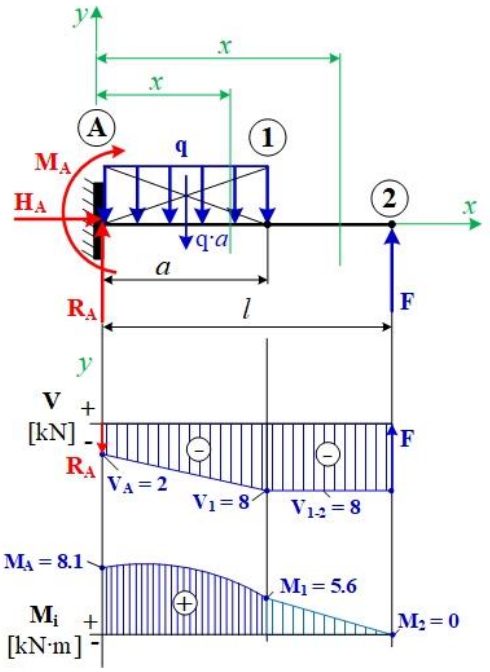
$$x = l \rightarrow M_2 = R_A \cdot l - q \cdot a \cdot \left(l - \frac{a}{2}\right) + M_A$$

$$x = 1.2 \rightarrow M_2 = -2 \cdot 1.2 - 12 \cdot 0.5 \cdot \left(1.2 - \frac{0.5}{2}\right) + 8.1$$

$$\rightarrow M_2 = 0\ kN \cdot m$$

c) Shear forces and bending moments diagrams

The corresponding shear-force and bending-moment diagrams are shown in the following figure:



d) Write the maximum efforts.

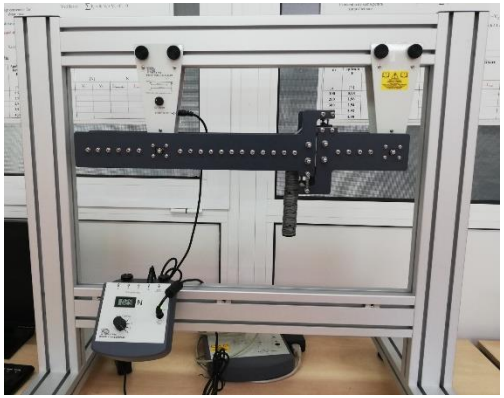
The maximum shear force (V) and bending moment (M) are:

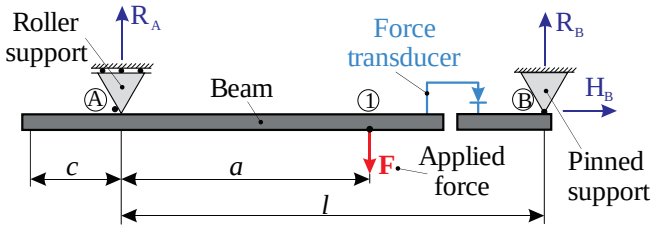
$V_{max} = V_{1-2} = 8$ kN; $M_{max} = M_A = 8.1$ kN·m

Topic 2: Beams subjected to plane bending (Experimental Applications)

Topic 2.1

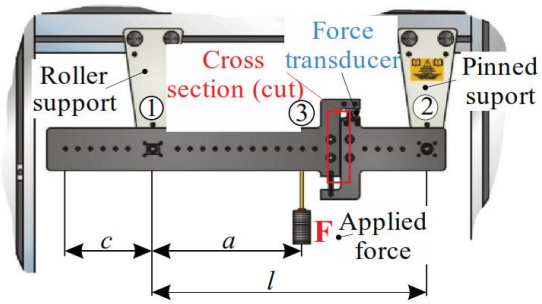
Shear force in a beam subjected to plane bending

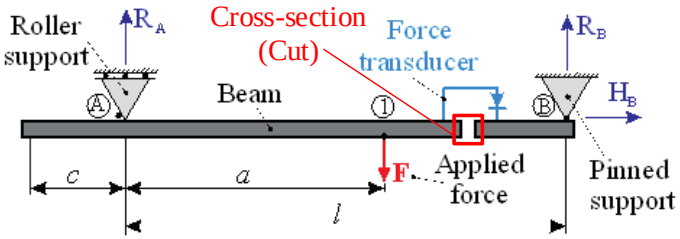


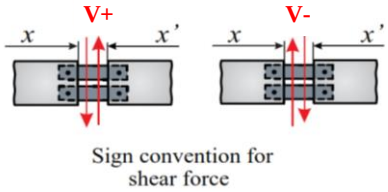


Experiment – Shear force variation under external loads

Laboratory Aim: Experimental determination of shear force in a beam subjected to bending and comparison with the calculated (theoretical) values.

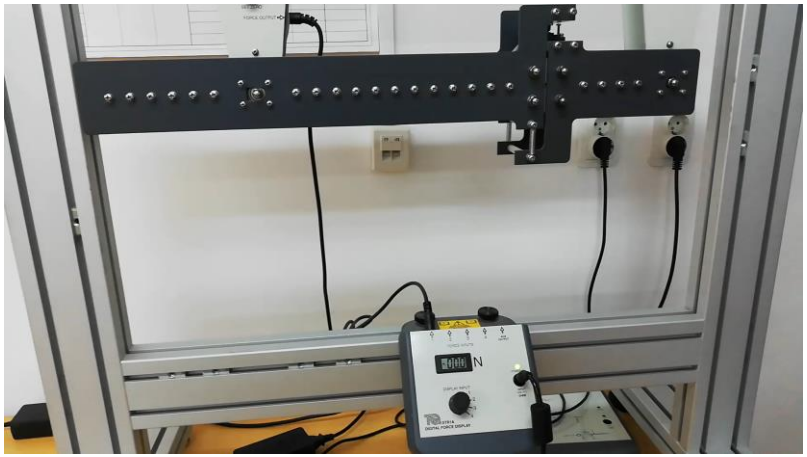




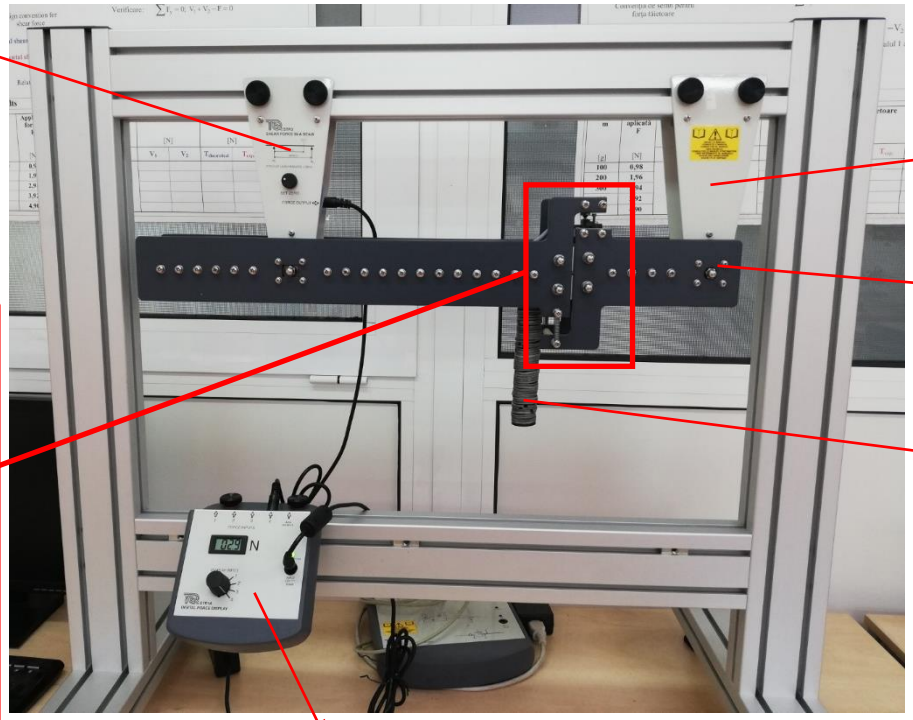


▪ The following steps will be taken to perform the experimental measurements:

1. The force transducer is connected to channel 1 of the digital force display via the signal conditioning system (mounted in the roller support);
2. It is checked if channel 1 shows 'zero' value. Otherwise, the 'zero' shall be set by means of the adjusting potentiometer (SET ZERO), considering the weight of the hanging rod of the applied mass;
3. It is applied the mass of 100 g to the left of the section, at "*a*" distance from roller support
4. The shear force in the cross section is measured by a force transducer mounted above the cross section of the beam. The value of the shear force is indicated by the digital display of the force transducer of the experimental set-up;
5. The measurements are repeated for masses from 200 g to 500 g;
6. The experimental values of the shear forces are introduced in the Table of results



Experimental set-up



Cross-section of the beam and force transducer

1. Theoretical calculus of shear force, $V_{theoretical}$

Known data: applied forces, **F [N] –** given in Results table;

a = 260mm; l = 440 mm

▪ ***Calculate the reaction forces using the relations below (obtained from equilibrium equations):***

$$R_A = F \cdot \frac{(l-a)}{l}, N \qquad (1)$$

$$R_B = F \cdot \frac{a}{l}, N \qquad (2)$$

▪ ***Calculate the shear force ($V_{theoretical}$) in the cross section by applying one of the relationships below***

$$V_{left} = R_A - F \quad \text{or} \quad V_{right} = -R_B \qquad (3)$$

Theoretical values of vertical reactions and shear forces must be introduced in Results table.

2. Experimental shear force in cross-section, V_{exp}

▪ The experimental values of the shear force for each applied mass obtained from the measurements are given in the Table of results.

Results table

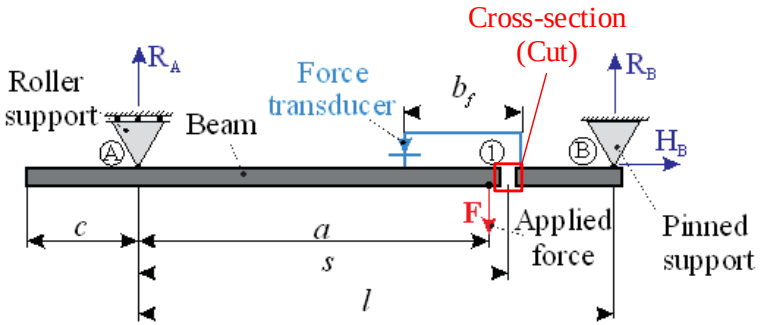
Mass m [g]	Applied force, F [N]	Distances [mm]			Reactions [N]		Shear force [N]		Rel. dev. [%]
		a	*c*	*l*	R_A	R_B	$V_{teoretic}$	$V_{exp.}$	
100	0.98	260	-	440				0.6	
200	1.96							1.2	
300	2.94							1.7	
400	3.92							2.3	
500	4.90							2.9	

$$Rel.dev. = \left| \frac{|V_{exp}| - |V_{theoretical}|}{|V_{exp}|} \right| \cdot 100 \rightarrow [\%]$$

Relative deviation calculus must be performed and introduced in Results table.

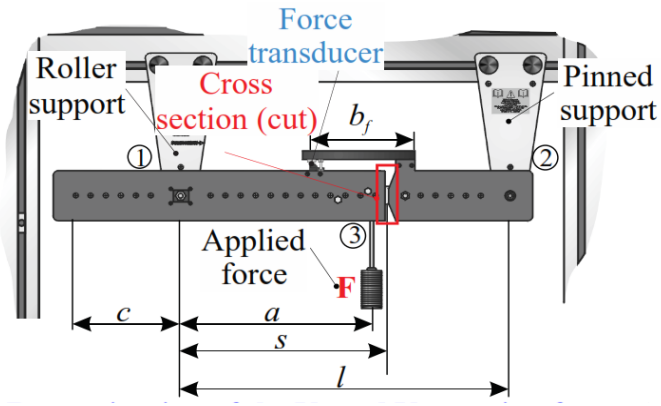
Topic 2.2

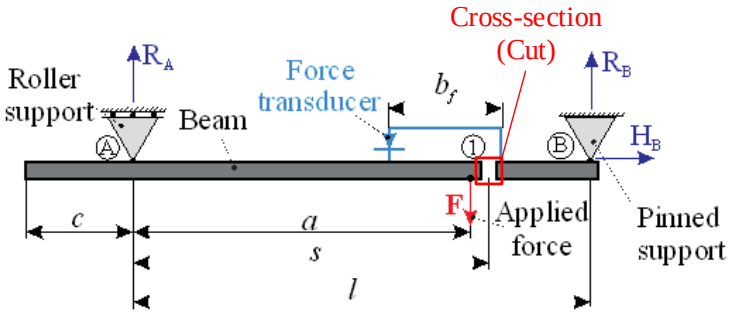
Bending moment in a beam subjected to plane bending

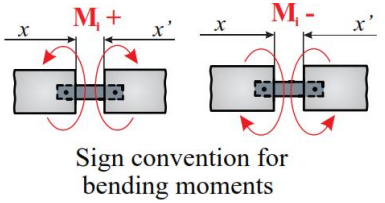


Laboratory Aim: Experimental determination of the bending moment in a beam subjected to plane bending and comparison with the calculated (theoretical) values.

Experiment – Bending moment variation under external loads



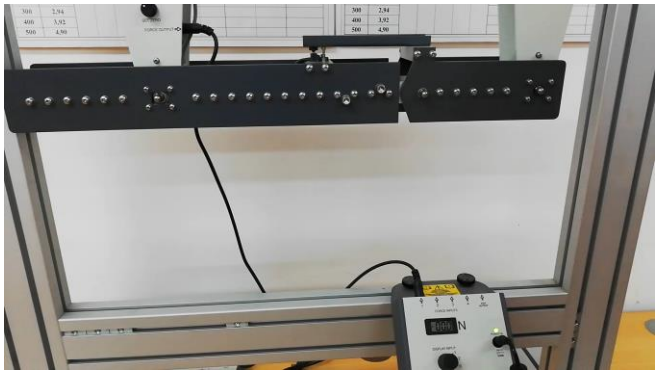




▪ The following steps will be taken to perform the experimental measurements:

1. The force transducer is connected to channel 1 of the digital force display via the signal conditioning system (mounted in the roller support);
2. It is checked if channel 1 shows 'zero' value. Otherwise, the 'zero' shall be set by means of the adjusting potentiometer (SET ZERO), considering the weight of the hanging rod of the applied mass;
3. It is applied the mass of 100 g to the left of the section, at "a" distance from roller support
4. The experimental bending moment is determined by multiplying the force value indicated on the digital display with b_f (moment arm):

$$M_{i_{exp.}} = F_{display} \cdot b_f$$

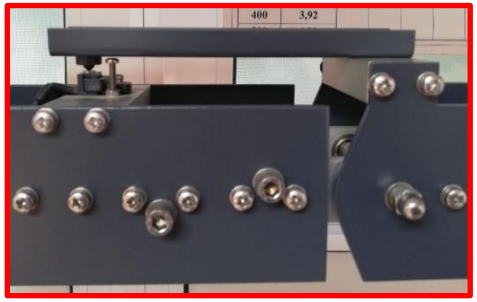


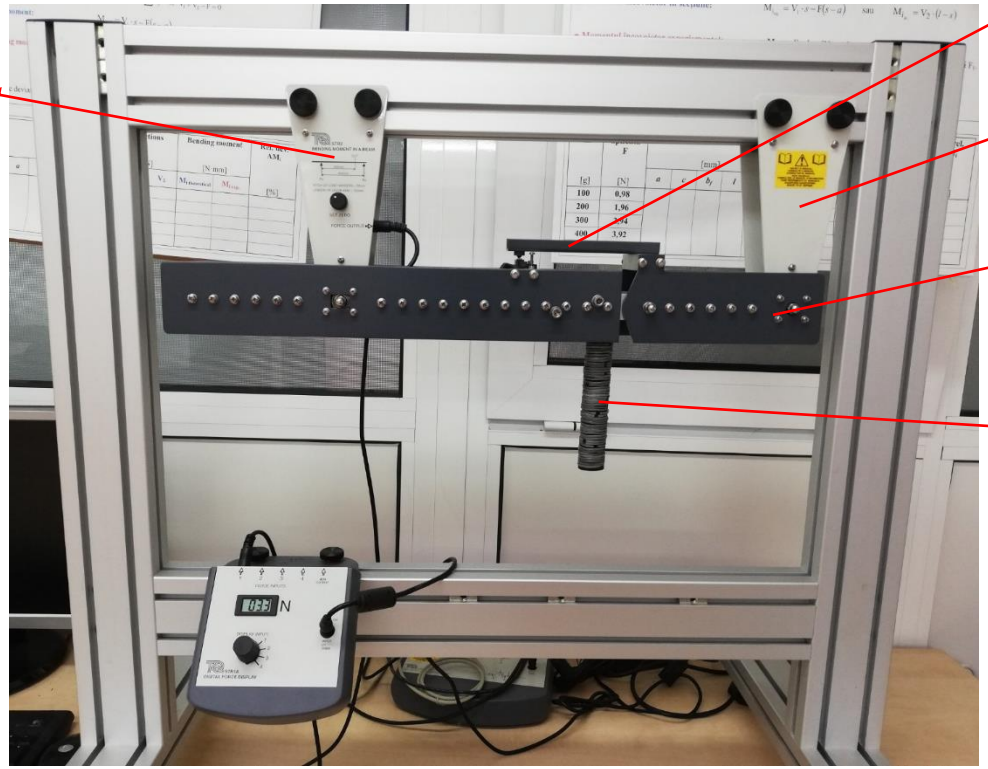
5. The measurements are repeated for masses from 200 g to 500 g;
6. The experimental values of the bending moments are introduced in the Table of results

Experimental set-up

Roller support

Cross-section of the beam and force transducer





Force arm (b_f)

Pinned support

Beam

Applied mass (force)

1. Theoretical calculus of bending moment, $M_{i_theoretical}$

Known data: applied forces, **F [N] –** are given in Results table;

a = 260mm; l = 440 mm; b_f = 125 mm; s = 300 mm.

▪ ***Calculate the reaction forces using the relations below (obtained from equilibrium equations):***

$$R_A = F \cdot \frac{(l-a)}{l}, N \quad (1)$$

$$R_B = F \cdot \frac{a}{l}, N \quad (2)$$

▪ ***Calculate the bending moment ($M_{i_theoretical}$) in the cross section by applying one of the relationships below***

$$M_{i_left} = R_A \cdot s - F(s-a) \quad \text{or} \quad M_{i_right} = R_B(l-s) \quad (3)$$

Theoretical and experimental values must be introduced in Results table.

Relative deviation calculus must be performed and introduced in Results table.

2. Experimental bending moment in cross section, M_{i_exp}

- Is calculated with the relation: $M_{i_{exp.}} = F_{display} \cdot b_f$

The following forces in the section were read from the experimental: stand:

Mass m [g]	$F_{display}$ [N]
100	0.7
200	1.4
300	2
400	2.6
500	3.3

$$Rel.dev. = \left| \frac{|M_{i_{exp.}}| - |M_{i_theoretical}|}{|M_{i_{exp.}}|} \right| \cdot 100 \rightarrow [\%]$$

Table results

Mass m [g]	Applied force, F [N]	Distances [mm]					Reactions [N]		Bending moment [N·mm]		Rel. dev. [%]
		a	*c*	b_f	*l*	*s*	R_A	R_B	$M_{i\ teoretic}$	$M_{i\ exp.}$	
100	0.98	260	-	125	440	300				$F_{display} \cdot b_f$	
200	1.96									$F_{display} \cdot b_f$	
300	2.94									$F_{display} \cdot b_f$	
400	3.92									$F_{display} \cdot b_f$	
500	4.90									$F_{display} \cdot b_f$	

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C1 – Strength of Materials

M2 – Torsion of Bars

HEI name: Technical University of Cluj-Napoca (TUCN)

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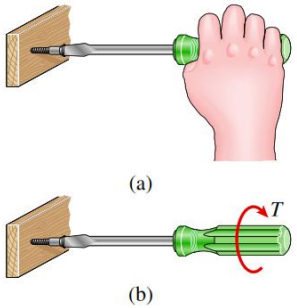
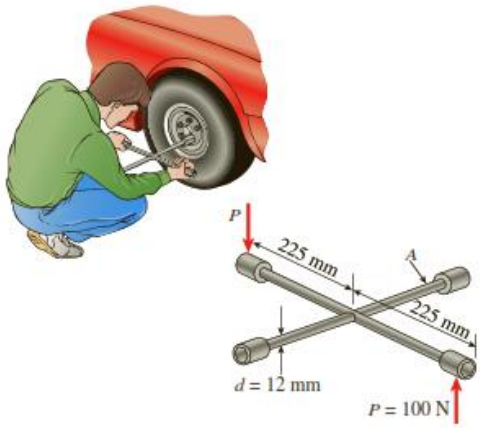
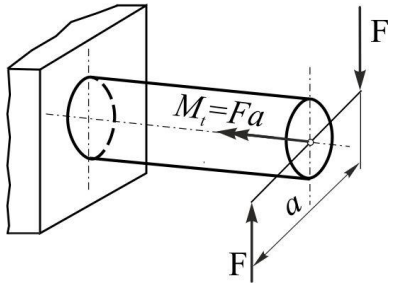
Torsion of bars

TORQUE DIAGRAMS



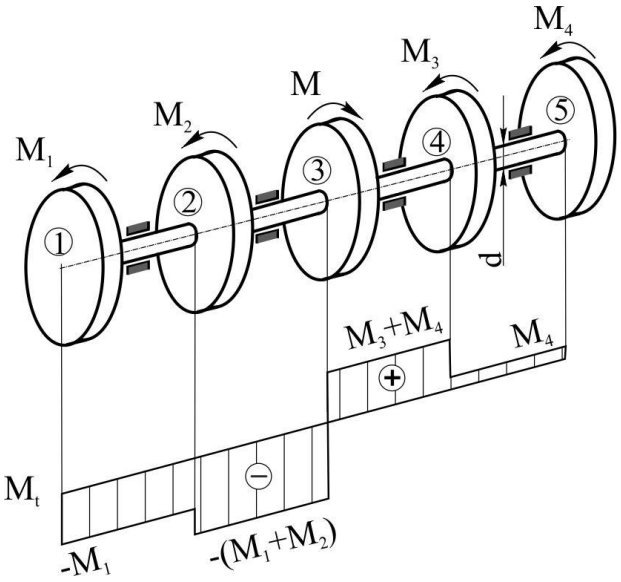




If the resultant of the internal forces about the centroid of the cross-section, has a single component $M_t = M_x$, we are dealing with a simple loading called ***pure torsion***. The internal force M_t in the cross-section is known as ***torque or twisting moment***.

In many engineering applications, members are required to carry torsional loads: shafts, coil springs, drills, torsion bars, aircraft structure, etc.

Torsion of bars

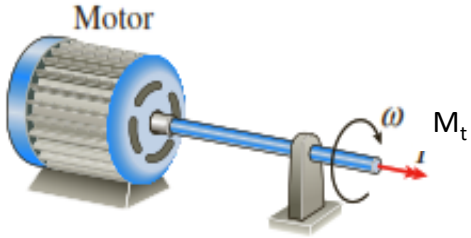


In order to determine the critical section of a bar subjected to torsion, it is necessary to calculate the value of the torques at different intervals and to construct their diagram.

Torsion of bars

EXPRESSION BETWEEN TORQUE AND THE TRASMITTED POWER

In some applications, the transmitted power and rotational speed of the shaft are given and for stress analysis we need to calculate the torque. To express the torque, we start from the known expression of the power P, in rotational motion:



$$P = M_t \cdot \omega = M_t \cdot 2\pi \frac{n}{60} = M_t \frac{\pi \cdot n}{30} \qquad \omega = 2\pi f \qquad n = 60 f \qquad \omega = \frac{2\pi \cdot n}{60} \qquad M_t = \frac{P}{\omega} = \frac{30}{\pi} \cdot \frac{P}{n}$$

$$M_t = 735,45 \frac{30}{\pi} \cdot \frac{P_{HP}}{n} = 7026 \frac{P_{HP}}{n} \; [\mathrm{N \cdot m}]$$

$$M_t = 1000 \frac{30}{\pi} \cdot \frac{P_{kW}}{n} = 9550 \frac{P_{kW}}{n} \; [\mathrm{N \cdot m}]$$

1HP = 75 $\frac{\mathrm{Kgf \cdot m}}{\mathrm{s}}$ = 73, 45 $\frac{\mathrm{N \cdot m}}{\mathrm{s}}$

1 kW = 1,36 HP ≈10^3 $\frac{\mathrm{N \cdot m}}{\mathrm{s}}$

Angular velocity ω [rad/s]
Frequency f [Hz or s^{-1}]
Revolution speed n [rot/min] or RPM

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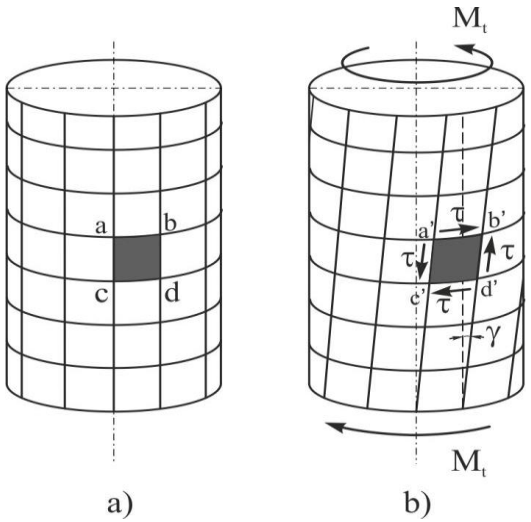
Torsion of bars

STRESS AND STRAIN IN CIRCULAR BARS SUBJECTED TO TORSION



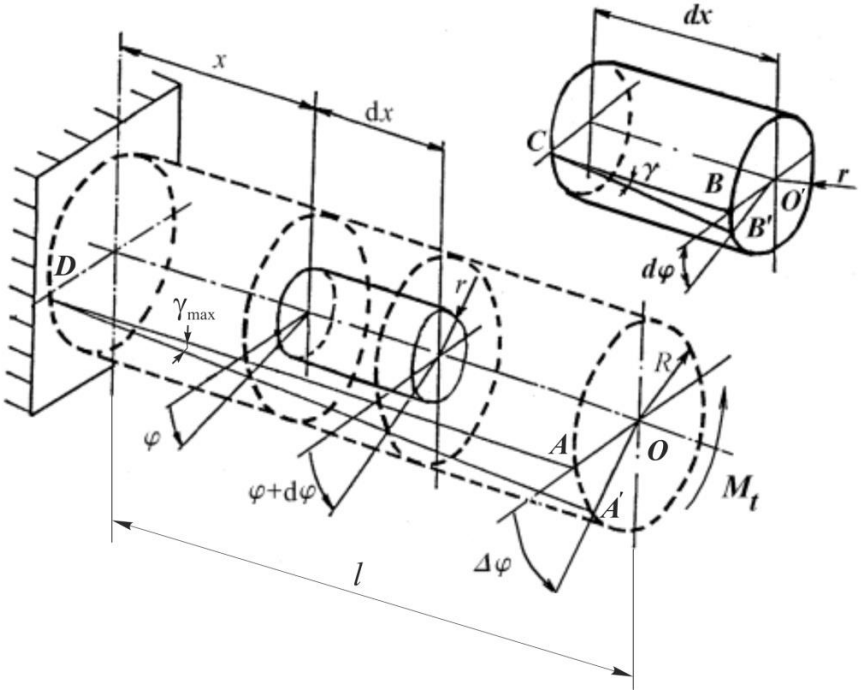
It is considered a straight bar with a circular section, on the contour of which are drawn a series of straight lines (generators) and steering circles, equidistant, located in planes perpendicular to the axis of the bar. Thus, a network of curvilinear squares is formed on the surface of the bar.
Analyzing the deformation of the bar under the torque M_t, it is found that:

- the cross sections are not distorted in any manner they remain plane, and the radius *r* does not change, and the length *L* of the shaft remains constant.
- the initially straight lines deforms into a helix, as a result, the square *abcd* deforms, turning into a parallelogram *a'b'c'd'*.

The following conclusions can be drawn based on these observations:

- the distances between cross sections do not change (the axial normal strain and stress is zero);
- in case of twisting the bars with symmetric sections (circular or annular) the validity of Bernoulli's hypothesis is confirmed (circular cross sections after loading remain plane (do not warp) and perpendicular to the axis of the shaft)
- two adjacent sections only rotate relative to each other, which confirms that only ***shear strain*** γ occur in the bar and generate a state of pure torsion. The ***shear stress*** τ occurs in the cross-sectional plane, the stresses are perpendicular to the radius.

Torsion of bars



Under the action of the moment M_t, the section with center in O rotates with angle $\Delta\varphi$ (angle of twist or angle of rotation) with respect to the fixed section of the bar. The point A on the contour moves in A', the angular deformation being γ_{max}. We recognize that the helix angle γ is the shear strain of the element.

$$AA' = l \cdot \gamma_{max}; \quad AA' = R \cdot d\phi$$

$$l \cdot \gamma_{max} = R \cdot \Delta\varphi; \quad \gamma_{max} = R\frac{\Delta\varphi}{l}.$$

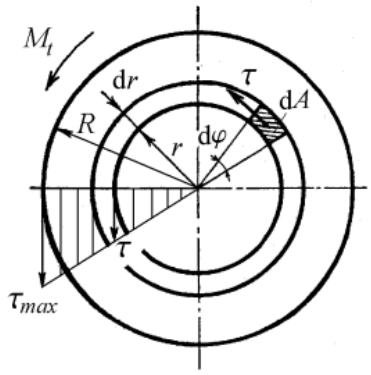
$$BB' = dx \cdot \gamma; \quad BB' = r \cdot d\phi$$

$$dx \cdot \gamma = r \cdot d\varphi; \quad \gamma = r\frac{d\varphi}{dx}.$$

$\frac{d\varphi}{dx} = \theta$ *angle of twist per unit length or rate of twist*, where θ is expressed in radians, represents the angle at which two cross-sections of the bar located at a distance equal to the unit rotate relative to each other

$$\gamma_{max} = R\theta$$

Torsion of bars



$$\tau_{\max} = G\gamma_{\max} = GR\theta$$

G is the shear modulus

τ_{max} *maximum shear stress* in the cross-sectional plane

$$\tau = G\gamma = Gr\theta \qquad \frac{\tau}{\tau_{\max}} = \frac{r}{R} \quad \text{or} \quad \tau = \frac{r}{R}\tau_{\max}$$

It is assumed that the sum of the moments of elementary stress τ*d*A with respect to the center of the circle is equal to the torque

$$M_t = \int_A \tau \cdot r\, dA = \int_A G\theta \cdot r^2\, dA = G\theta \int_A r^2\, dA, \qquad \int_A r^2\, dA = I_p$$

represents *polar moment of inertia*

$$M_t = G\theta\, I_P \qquad \theta = \frac{M_t}{GI_P}$$

product GI_p represents *torsional rigidity*

$$\tau = \frac{M_t\, r}{I_p}$$

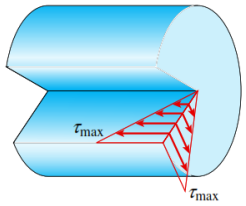
The maximum shear stress, denoted by τ_{max} , occurs at the surface of the shaft (contour of the cross section)

$$\tau_{\max} = \frac{M_t\, r_{\max}}{I_p} = \frac{M_t}{W_p}$$

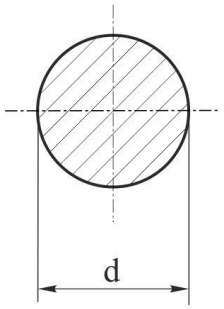
$$W_p = \frac{I_p}{r_{\max}}$$

W_p is called ***polar section modulus***

Longitudinal and transverse shear stresses in a circular bar subjected to torsion



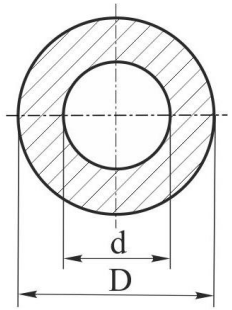
Torsion of bars



a)

$$I_p = \frac{\pi d^4}{32}$$

$$W_p = \frac{I_p}{d/2} = \frac{\pi d^3}{16}$$



b)

$$I_p = \frac{\pi}{32} \cdot \left(D^4 - d^4\right)$$

$$W_p = \frac{I_p}{\frac{D}{2}} = \frac{\pi \left(D^4 - d^4\right)}{16\,D}$$

Fundamental problems of Strength of Materials in torsion

- **Design** $W_{p_{nec}} = \frac{M_t}{\tau_a}$
- **Checking** $\tau_{ef} = \frac{M_t}{W_{pef}} \leq \tau_a$
- **Allowable (permissible) torque** $M_{t_{cap}} = W_{p_{ef}} \cdot \tau_a$

Torsion of bars

Knowing the expression of the rate of twist, one can calculate the angle of twist of two sections situated at a distance *l:*

$$\Delta\varphi = \int_0^l d\varphi = \int_0^l \theta\, dx = \int_0^l \frac{M_t}{GI_p} dx = \frac{M_t l}{GI_p}$$

Design of transmission shafts take into account the strength condition or deformation condition.

- Calculus of shafts based on strength condition

$$W_{p_{nec}} = \frac{M_t}{\tau_a} \quad \Rightarrow \quad \frac{\pi d^3}{16} = 7026 \frac{P_{CP}}{n\,\tau_a} \qquad \frac{\pi d^3}{16} = 9550 \frac{P_{kW}}{n\,\tau_a}$$

- Calculus of shafts based on deformation condition

$$\theta = 7026 \frac{P_{CP}}{n} \frac{32}{G\pi d^4} \text{ sau } \theta = 9550 \frac{P_{kW}}{n} \frac{32}{G\pi d^4}$$

Allowable angle of twist per unit length varies between ¼ °/m and 1 °/m.

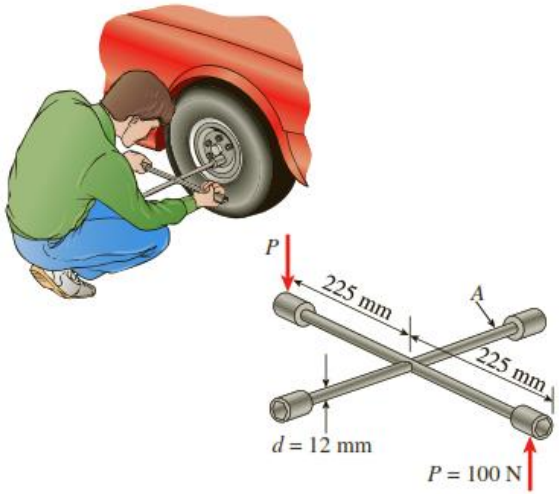
Torsion of bars

Examples

While removing a wheel to change a tire, a driver applies forces $P = 100$ N at the ends of two of the arms of a lug wrench (see figure). The wrench is made of steel with shear modulus of elasticity $G = 78$ GPa. Each arm of the wrench is 225 mm long and has a solid circular cross section of diameter $d = 12$ mm.

(a) Determine the maximum shear stress in the arm that is turning the lug nut (arm A).

(b) Determine the angle of twist (in degrees) of this same arm.



$M_t = 2 \cdot P \cdot 225 = P \cdot 450 = 100 \cdot 450 = 45000$ N·mm

45 N·m

a) $\tau = \frac{M_t}{W_p}$ d $W_p = \frac{\pi \cdot d^3}{16}$

$W_p = \frac{3{,}14 \cdot 12^3}{16} = 339{,}12$ mm^3

$\tau = \frac{45000}{339{,}12} = 132{,}69$ N/mm^2

b) $\Delta\varphi = \frac{M_t \cdot l}{G \cdot I_p}$ $I_p = \frac{\pi d^4}{32}$; $W_p = \frac{I_p}{\frac{d}{2}}$

$I_p = \frac{3{,}14 \cdot 12^4}{32} = 2034{,}72$ mm^4

$\Delta\varphi = \frac{45000 \cdot 225}{78 \cdot 10^3 \cdot 2034{,}72} = 0{,}06379$ rad

180° ... π rad

x ... 0,0637

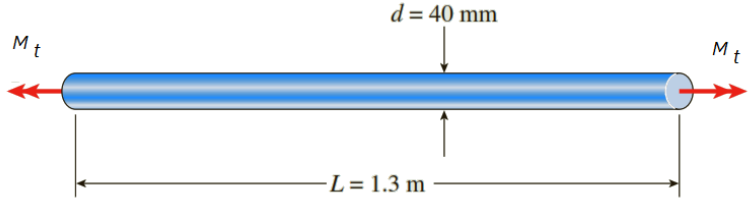
$x \cdot \frac{180}{\pi} = 3{,}65°$

Torsion of bars

A solid steel bar of circular cross section has diameter d=40mm, length L=1.3m, and shear modulus of elasticity G=80 GPa. The bar is subjected to torque M_t acting at the ends.

a) If the torque have magnitude M_t=340 N·m, what is the maximum shear stress in the bar? What is the angle of twist between the ends?

b) If the allowable shear stress is 42 MPa and the allowable angle of twist is 2.5°, what is the maximum permissible torque?



a) $\tau = \frac{M_t}{W_p}$ $M_t = 340\ N\cdot m$ $W_p = \frac{\pi d^3}{16} = \frac{3{,}14\cdot 40^3}{16} = 12566{,}4\ mm^3$

$\tau = \frac{340\cdot 10^3}{12566{,}4} = 27{,}06\ N/mm^2\ (MPa) < \tau_a\ (42\ MPa)$

$\Delta\varphi = \frac{M_t \cdot L}{G\cdot I_p}$ $I_p = \frac{\pi d^4}{32} = \frac{3{,}14\cdot 40^4}{32} = 251327{,}4\ mm^4$

$\Delta\varphi = \frac{340\cdot 10^3 \cdot 1{,}3\cdot 10^3}{80\cdot 10^3 \cdot 251327{,}4} = 0{,}02198\ rad \times \frac{180}{\pi} = 1{,}26^\circ$

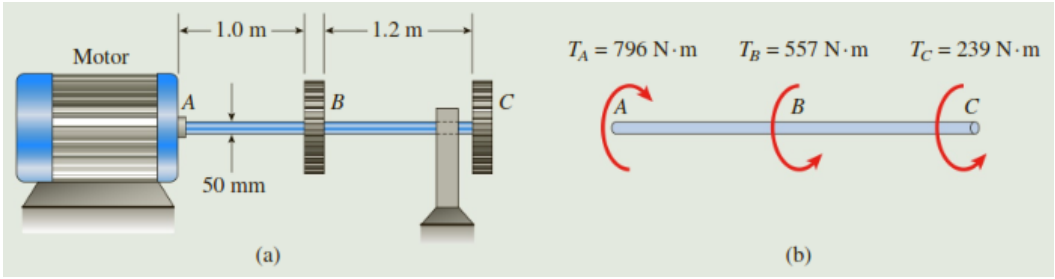
b) $M_{t\,cap_1} = \tau_a \cdot W_p = 12566{,}4 \cdot 42 = 527788{,}8\ N\cdot mm = 526{,}8\ N\cdot m$

$M_{t\,cap_2} = \frac{G\cdot I_p \cdot \Delta\varphi_a}{L} = \frac{80\cdot 10^3 \cdot 251327{,}4 \cdot 2{,}5\cdot \frac{\pi}{180}}{1{,}3\cdot 10^3} = 674302{,}6\ N\cdot mm = 674{,}5\ N\cdot m$

$M_{t\,cap} = \min(M_{t\,cap_1}; M_{t\,cap_2}) = 526{,}8\ N\cdot m$

Torsion of bars

A steel shaft with diameter d=50 mm is turned by a motor that transmit a power of 50 kW at a frequency of 10 Hz, connected in point A. Wheels B and C drive an equipment that require the power of 35 kW and 15 kW respectively. Calculate the maximum shear stress in the shaft and angle of twist between the motor and the wheel C. It is known the shear modulus G=80GPa.



$M_t = 9550 \cdot \frac{P_{kW}}{n_{RPM}}$ [N·m] $\quad n_{RPM} = 60 f$ [Hz] $\quad M_t = 9550 \cdot \frac{P_{kW}}{60 \cdot f} = 159{,}16 \cdot \frac{P_{kW}}{f}$

$M_{t_A} = 159{,}16 \cdot \frac{50}{10} = 796$ N·m ; $M_{t_B} = 159{,}16 \cdot \frac{35}{10} = 557$ N·m ; $M_{t_C} = 159{,}16 \cdot \frac{15}{10} = 239$ N·m

$\sigma = \frac{M_t}{W_p}$ $\quad W_p = \frac{\pi d^3}{16} = \frac{3{,}14 \cdot 50^3}{16} = 24531{,}25$ mm³

$\sigma_{max} = \frac{M_{t max}}{W_p}$ $\quad M_{t max} = M_{t BA} = 796$ N·m $\quad \sigma_{max} = \frac{796 \cdot 10^3}{24531{,}25} = 32{,}44$ N/mm² (MPa)

$\Delta\varphi_{AC} = ?$ $\quad \Delta\varphi_{AC} = \Delta\varphi_{CB} + \Delta\varphi_{BA} = \frac{239 \cdot 10^3 \cdot 1{,}2 \cdot 10^3}{80 \cdot 10^3 \cdot 613281{,}25} + \frac{796 \cdot 10^3 \cdot 1 \cdot 10^3}{80 \cdot 10^3 \cdot 613281{,}25} =$

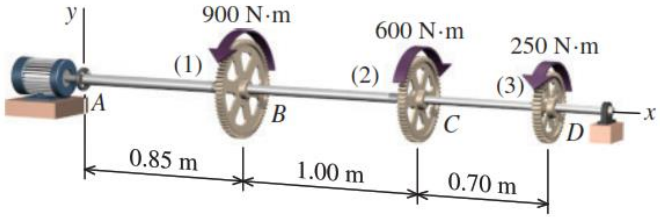
$\Delta\varphi_{CB} = \frac{M_{t CB} \cdot 1{,}2m}{G \cdot I_p}$; $\Delta\varphi_{BA} = \frac{M_{t BA} \cdot 1m}{G \cdot I_p}$ $= \frac{(286{,}8 + 796) \cdot 10^3}{80 \cdot 613281{,}25} = 0{,}02206$ rad

$I_p = \frac{\pi d^4}{32} = \frac{3{,}14 \cdot 50^4}{32} = 613281{,}25$ mm⁴

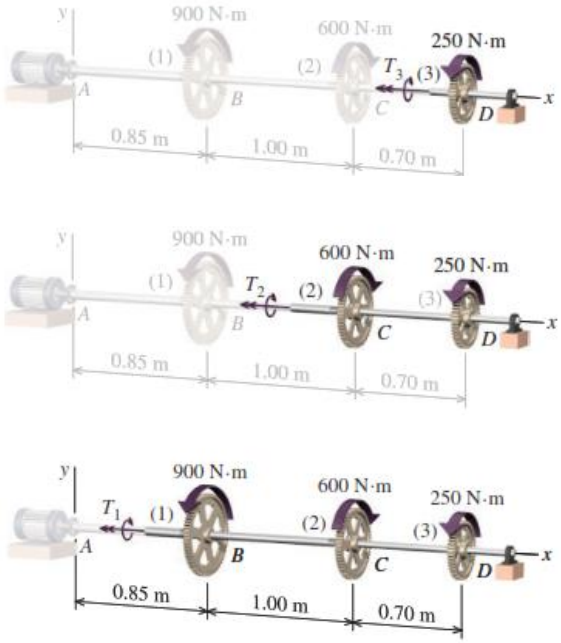
Torsion of bars

A solid steel shaft (G=80 GPa) of variable diameter is subjected to the torques shown. Segment (1) of the shaft has a diameter of 36mm, segment (2) has a diameter of 30 mm, and segment (3) has a diameter of 25 mm. The bearing shown allows shaft to turn freely.

a) Determine the internal torque in segments (1), (2), and (3) of the shaft. Plot a diagram showing the internal torques in all segments of the shaft.
b) Compute the magnitude of the maximum shear stress in each segment of the shaft.
c) Determine the rotation angles along the shaft measured at gears B, C, and D relative to the flange A. Plot a diagram showing the rotation angles at all points on the shaft.



MDSolids
Educational Software for Mechanics of Materials



$M_{t_{DC}} = 250\ N\cdot m \quad (T_3)$

$\tau_{DC} = \frac{M_{t_{DC}}}{W_{p_3}} = 81{,}49\ MPa$

$W_{p_3} = \frac{\pi d_3^3}{16} = \frac{\pi \cdot 25^3}{16}$

$I_{p_3} = \frac{\pi d_3^4}{32} =$

$\Delta\varphi_{DC} = \frac{M_{t_{DC}} \cdot 0{,}7 \cdot 10^3}{80 \cdot 10^3 \cdot I_{p_3}} = \ldots 0{,}03746\ rad$

$M_{t_{CB}} = 250 - 600 = -350\ N\cdot m$

$\tau_{CB} = \frac{M_{t_{CB}}}{W_{p_2}} = 66{,}02\ MPa$

$W_{p_2} = \frac{\pi d_2^3}{16} = \frac{\pi \cdot 30^3}{16} =$

$\Delta\varphi_{CB} = \frac{M_{t_{CB}} \cdot l_2}{G \cdot I_{p_2}}$

$M_{t_{BA}} = 250 - 600 + 900 = 550\ N\cdot m$

$\tau_{BA} = \frac{M_{t_{BA}}}{W_{p_1}} = 60{,}04\ MPa$

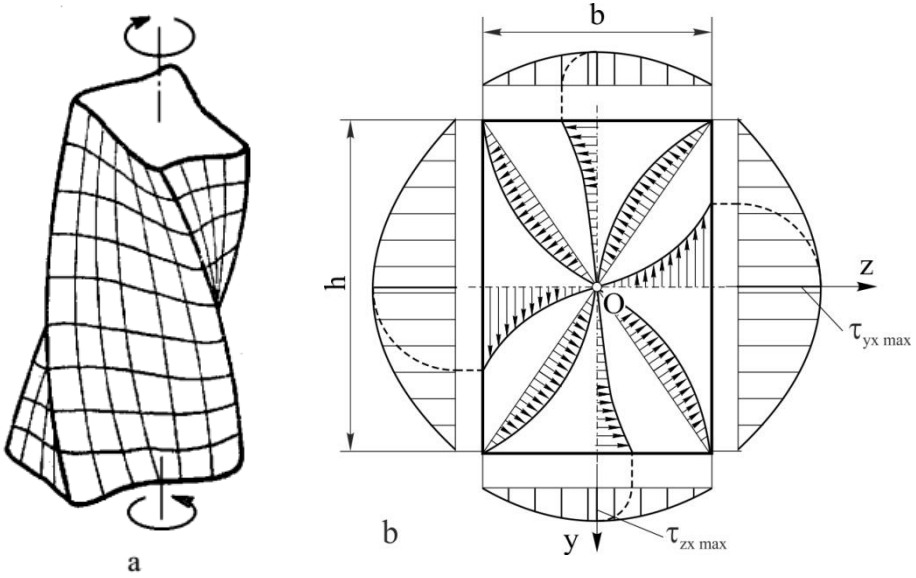
$W_{p_1} = \frac{\pi d_1^3}{16} = \frac{\pi \cdot 35^3}{16} =$

$I_{p_1} = \frac{\pi d_1^4}{32} = \ldots$

$\Delta\varphi_{BA} = \frac{M_{t_{BA}} \cdot l_1}{G \cdot I_{p_1}}$

Torsion of bars

TORSION OF PRISMATIC BARS



Bernoulli's hypothesis is no more confirmed, different points of the cross-section having different displacements along the bar's axis (warping of the cross-section).
The rectangles on the side surface of the bar are deformed into parallelograms, their deformation being the higher the closer they are to the middle of the side face. The rectangles near the edges remain almost undeformed.

Maximum shear stress is produced at the midpoint of the longer side of the rectangular cross-section ($h > b$) and has the value:

$$\tau_{yx_{\max}} = \frac{M_t}{W_t} = \frac{M_t}{\alpha\ hb^2} = \tau_{\max}\,.$$

$$\tau_{zx\ \max} = \gamma \cdot \tau_{yx\ \max}$$

Torsion of bars

Angle of twist per unit length is calculated by the formula: $\theta = \frac{M_t}{GI_t} = \frac{M_t}{G\beta hb^3}.$

Values of the coefficients α, β și γ

$\frac{h}{b}$	1	1,5	1,75	2	2,5	3	4	6	8	10	∞
α	0,208	0,231	0,239	0,246	0,258	0,267	0,282	0,299	0,307	0,313	0,333
β	0,141	0,196	0,214	0,229	0,249	0,263	0,281	0,299	0,307	0,313	0,333
γ	1,000	0,859	0,820	0,795	0,766	0,753	0,745	0,743	0,742	0,742	0,742

The maximum shear stresses can be calculated, with sufficient precision, using generalized relations:

$$\tau_{\max} = \frac{M_t}{W_t}, \qquad \theta = \frac{M_t}{GI_t}$$

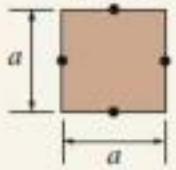
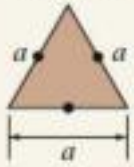
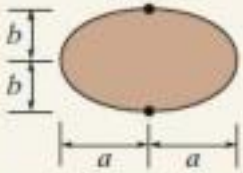
where W_t is the equivalent (conventional) section modulus, and I_t is the **torsion constant** for the cross section

$$I_t = \beta hb^3 \qquad W_t = \alpha\ hb^2$$

For narrow rectangular bars $\frac{h}{b} \geq 10$ ⇒ $\tau_{\max} = \frac{M_t}{W_t} = \frac{3M_t}{hb^2} \leq \tau_a; \quad W_t = \frac{M_t}{\tau_a}$ $\theta = \frac{M_t}{GI_t} = \frac{3M_t}{Ghb^3} \leq \theta_a; \quad \varphi = \frac{M_t l}{G I_t}.$

Torsion of bars

TORSION OF BARS WITH PRISMATIC CROSS-SECTIONS

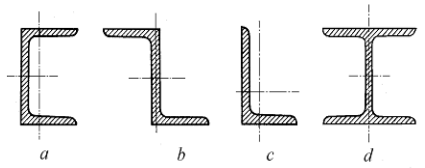
Shape of cross section	τ_{max}	ϕ
Square 	$\frac{4.81\,T}{a^3}$	$\frac{7.10\,TL}{a^4G}$
Equilateral triangle 	$\frac{20\,T}{a^3}$	$\frac{46\,TL}{a^4G}$
Ellipse 	$\frac{2\,T}{\pi ab^2}$	$\frac{(a^2+b^2)TL}{\pi a^3b^3G}$

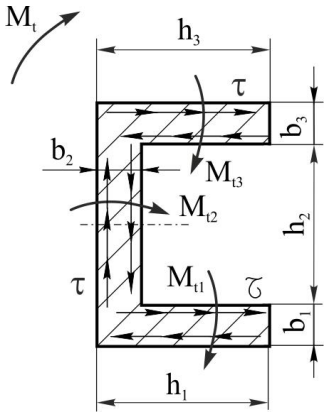
The drill shaft is connected to the soil auger using a shaft having a square cross section.

Torsion of thin-walled tubes

TORSION OF THIN-WALLED TUBES

1. OPEN THIN-WALLED TUBES





Solution for torsion of bars with prismatic cross-sections can be applied for open thin-walled tubes. For the profile shown in the figure, we can consider that each rectangle twists independently, the moment of inertia will be given by the sum of the moments of inertia of the component rectangles.

$$I_t = \sum_{i=1}^{n} \beta_i \, h_i \, b_i^3 , \qquad W_t = \frac{I_t}{b_{i_{\max}}}$$

where: h_i şi b_i are the rectangle dimensions; n – number of rectangles

In the case of open profiles with composed sections of rectangles with the aspect ratio:

$$\frac{h_i}{b_i} \geq 10; \quad \beta_i = \frac{1}{3} \qquad I_t = \frac{1}{3} \sum_{i=1}^{n} h_i \, b_i^3$$

Maximum shear stress will arise in the middle of the height of the component rectangle with the greatest thickness:

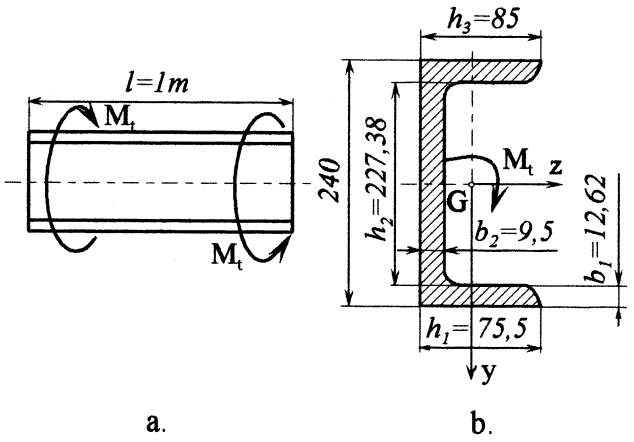
$$\tau_{\max} = \frac{M_t}{W_{t\,\max}} = \frac{M_t \, b_{i\,\max}}{I_t} \qquad \theta = \frac{M_t}{GI_p} = \frac{M_{ti}}{GI_{ti}}$$

M_{ti} represents the torque corresponding to the rectangle i;
I_{ti} – torsion constant of the i rectangle.

Torsion of thin-walled tubes

Example:

A straight steel bar of length *l* = 1 m, made of hot-rolled steel, is subject to free torsion. Determine: a) allowable torque (τ_a=80 MPa); b) rate of twist and angle of twist between the ends of the profile.



The shape and dimensions of the profile are chosen from EN 10279:2002

$$M_{t_{cap}} = W_t \tau_a = \frac{I_t}{b_{i_{max}}} \tau_a = \frac{\frac{1}{3}\sum_{i=1}^{3} h_i b_i^3}{b_{i_{max}}} \tau_a = \frac{\frac{1}{3}\left(h_1 b_1 + h_2 b_2 + h_3 b_3\right)}{b_1} \tau_a =$$

$$= \frac{\frac{1}{3}\left(75,5 \cdot 12,62^3 + 227,38 \cdot 9,5^3 + 85 \cdot 12,62^3\right)}{12,62} 80 = 1,0936 \cdot 10^6 \text{ Nmm}$$

$$\theta = \frac{M_t}{GI_t} = \frac{M_t}{G \cdot \frac{1}{3}\sum_{i=1}^{3} h_i b_i^3} = \frac{1,0936 \cdot 10^6}{0,81 \cdot 10^5 \cdot 1782513,85}$$

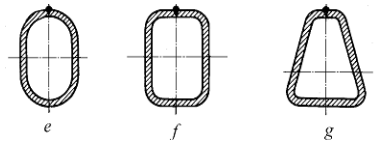
$$= 7,826 \cdot 10^{-5}\ rad/mm = 4,48\ °/m$$

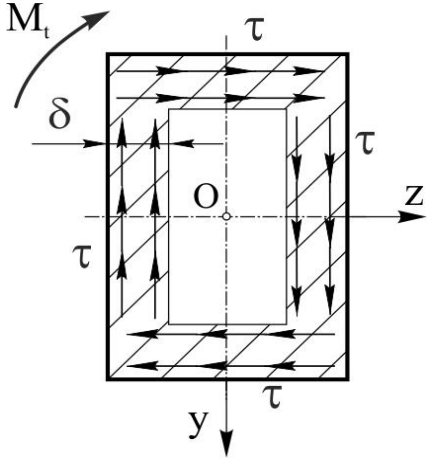
Angle of twist between the ends of the profile will be:

$$\Delta\varphi = \theta l = 7,826 \cdot 10^{-5} \cdot 1 \cdot 10^3 = 7,826 \cdot 10^{-2}\ rad = 4,48°$$

Torsion of thin-walled tubes

2. Thin-walled tubes with closed cross-section





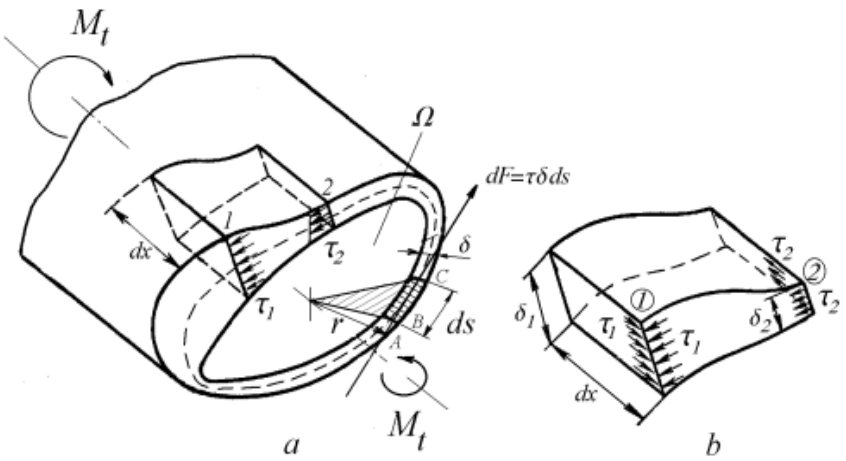
The fundamental difference that occurs in the case of torsion of thin-walled bars with a closed cross-section compared to the torsion of those with open cross-section is that the elementary forces τdA are not reduced in section to torques M_{ti}, corresponding to each component rectangle, but directly at the moment of external torsion, Mt, through the flow of tangential tensions throughout the closed contour of the section.

Bredt hypotheses:

1. Shear stresses are constant over thickness;
2. The shear stresses τ_1 and τ_2 are constant over the wall thickness. Shear stresses are directed after tangent to the midline of section;
3. The product of the shear stress τ and the thickness of the profile δ, called the **shear flow**, is found along the midline of the profile, τδ = constant.

We isolate an infinitesimal element from the profile wall of width d*x* parallel to the axis of the bar and of arbitrary length along the midline of the profile.

Torsion of thin-walled tubes



- The shear stresses τ1 and τ2 are constant over the wall thickness.
- The shear force on face 1, along the axis of the bar, is $\tau_1\delta_1 dx$.
- This force must be equal to the force $\tau_2\delta_2 dx$ acting on face 2 considering equilibrium of the isolated element.
- It follows $\tau_1\delta_1 dx = \tau_2\delta_2 dx$, and since points 1 and 2 were chosen arbitrarily, the product $\tau\cdot\delta$ is constant along the contour, which confirms Bredt's hypothesis.
- The magnitude $q=\tau\cdot\delta$ is called, as mentioned, shear flow or tangential stress flow and represents a shear force per unit length of the midline of the thin-walled section.
- The force dF acting tangentially to the contour, on an element of length ds, is $dF = \tau\delta ds$.

The moment of this force with respect to the axis of the bar is:

$$dM_t = \tau \cdot r \cdot \delta \cdot ds$$

$$M_t = \int dM_t = \oint \tau \cdot \delta \cdot r \cdot ds \quad = \tau \cdot \delta \cdot \oint r ds$$

$$M_t = 2 \cdot \tau \cdot \delta \cdot \Omega$$

$$\tau = \frac{M_t}{2\Omega\delta} \qquad \tau_{max} = \frac{M_t}{2\Omega\delta_{min}}$$

$$\oint r\,ds = 2\Omega$$

The product *rds* represents twice the area between the polar radii and the length element *ds*, and the integral represents twice the area bounded by the midline of section Ω

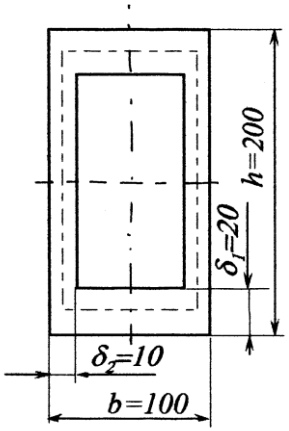
Torsion of thin-walled tubes

Expression of angle of twist per unit length: $\theta = \frac{M_t}{4G\Omega^2}\oint\frac{ds}{\delta} = \frac{M_t}{GI_t}$

where the conventional torsional moment of inertia is : $I_t = \frac{4\Omega^2}{\oint\frac{ds}{\delta}}$

The integral $\oint\frac{ds}{\delta}$ can be calculated by summing up the ratios $\frac{\Delta s_i}{\delta_i}$ of the elements Δs_i, midline and thickness δ_i

A bar of length l=2 m made of steel (τ_a = 80 Mpa) having the cross section shown in figure, is subjected to torsion by the torque M_t. It is required:
(a) value of allowable torque;
(b) the value of the angular twist and the relative rotation between the ends of the bar.



$$M_{t\,cap} = 2\cdot\tau_a\cdot\delta_{\min}\cdot\Omega$$

Ω = (200 – 20)·(100 – 10) = 16200 mm²;
δ_{min} = 10 mm; $M_{t\,cap}$ = 2·16200·10·80 = 25,92 10^6 N·mm.

$$\theta = \frac{M_t}{4G\Omega^2}\oint\frac{ds}{\delta} = \frac{M_t}{4G\Omega^2}\,2\left(\frac{h-\delta_1}{\delta_2}+\frac{b-\delta_2}{\delta_1}\right) =$$

$$= \frac{25{,}92\cdot10^6\cdot2}{4\cdot0{,}81\cdot10^5\cdot16200^2}\cdot\left(\frac{200-20}{10}+\frac{100-10}{20}\right) =$$

$$= 1{,}37\cdot10^{-5}\ \text{rad/mm} = 7{,}86\cdot10^{-4}\ °/\text{mm} =$$

$$= 0{,}786\ °/\text{m}$$

$$\varphi = \theta\, l = 1{,}37\cdot10^{-5}\cdot2\cdot10^3 = 2{,}74\cdot10^{-2}\ \text{rad} = 1{,}57°.$$

Torsion of bars – online resources

On-line classes: **JAMK**

Torsion of bars theory:

Example:

C1 – Strength of Materials

M2 – Torsion of Bars

Theoretical and Experimental Aplications

HEI name: Technical University of Cluj-Napoca (TUCN)

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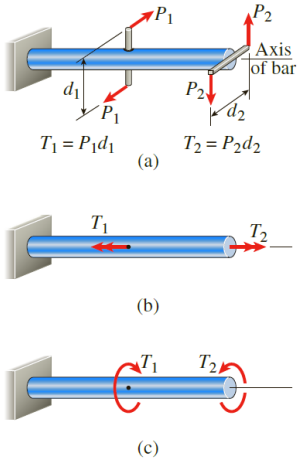
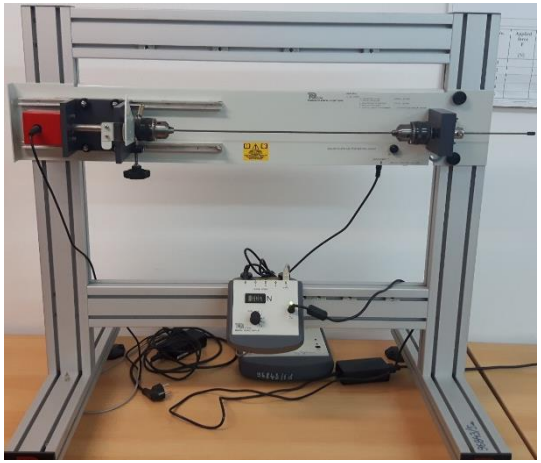
Module 2 - Torsion of circular rods

Theoretical and Experimental Aplications





Module 2 - Torsion of circular rods

Theoretical and Experimental Aplications

Upon completion of this module, the student will be able to:

1) Calculate and draw the diagrams for twisting moments
2) Calculate the calculate shear stresses and deformations for circular rods
3) Perform design calculations
4) Perform experimental measurements of twisting angle of a circular rod.

Content

- Introduction - Theoretical backgrounds
- Topic 1: Torsion of circular rods (Theoretical Applications)

  Topic 1.1: Application 1

  Topic 1.2: Application 2
- Topic 2: Torsion of circular cross-section rods (Experimental Application)

Introduction

Introduction

Theoretical backgrounds

Torsion refers to the twisting of a straight circular bar (or rod) as a result of a torque producing its rotation about its longitudinal axis. In the cross section of the bar will be only one effort, namely the *torsional moment (or torque, twisting), T*.

The twisting moment, T does not remain constant along a bar subjected to torsion. To determine the most stressed section of the bar, it is necessary to know the variation diagram of the twisting moment along the bar.

The twisting moment, T in a certain section of the bar, is defined as the sum of all the torsional moments to the left of the section, or to the right of it, taken with the sign changed. The sign is determined by choosing a certain direction of rotation of the section as positive, and its reverse will be considered negative.

Deformations and shear stresses

- For the bar with total length *"l"*, the total twist angle can be calculated with the relation:

$$\theta = \frac{T \cdot l}{G \cdot I_p}$$

where, I_p is the polar moment of inertia, and for the circular section can be calculated:

$$I_p = \frac{\pi \cdot d^4}{32} \quad mm^4$$

- Shear stress can be obtained with the generalized formula:

$$\tau = \frac{T}{I_p} \cdot R$$

where,T is the the twisting moment and G·Ip is the torsional rigidity of the bar.

Relation (2) shows that the shear stresses vary linearly with the radial distance from the center of the bar.

The relation (2) can also be written in the form:

$$\tau = \frac{T}{W_p}$$

where, W_p is the polar moment, and for the circular section can be calculated:

$$W_p = \frac{\pi \cdot d_{ef}^3}{16}, mm^3$$

Topic 1: Torsion of circular rod (Theoretical Applications)

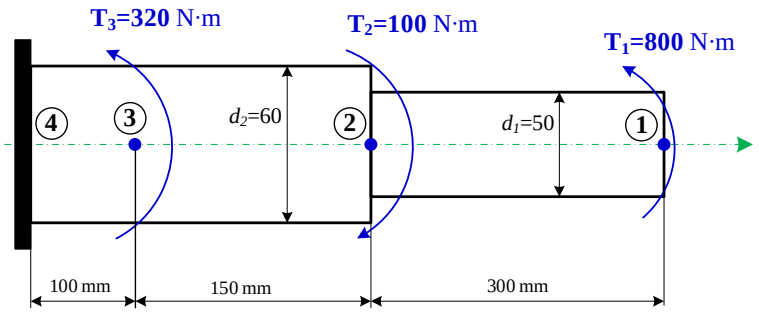
Topic 1.1

Application 1

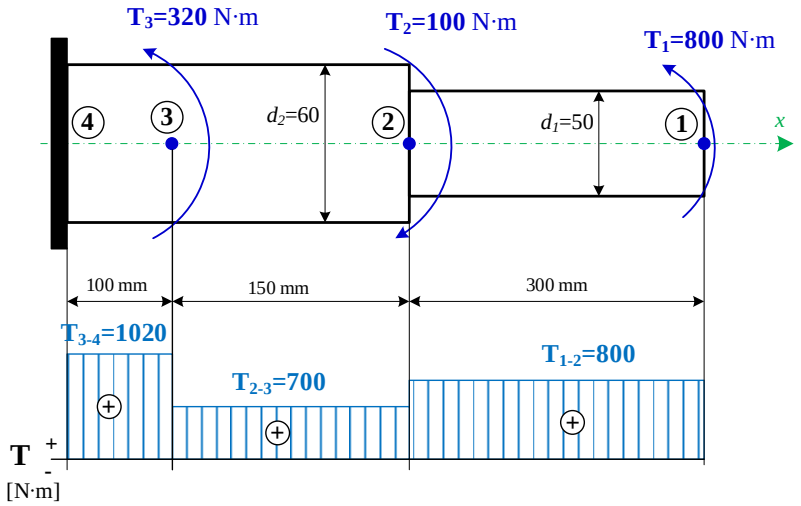
A steel bar with variable circular section, fixed at one end and free at the other, is subjected to the action of torsional moments with the values given in the figure.

a) Check the bar, knowing that the admissible resistance of the material is $\tau_a = 55\ N/mm^2$

b) Calculate the twisting deformation along the length of the bar, respectively the total deformation of the bar.



Solution



- The torques on each interval are calculated:

Interval 1-2:	$T_{1-2} = 800 \ N \cdot m$
Interval 2-3	$T_{2-3} = 800 - 100 = 700 \ N \cdot m$
Interval 3-4	$T_{3-4} = 800 - 100 + 320 = 1020 \ N \cdot m$

The variation diagram of twisting moments is obtained.

a) Verification calculation – the relationship is used:

$$\tau_{ef} = \frac{T}{W_p} \leq \tau_a$$

where, for the circular section, the polar moment is calculated:

$$W_p = \frac{\pi \cdot d_{ef}^3}{16}, mm^3$$

$$W_{p_1} = \frac{\pi \cdot 50^3}{16} = 24543.7 \ \ mm^3$$

$$W_{p_2} = \frac{\pi \cdot 60^3}{16} = 42411.5 \ \ mm^3$$

Interval 1-2:	$\tau_{ef_{1-2}} = \frac{T_{1-2}}{W_{p1}} = \frac{800 \cdot 10^3}{24543.7} = 32.6 \frac{N}{mm^2} < \tau_a \rightarrow checked$
Interval 2-3	$\tau_{ef_{2-3}} = \frac{T_{2-3}}{W_{p2}} = \frac{700 \cdot 10^3}{42411.5} = 16.5 \frac{N}{mm^2} < \tau_a \rightarrow checked$
Interval 3-4	$\tau_{ef_{3-4}} = \frac{T_{3-4}}{W_{p2}} = \frac{1020 \cdot 10^3}{42411.5} = 24.05 \frac{N}{mm^2} < \tau_a \rightarrow checked$

b) Calculation of torsional deformation - the relation is used: $\varphi = \frac{M_t \cdot l}{G \cdot I_p}$

where, G is the shearing modulus modulus (or Poisson modulus): G = 8,1·10^4 N/mm^2 .

$$I_{p_1} = \frac{\pi \cdot 50^4}{32} = 613592.31 \ \ mm^4$$

$$I_{p_2} = \frac{\pi \cdot 60^4}{32} = 1272345.025 \ \ mm^4$$

$$\theta_{total} = \theta_{1-2} + \theta_{2-3} + \theta_{3-4}$$

$$\theta_{total} = \frac{T_{1-2} \cdot l_{1-2}}{G \cdot I_{p1}} + \frac{T_{2-3} \cdot l_{2-3}}{G \cdot I_{p2}} + \frac{T_{3-4} \cdot l_{3-4}}{G \cdot I_{p2}}$$

$$\theta_{total} = \frac{800 \cdot 10^3 \cdot 300}{8.1 \cdot 10^4 \cdot 613592.31} + \frac{700 \cdot 10^3 \cdot 150}{8.1 \cdot 10^4 \cdot 1272345.025} + \frac{1020 \cdot 10^3 \cdot 150}{8.1 \cdot 10^4 \cdot 1272345.025}$$

$$\rightarrow \theta_{total} = \frac{0.0073322[rad] \cdot 180^o}{\pi} \rightarrow \theta_{total} = 0.42\ [°]$$

Topic 1.2

Application 2

What is the minimum diameter of a full circular section shaft required to transmit a power P = 40 kW at a speed of n = 700 rpm without exceeding the admissible tangential stress $\tau_a = 30$ N/mm^2 ?

Solution

▪ The transmitted torque is calculated, depending on the power P [kW] and the speed n [rot/min], as follows:

$$T = 9550 \cdot \frac{P[kW]}{n\left[\frac{rot}{min}\right]}$$

$$T = 9550 \cdot \frac{40}{700} \rightarrow T = 545.72\ N \cdot m$$

▪ For shaft design the following relations are used: $W_{p_nec} = \frac{T}{\tau_a}$ $W_{p_nec} = \frac{\pi \cdot d_{nec}^3}{16}$

With (1) and (2) is obtained: $\frac{\pi \cdot d_{nec}^3}{16} = \frac{T}{\tau_a} \rightarrow d_{nec} = \sqrt[3]{\frac{16 \cdot T}{\pi \cdot \tau_a}}$

$$\rightarrow d_{nec} = \sqrt[3]{\frac{16 \cdot 545.72 \cdot 10^3}{\pi \cdot 30}} \rightarrow d_{nec} = 45.24\ mm \rightarrow d_{ef} = 46\ mm$$

▪ Verification (check) calculus

For shaft verification the following relations are used:

$$\tau_{ef} = \frac{T}{W_{p_ef}} \leq \tau_a$$

The effective polar modulus: $W_{p_ef} = \frac{\pi \cdot d_{ef}^3}{16}$

$$W_{p_ef} = \frac{\pi \cdot 46^3}{16} = 19111.87\ mm^3$$

The effective shear stress is:

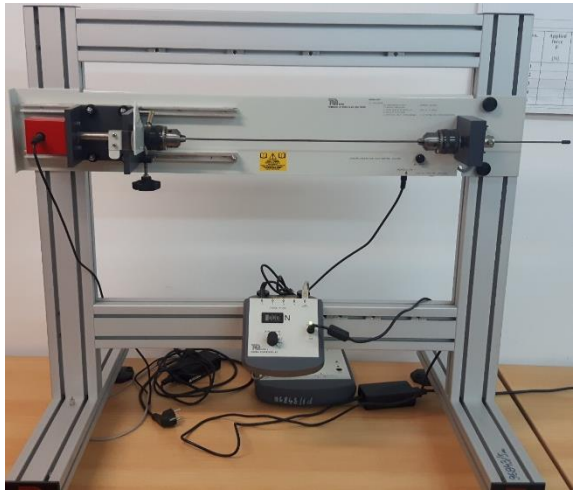
$$\tau_{ef} = \frac{545.72 \cdot 10^3}{19111.87} = 28.58\ N/mm^3$$

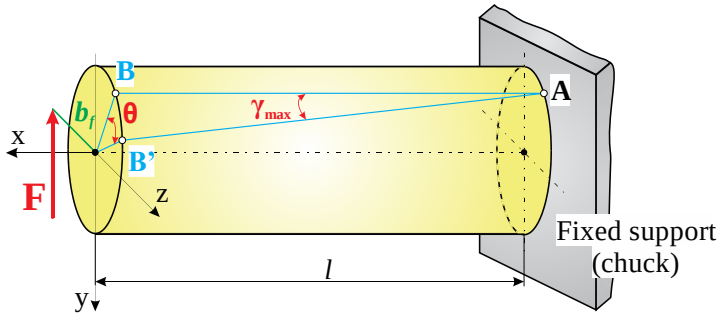
$$\tau_{ef} < \tau_a \rightarrow checked$$

Topic 2: Torsion of circular cross-section rods (Experimental Application)

Topic 2

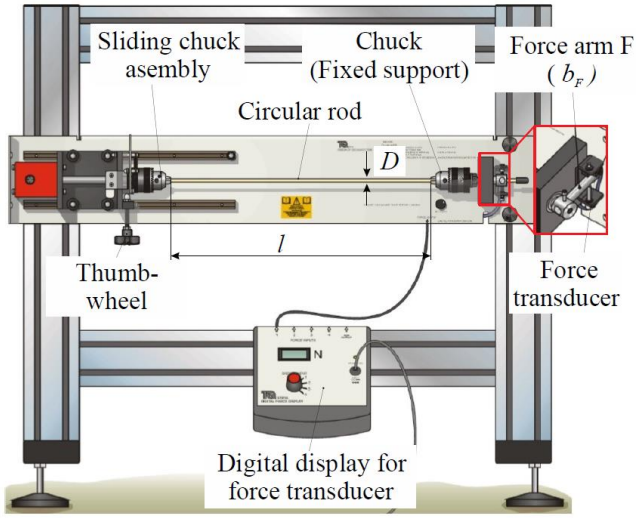
Torsion of circular cross-section rods

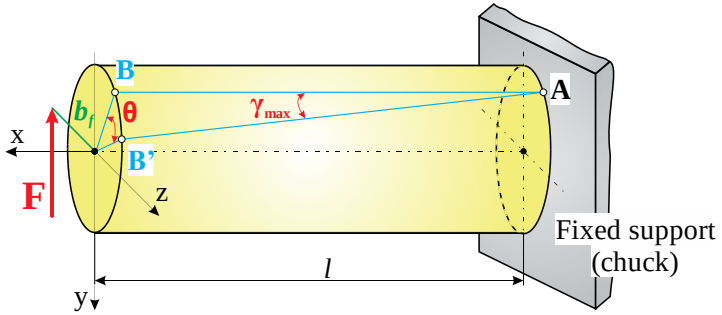




Experiment – Angle of twist variation under external loads

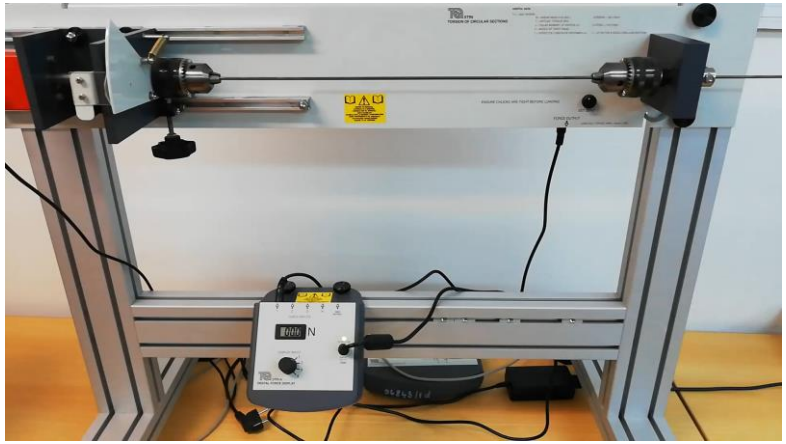
Laboratory Aim: Experimental determination of the angle of twist (θ) for a circular rod subjected to torsion and comparison of the experimental results with the calculated (theoretical) values.



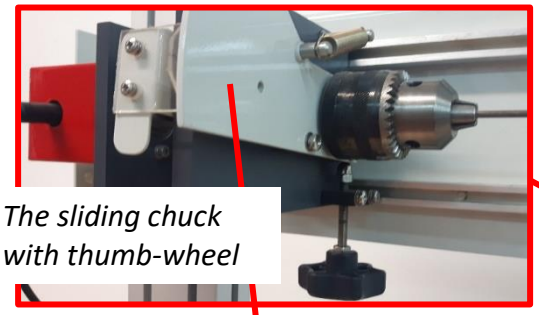


▪ The following steps will be taken to perform the experimental measurements:

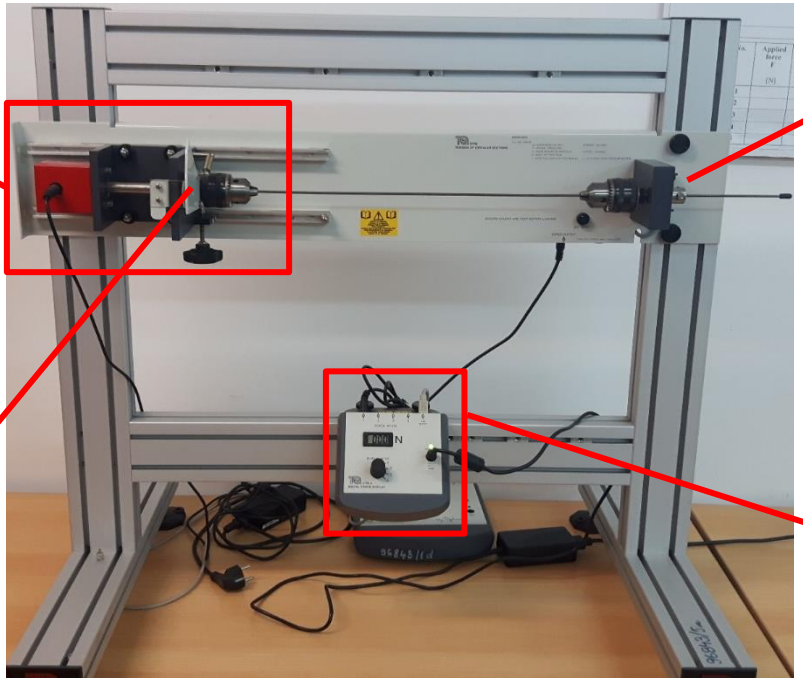
1. The circular rod is fixed between the two chucks (fixed chuck and sliding chuck), to obtain the length *l* [mm] of the bar;
2. The circular rod is subjected to torsion by the thumb-wheel by different forces. The applied forces are displayed on the digital display of the force transducer;
3. To obtain the twisting moments in cross-section of the rods, the applied forces are multiplied by force arm (b_f). The force arm is a metal body from the rod to the force transducer;
4. The experimental values of the twisting angles (ϕ_{exp}) are measured by means of a graduated element, from 0° up to 30°
5. The theoretical and experimental values of twisting angles are introduced in the Table of results.

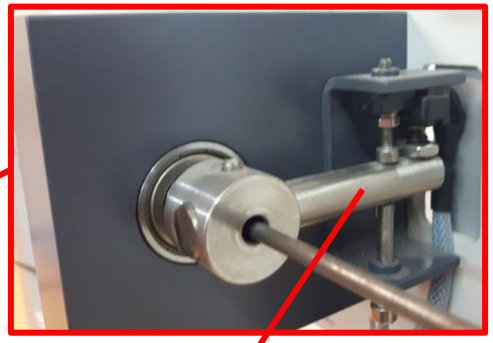


Experimental set-up



The sliding chuck with thumb-wheel





Force arm

The graduated element

Digital display of force transducer

1. Theoretical calculus of twisting angle, $\theta_{theoretic}$

Known data: applied forces, **F [N]** – given in the Results Table;

l = 500 mm; D = 3,02 mm; b_F = 50 mm;

G = 0.795·10^5 N/mm^2

$$T = F \cdot b_F \ [N \cdot mm] \qquad (1)$$

$$\theta_{theoretic} = \frac{T \cdot l}{G \cdot I_p} \qquad [rad] \qquad (2)$$

$I_p = \frac{\pi \cdot D^4}{32}$ $[mm^4]$ → polar momentum of the circular cross-section

After performing the theoretical calculations, the angle is obtained in radians. To obtain the angle in degrees, use the relationship:

$$\theta_{theoretic}\,[°] = \frac{\theta_{theoretic}\,[rad] \cdot 180°}{\pi} \qquad (3)$$

Theoretical values of twisting angle must be introduced in Results table.

2. Experimental twisting angle $\theta_{exp.}$

- The experimental values of the twisting angles, $\theta_{exp.}$ [°] are measured by means of a graduated element of the experimental set-up.

No.	Applied force, F [N]	Torsional moment, T [N·mm]	Angle of twist, θ [°]		Rel. dev. [%]
			$\theta_{teoretic}$	$\theta_{exp.}$	
1				8	
2				9.5	
3				11	
4				12.5	
5				14	

$$Rel.dev. = \left| \frac{|\theta_{exp.}| - |\theta_{theoretic}|}{|\theta_{exp.}|} \right| \cdot 100 \rightarrow [\%]$$

Relative deviation calculus must be performed and introduced in Results table.

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NextGEng

C1 – Strength of Materials

M3 - Deflection of Beams

Jamk University of Applied Sciences

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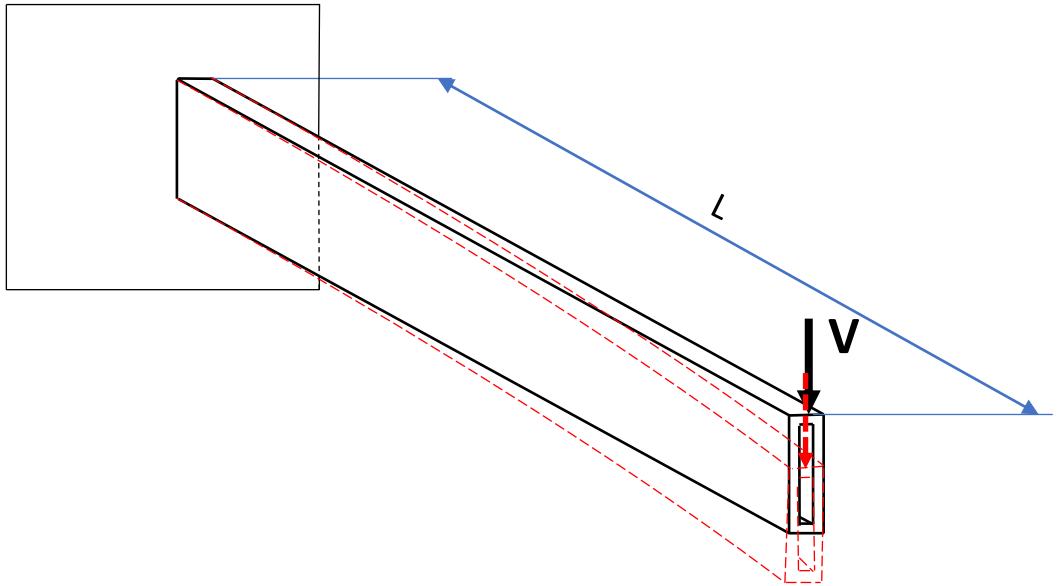
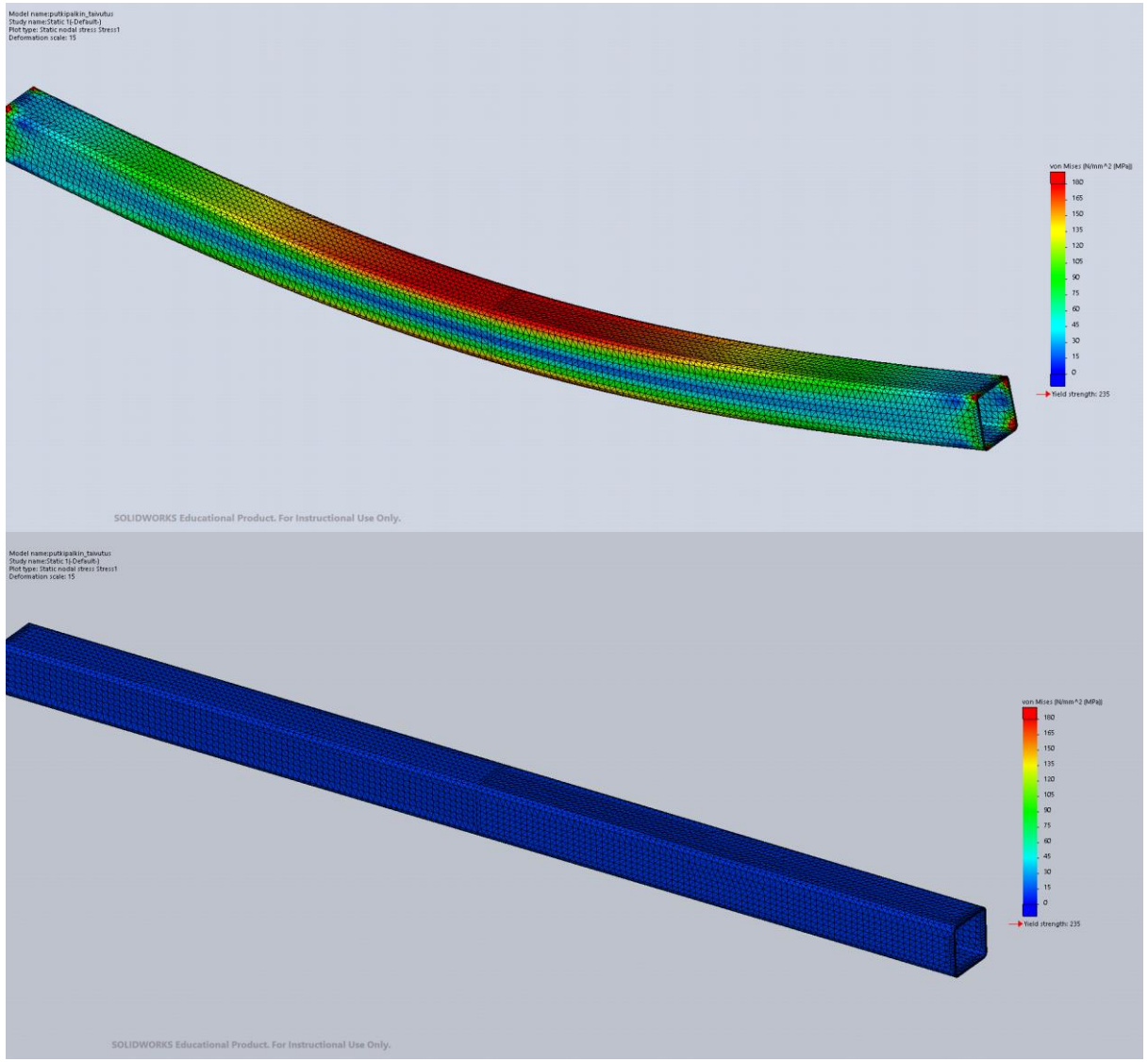
Deflection of Beams





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Deflection of Beams

Upon completion of this module, the student will be able to:

1) Understand the principle of deflection of beams.
2) Calculate the deflection of the beams with some restrictions.

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Content

- Introduction
- Differential Equations of the Deflection curve
- Deflection Curve
- Deflection of Hyperstatic Beams

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Introduction

Introduction

Subtitle

- text
- tables
- pictures
- movies
- etc.

Topic 1

Differential Equations of the Deflection curve

Restrictions:

- Pure bending (i.e. without shear stress) with straigth beam and normal stress under proportional limit and small deflection

Differential Equations of the Deflection curve

Pure bending (i.e., without shear stress) with straight beam and normal stress under proportional limit and small deflection /

$$E'F' = (R + y)\frac{dx}{R} \Longrightarrow$$

$$E'F' - EF = (R + y)\frac{dx}{R} - dx = \frac{y}{R}dx$$

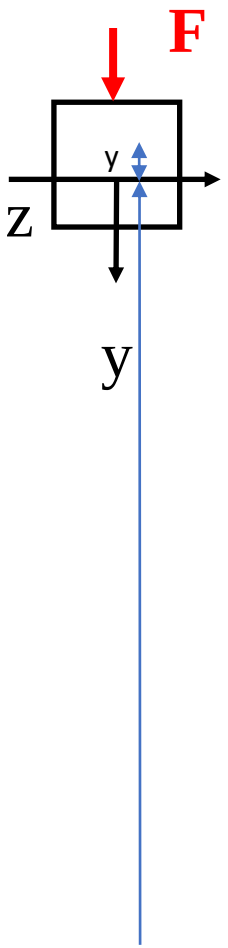
Where :

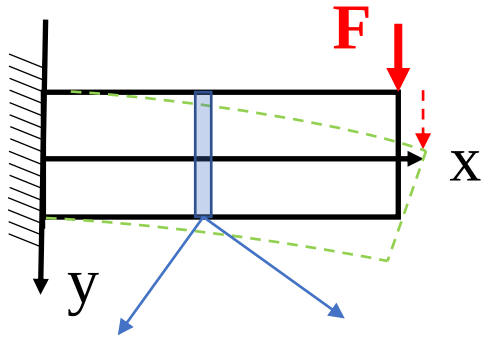
R is the radius created by bending

$$\varepsilon = \frac{\frac{y}{R}dx}{dx} = \frac{y}{R}$$

Where :

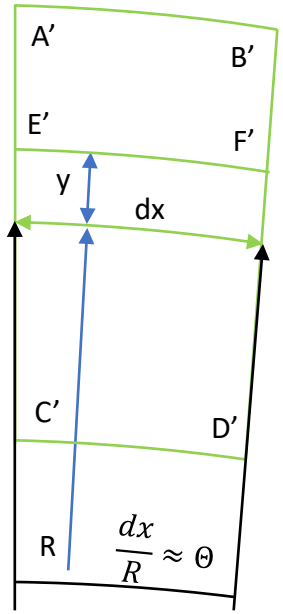
ε is strain

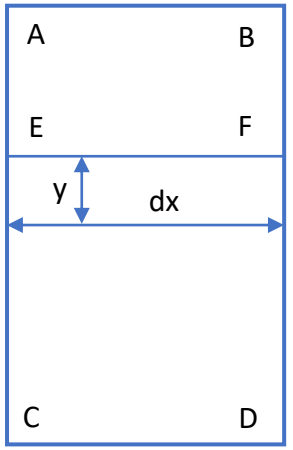




At bended (stretched state) state

Original state





Differential Equations of the Deflection curve

Pure bending (i.e., without shear stress) with straight beam and normal stress under proportional limit and small deflection

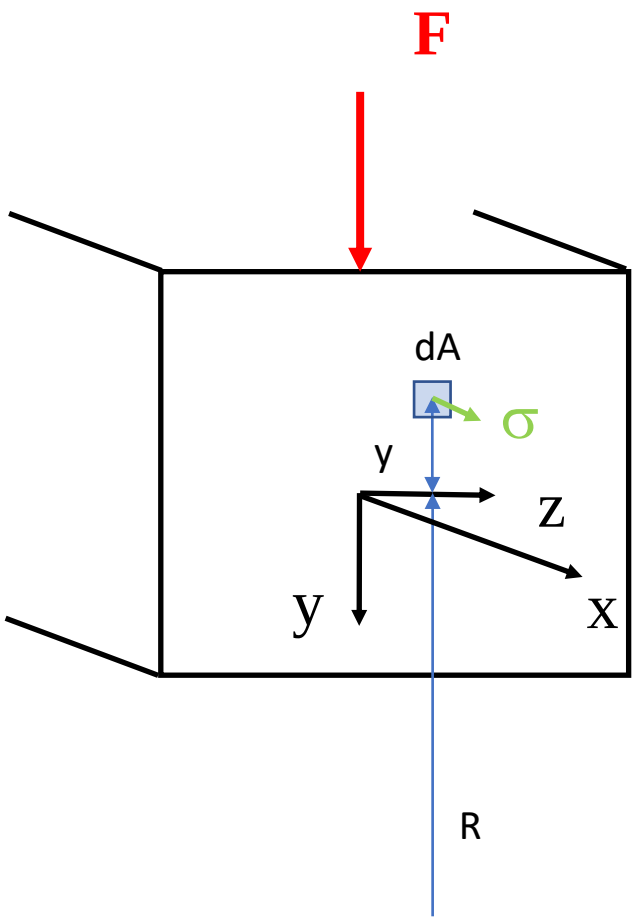
$$\sigma = E\varepsilon = E\frac{y}{R}$$

$$M(x) = M_z = \int_A \sigma y dA = \frac{E}{R}\int_A y^2 dA = \frac{E}{R} I \Longrightarrow R = \frac{EI}{M(x)}$$

also, by geometry $R = \frac{\mp[1+(v\prime)^2]^{\frac{3}{2}}}{v''}$

and with small deflections (compared to the length of the beam) we can neglect the first derivate

$$[1 + (v')^2]^{\frac{3}{2}} \approx 1 \Rightarrow \quad v''(x)\left(= \frac{d^2v(x)}{dx^2}\right) = \mp\frac{M(x)}{EI}$$



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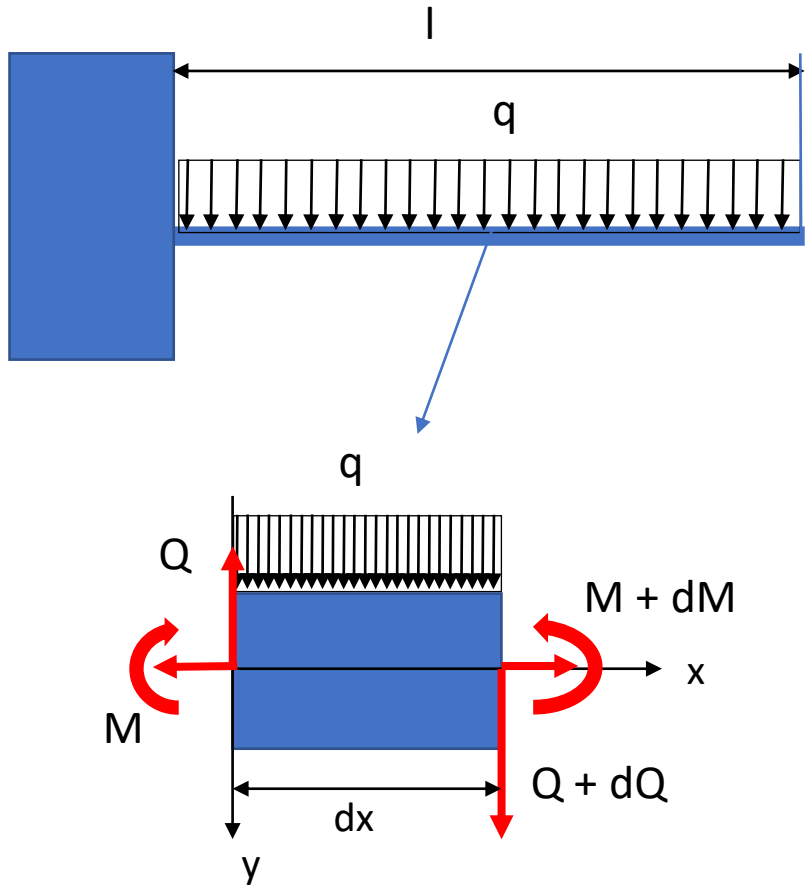
Differential Equations of the Deflection curve

$$\uparrow \sum Q = 0: Q - qdx - (Q + dQ) = 0 \Longrightarrow q = -\frac{dQ}{dx}$$

$$\circlearrowleft \sum M = 0: -M + (M + dM) - Qdx + \left(q\frac{dx^2}{2} \approx 0\right) = 0 \Longrightarrow$$

$$Q = \frac{dM}{dx} \; and \; q = -\frac{d^2M}{dx^2}$$



and combined with the earlier equation

$$-\frac{M(x)}{EI} = \frac{d^2}{dx^2}v(x) \Longrightarrow M(x) = -\frac{d^2}{dx^2}v(x)\mathrm{EI} \Longrightarrow q = -\frac{d^2M}{dx^2} = \frac{d^4}{dx^4}v(x)\mathrm{EI}$$

Differential Equations of the Deflection curve

$$v''(x)\left(=\frac{d^2v(x)}{dx^2}\right)=-\frac{M(x)}{EI}$$

by derivation once

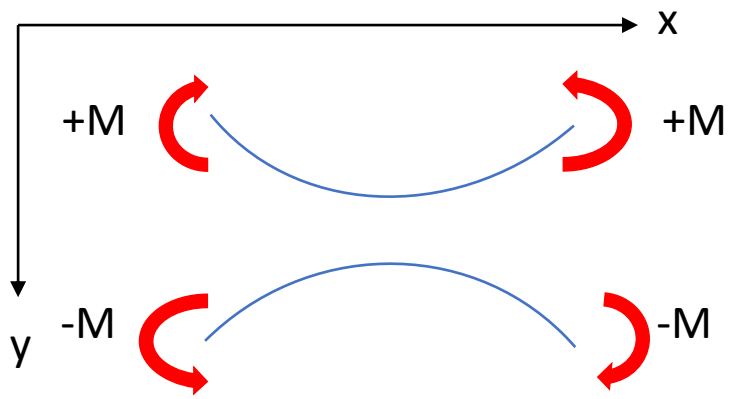
$$\frac{d^3v(x)}{dx^3}=-\frac{Q(x)}{EI}$$

and twice

$$\frac{d^4v(x)}{dx^4}=\frac{q(x)}{EI}$$

integrating twice

$$v=-\frac{1}{EI}\int\int M(x)dxdx+C_1x+C_2$$



If there is a change in E, I, A or loads, the integration must be done separately on different sides of the change

Deflection Curve

Differential equation of deflection curve

EI = bending stiffness

Applies with small bending and does not take account glide

Generic differential equation for beam (fourth order differential equation)

$$v''''(x) = \frac{d^4}{dx^4}v(x) = \frac{q(x)}{EI},$$

$$v'''(x) = Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx,$$

$$v''(x) = M(x) = M_2 + \int_{x_2}^{x} Q(x)dx,$$

$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx,$$

$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx$$

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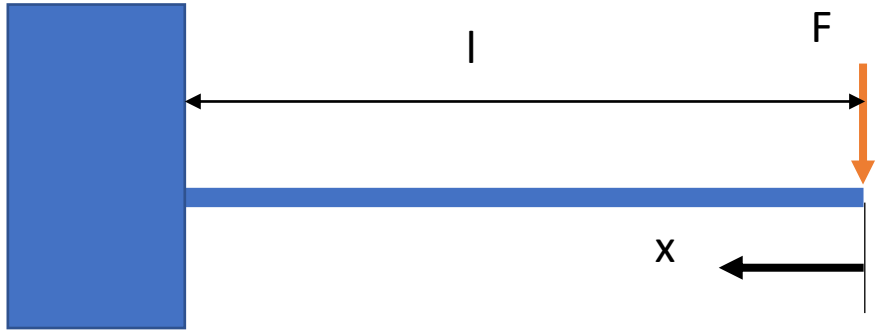
Deflection Curve

Define the deflection curve of the beam in the image



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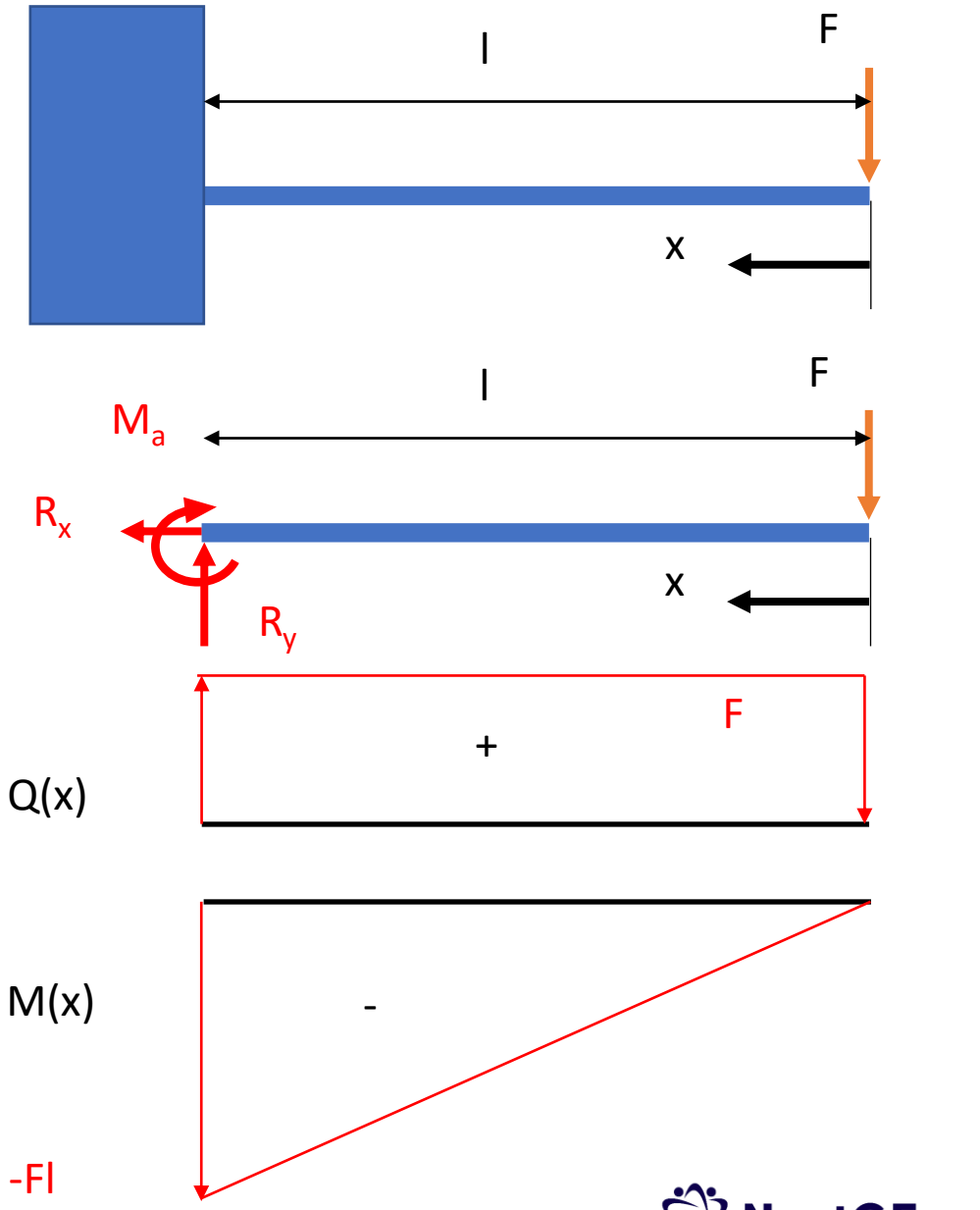
Deflection Curve

Define the deflection curve of the beam in the image

$$\leftarrow \sum \boldsymbol{F_x = 0: R_x = 0}$$

$$\uparrow \sum \boldsymbol{F_y = 0: R_y - F = 0 \Rightarrow R_y = F}$$

$$\circlearrowleft \sum \boldsymbol{M_A = 0: -M_a - F * l = 0 \Rightarrow M_a = -Fl}$$



$$M(x) = -F * x$$

Deflection Curve

Define the deflection curve of the beam in the image

$$v'''(x) = Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx,$$

$$v''(x) = M(x) = M_2 + \int_{x_2}^{x} Q(x)dx,$$

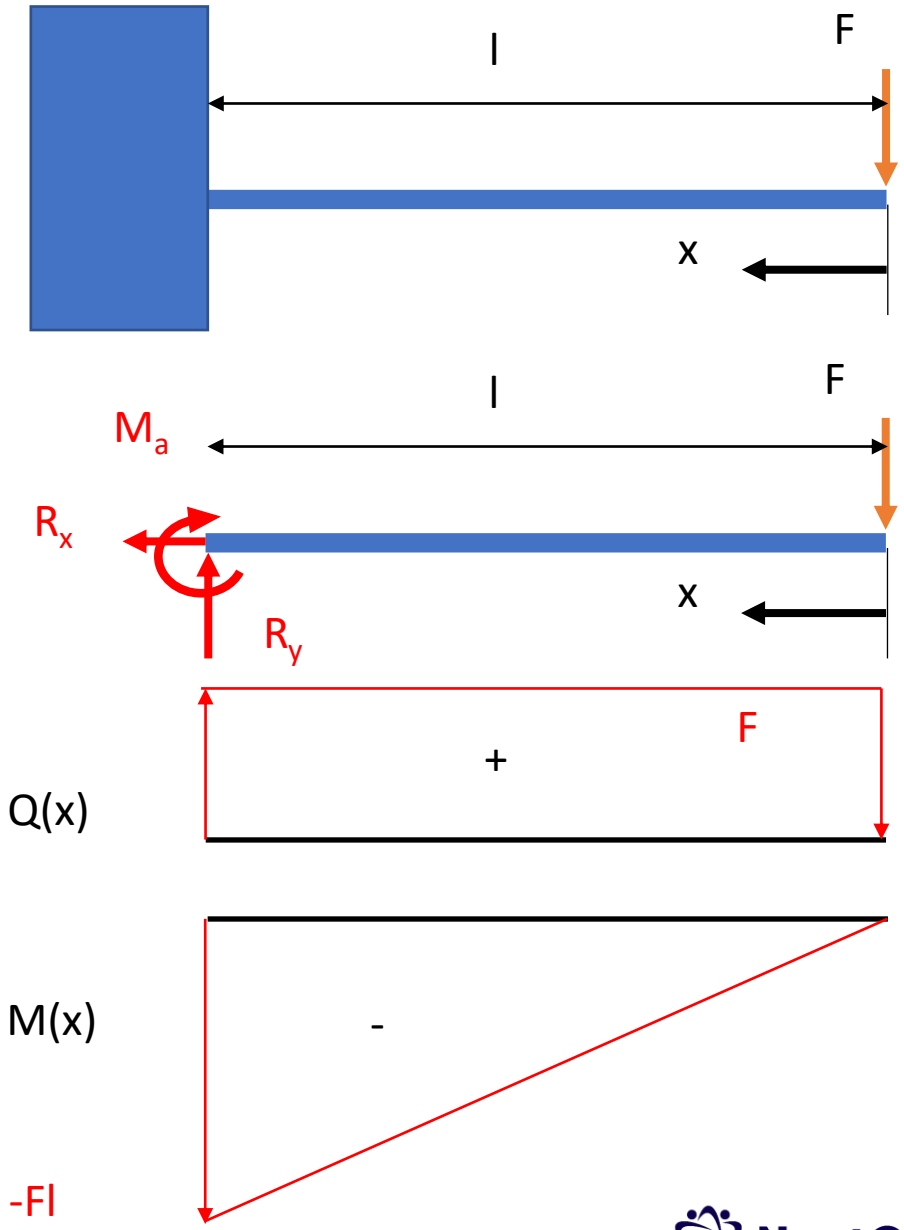
$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx,$$

$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx,$$

$$Q(x) = (Q_1 - \int_{x_1}^{x} q(x)dx \Longrightarrow)\ Q(x) = -F$$

$$M(x) = M_2 + \int_{x_2}^{x} Q(x)dx \Longrightarrow M(x) = -F * x + C_2$$

$C_2 = 0$ why?



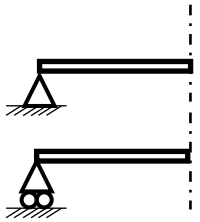
Deflection Curve

$$M = 0 \Leftrightarrow v'' = 0$$
$$Q = 0 \Leftrightarrow v''' = 0$$

Free end

$$\varphi = 0 \Leftrightarrow v' = 0$$
$$Q = 0 \Leftrightarrow v''' = 0$$

Slide support



$$M = 0 \Leftrightarrow v'' = 0$$
$$v = 0$$

Pin support

$$\varphi = 0 \Leftrightarrow v' = 0$$
$$v = 0$$

Rigid support

Deflection Curve

Define the deflection curve of the beam in the image

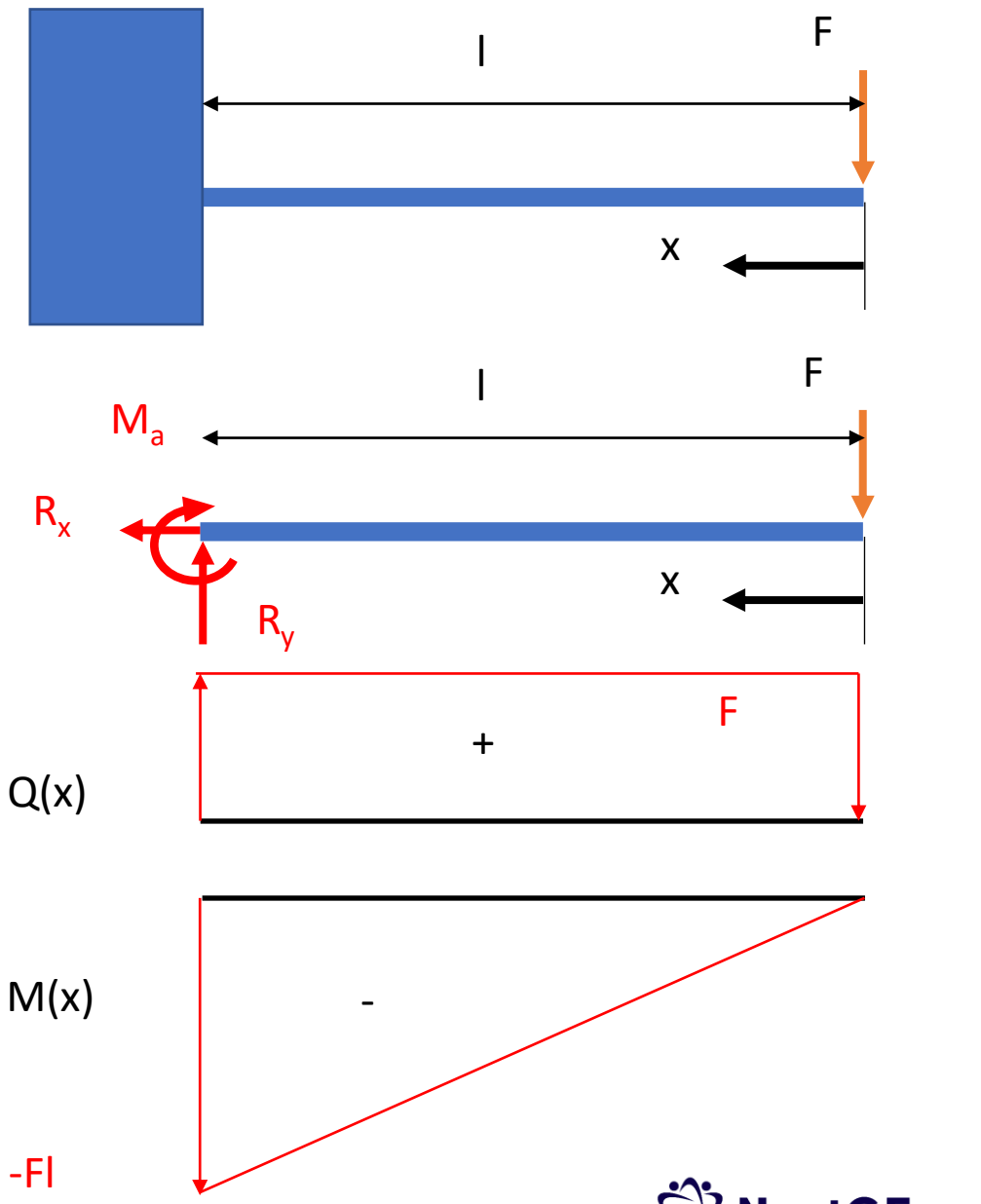
$$v'''(x) = Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx,$$
$$v''(x) = M(x) = M_2 + \int_{x_2}^{x} Q(x)dx,$$
$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx,$$
$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx,$$

$$M(x) = -F * x$$

$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx \; \varphi(x) = \frac{F * x^2}{2EI} + c_3$$

$$v'(l) = 0 \Longrightarrow \frac{F * l^2}{2EI} + c_3 = 0 \Longrightarrow c_3 = -\frac{F * l^2}{2EI}$$

$$v'(x) = \varphi(x) = \frac{F * x^2}{2EI} + -\frac{F * l^2}{2EI}$$



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NextGEng

Deflection Curve

Define the deflection curve of the beam in the image

$$v'''(x) = Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx,$$

$$v''(x) = M(x) = M_2 + \int_{x_2}^{x} Q(x)dx,$$

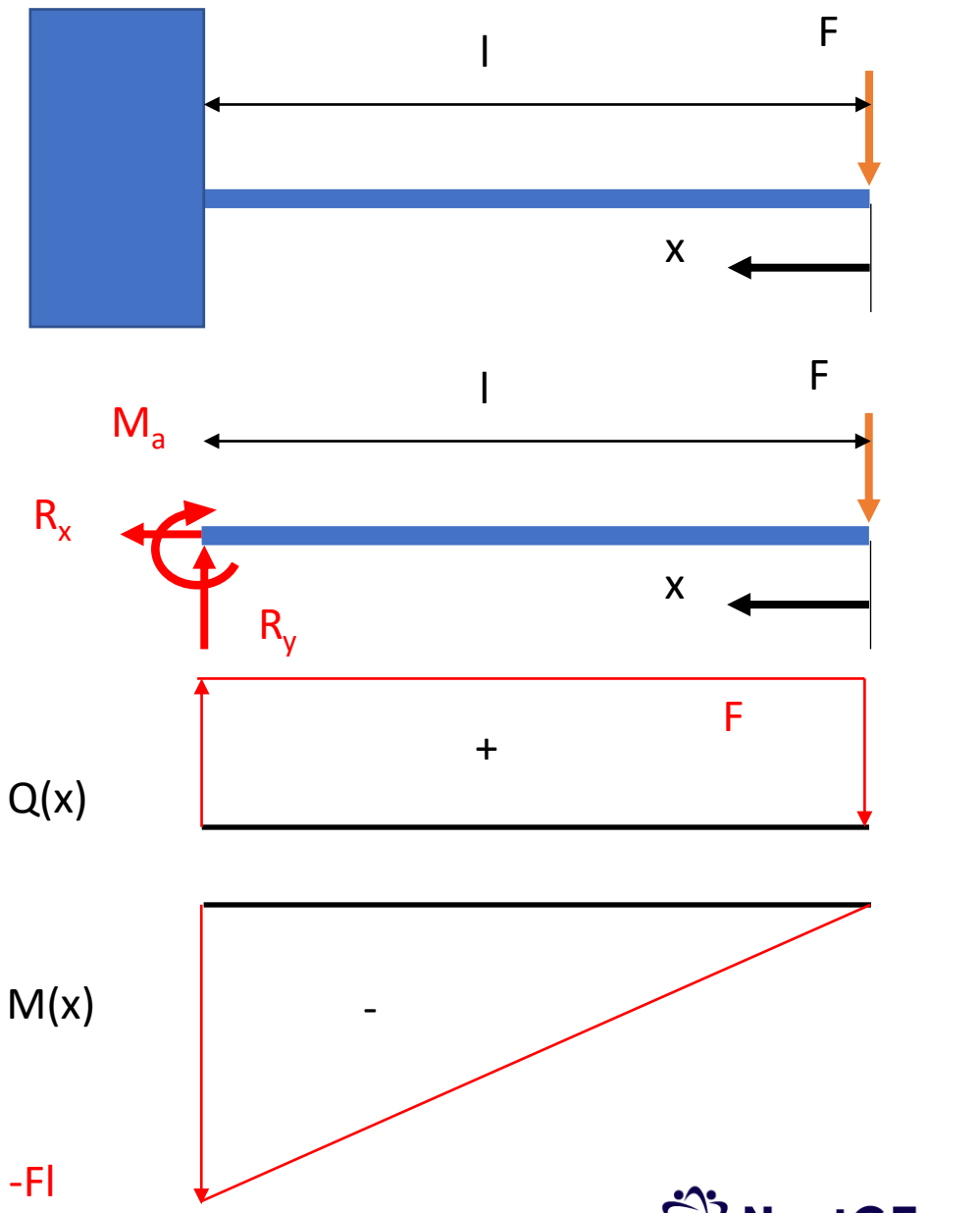
$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx,$$

$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx,$$

$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx = \frac{Fx^3}{6EI} - \frac{Fl^2x}{2EI} + C_4$$

$$v(l) = 0 \Rightarrow \frac{Fl^3}{6EI} - \frac{Fl^3}{2EI} + C_4 = 0 \Rightarrow C_4 = \frac{Fl^3}{3EI}$$

$$v(x) = \frac{Fx^3}{6EI} - \frac{Fl^2x}{2EI} + \frac{Fl^3}{3EI} = \frac{Fl^3}{6EI}\left(2 - 3\frac{x}{l} + \frac{x^3}{l^3}\right)$$



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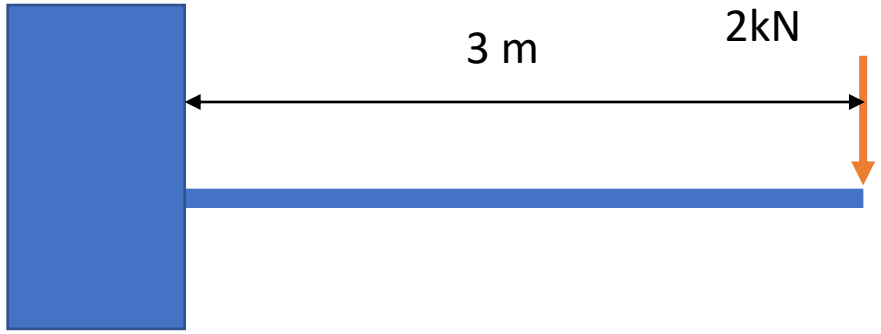
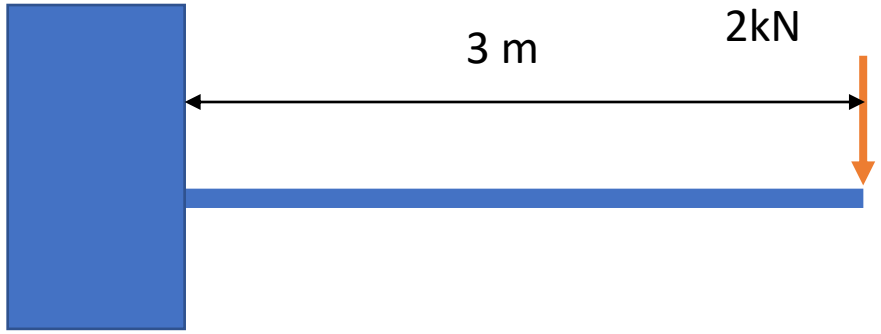
NextGEng

Deflection Curve



What would be the deflection and angle at the midlle of the beam?
Cross section of the beam is 75 mm x 75 mm and E = 210 000 N/mm^2

Deflection Curve



What would be the deflection and angle at the midlle of the beam? Cross section of the beam is 75 mm x 75 mm and E = 210 000 N/mm^2

$$I = \frac{a^4}{12} = \frac{(75\ mm)^4}{12} = 2636718{,}75\ mm^4$$

$$v(x) = \frac{Fl^3}{6EI}\left(2 - 3\frac{x}{l} + \frac{x^3}{l^3}\right) \Longrightarrow v(1{,}5m) = \frac{2000\ N * (3000\ mm)^3}{6 * 210000\frac{N}{mm^2} * 2636718{,}75mm^4}\left(2 - 3\frac{1500\ mm}{3000\ mm} + \frac{(1500\ mm)^3}{(3000\ mm)^3}\right)$$

$$= 10{,}2\ mm$$

$$v'(x) = \varphi(x) = \frac{F * x^2}{2EI} - \frac{F * l^2}{2EI} \Longrightarrow \varphi(1500mm) = \frac{2000\ N * (1500\ mm)^2}{2 * 210000\ \frac{N}{mm^2} * 2636718{,}75mm^4} - \frac{2000\ N * (3000mm)^2}{2 * 210000\ \frac{N}{mm^2} * 2636718{,}75\ mm^4}$$

$$= 0{,}0617\ rad\ (3{,}5\ degree)$$

$$M_{max} = 6000\ 000\ Nmm;\ \sigma_{max} = \frac{M_{max}}{I}y = \frac{6000000\ Nmm}{2636718{,}75\ mm^4}25\ mm = 56{,}9\ MPa$$

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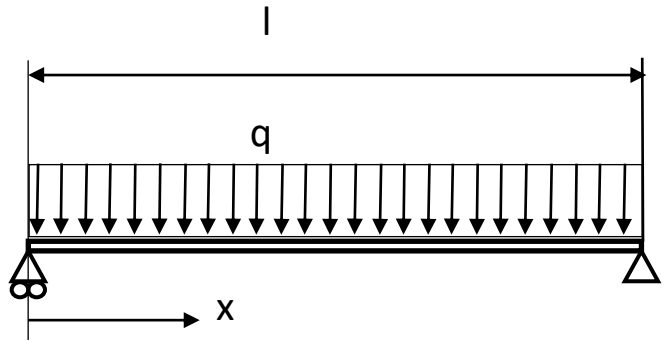
Deflection Curve

Define the deflection curve of the beam in the image



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Deflection Curve

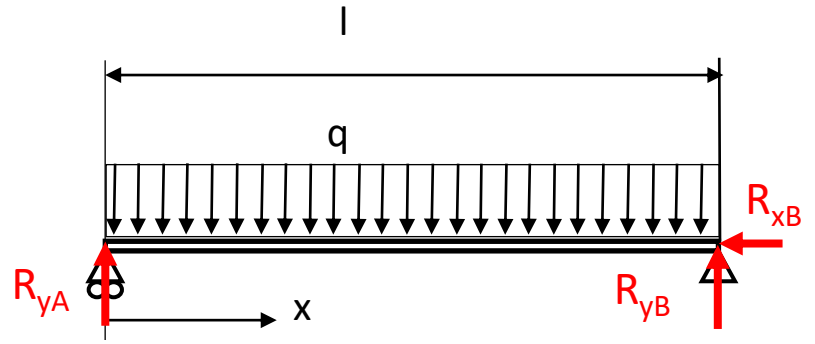
Define the deflection curve of the beam in the image

$$v'''(x) = Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx,$$

$$v''(x) = M(x) = M_2 + \int_{x_2}^{x} Q(x)dx,$$

$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx,$$

$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx,$$



$$Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx \Longrightarrow\ Q(x) = \frac{ql}{2} - qx + C_1$$

$$M(x) = M_2 + \int_{x_2}^{x} Q(x)dx \Longrightarrow M(x) = \frac{qlx}{2} - \frac{qx^2}{2} + C_1x + C_2$$

$$M(0) = \frac{ql0}{2} - \frac{q0^2}{2} + C_10 + C_2 \Longrightarrow C_2 = 0$$

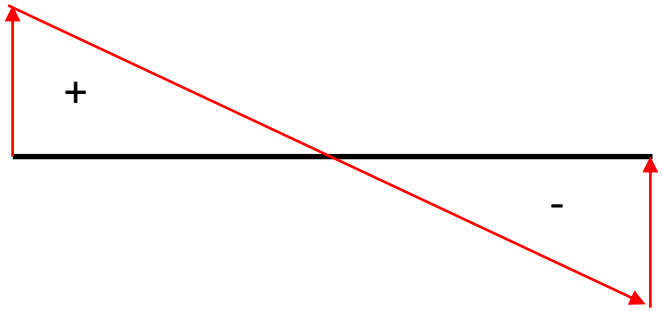
$$M(l) = \frac{ql^2}{2} - \frac{ql^2}{2} + C_1l = 0 \Longrightarrow C_1 = 0$$

$$M(x) = M(x) = \frac{qlx}{2} - \frac{qx^2}{2}$$

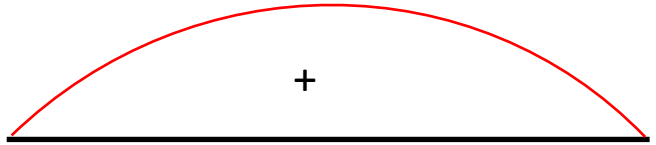
$$R_{xB} = 0;\ R_{yA} = R_{yB} = \frac{ql}{2}$$

$$M(0) = 0; M(l) = 0:$$

Q(x)



M(x)



Deflection Curve

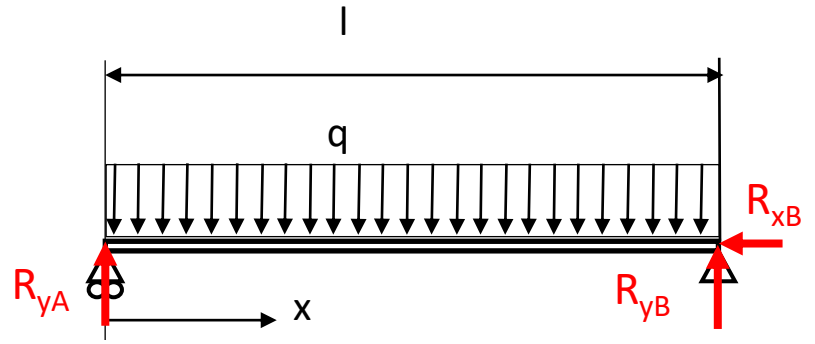
$$v'''(x) = Q(x) = Q_1 - \int_{x_1}^{x} q(x)dx,$$

$$v''(x) = M(x) = M_2 + \int_{x_2}^{x} Q(x)dx,$$

$$v'(x) = \varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx,$$

$$v(x) = v_4 + \int_{x_4}^{x} \varphi(x)dx,$$

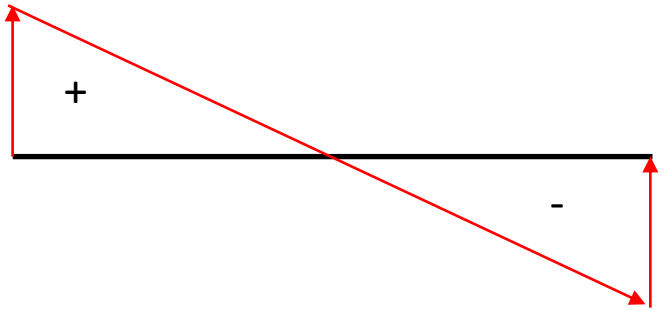
Define the deflection curve of the beam in the image



$$M(x) = M(x) = \frac{qlx}{2} - \frac{qx^2}{2}$$

$$\varphi(x) = \varphi_3 - \int_{x_3}^{x} \frac{M(x)}{EI}dx \Rightarrow \varphi(x) = \frac{1}{EI}\left(-\frac{qlx^2}{4} + \frac{qx^3}{6} + C_3\right)$$

Q(x)

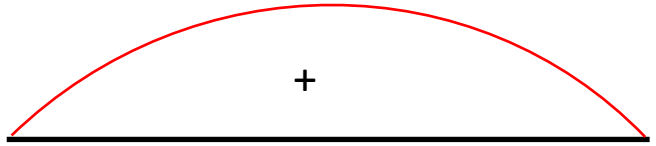


$$v(x) = v_4 + \frac{1}{EI}\int_{x_4}^{x} \varphi(x)dx \Rightarrow v(x) = \frac{1}{EI}\left(-\frac{qlx^3}{12} + \frac{qx^4}{24} + C_3x + C_4\right)$$

$v(0) = 0; v(l) = 0$:

$$v(0) = -\frac{ql0^3}{12} + \frac{q0^4}{24} + C_30 + C_4 \Rightarrow C_4 = 0 \qquad v(l) = -\frac{ql^4}{12} + \frac{ql^4}{24} + C_3l = 0 \Rightarrow C_3 = \frac{ql^3}{24}$$

M(x)



$$\varphi(x) = \frac{ql^3}{24EI}\left(-\frac{6x^2}{l^2} + \frac{4x^3}{l^3} + 1\right) \qquad v(x) = \frac{ql^4}{24EI}\left(-\frac{2x^3}{l^3} + \frac{x^4}{l^4} + \frac{x}{l}\right)$$

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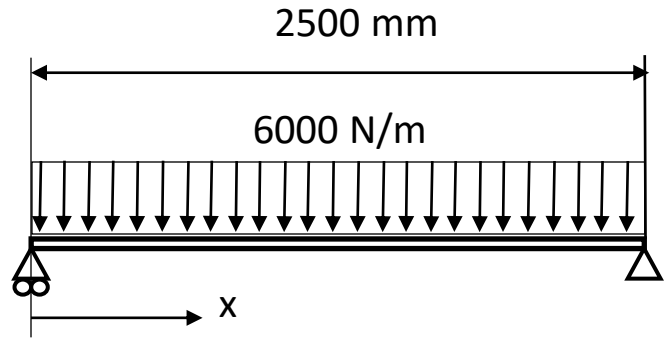
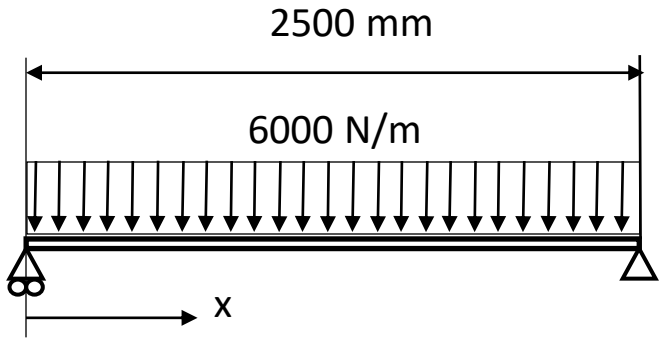
Deflection Curve



What would be the deflection at the middle of the beam and angle at the end of the beam? Cross section of the beam is 75 mm x 75 mm and E = 210 000 N/mm^2

Deflection Curve



What would be the deflection at the middle of the beam and angle at the end of the beam? Cross section of the beam is 75 mm x 75 mm and E = 210 000 N/mm^2

$$I = \frac{a^4}{12} = \frac{(75\ mm)^4}{12} = 2636718{,}75\ mm^4$$

$$\varphi(x) = \frac{ql^3}{24EI}\left(-\frac{6x^2}{l^2} + \frac{4x^3}{l^3} + 1\right) \qquad v(x) = \frac{ql^4}{24EI}\left(-\frac{2x^3}{l^3} + \frac{x^4}{l^4} + \frac{x}{l}\right)$$

$$v(1250) = \frac{6\ \frac{N}{mm} * (2500\ mm)^4}{24 * 210000 \frac{N}{mm^2} * 2636719\ mm^4}\left(-\frac{2 * (1250\ mm)^3}{(2500\ mm)^3} + \frac{(1250\ mm)^4}{(2500\ mm)^4} + \frac{1250\ mm}{2500\ mm}\right) = 5{,}51\ mm$$

$$\varphi(0) = \frac{6\ \frac{N}{mm}(2500\ mm)^3}{24 * 210000\ \frac{N}{mm^2} * 2636719\ mm^4}\left(-\frac{6(0mm)^2}{(2500\ mm)^2} + \frac{4(0\ mm)^3}{(2500\ mm)^3} + 1\right) = 0{,}007\ rad = 0{,}4\ degree$$

$$\sigma_{max} = \frac{M_{max}}{I}e = \frac{\frac{ql}{2} * \frac{l}{2} - \frac{ql}{2} * \frac{l}{4}}{I}e = \frac{\frac{ql^2}{8}}{I}e = \frac{6\frac{N}{mm} * (2500\ mm)^2}{8} 37{,}5\ mm = 66{,}7\frac{N}{(mm)^2}$$

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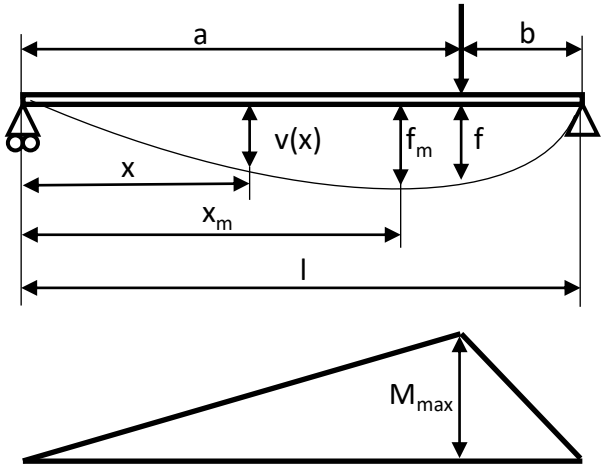
Deflection Curve

Load case, bending moment diagram



Reaction forces, bending moments

A = Fb/l; B = Fa/l
M_{max} = Fab/l
0 ≤ x ≤ a: M(x) = Fbx/l
a ≤ x ≤ l: M(x) = Fa(1-x/l)

Deflection curve

0 ≤ x ≤ a:

$$v(x) = \frac{Fab^2}{6EI}\left[\left(1+\frac{l}{b}\right)\frac{x}{l} - \frac{x^3}{abl}\right]$$

a ≤ x ≤ l:

$$v(x) = \frac{Fa^2b}{6EI}\left[\left(1+\frac{l}{a}\right)\frac{l-x}{l} - \frac{(l-x)^3}{abl}\right]$$

$$f = \frac{Fa^2b^2}{3EIl}$$

$$a > b\text{: } f_m = \frac{Fb\sqrt{(l^2-b^2)^3}}{9\sqrt{3}EIl}$$

at $x_m = \sqrt{\frac{l^2-b^2}{3}}$

$$a < b\text{: } f_m = \frac{Fa\sqrt{(l^2-a^2)^3}}{9\sqrt{3}EIl}$$

at $x_m = l - \sqrt{\frac{l^2-a^2}{3}}$

$$\alpha_A = \frac{Fab(l+b)}{6EIl}$$

$$\alpha_B = \frac{Fab(l+a)}{6EIl}$$

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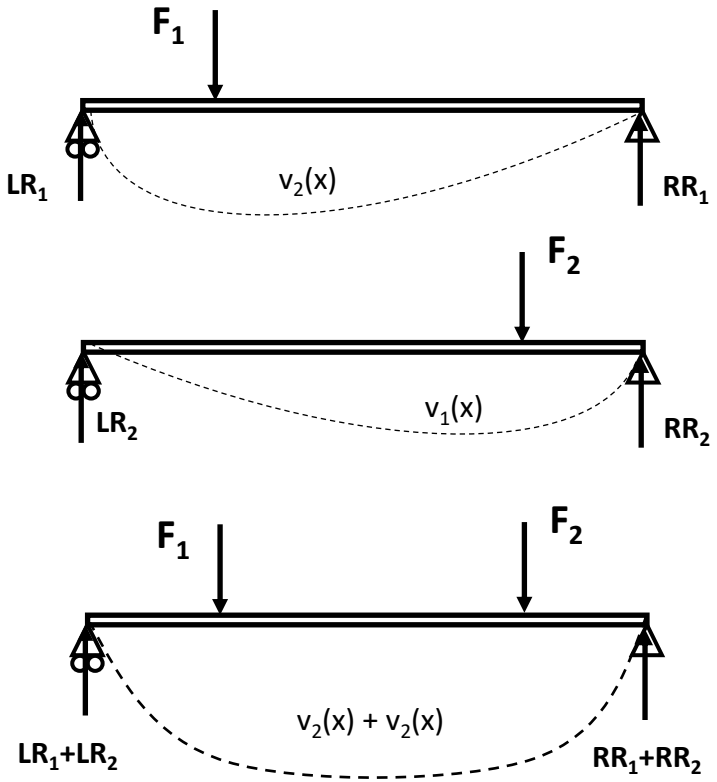
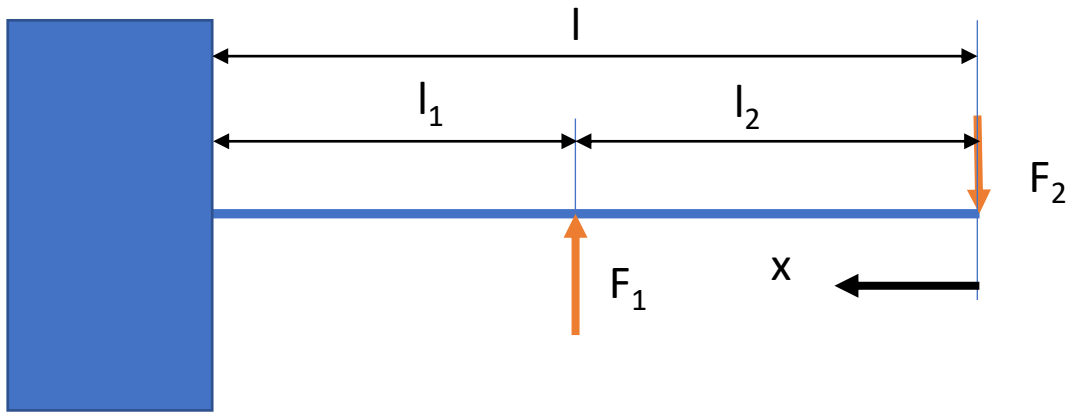
Principle of Superposition



Principle of Superposition



When only F_1 / Kun ainoastaan F_1

$$M_2(x) = - -F_1 * (x - l_2), when\ l_2 \leq x \leq l$$

$$M_2(x) = 0, when\ l_2 \geq x \geq 0$$

$$v_2'(x) = \varphi_2(x) = \frac{-F_1 * (x - l_2)^2}{2EI} - \frac{-F_1 * l_1^2}{2EI}, when\ l_2 \leq x \leq l$$

$$v_2'(x) = \varphi_2(x) = -\frac{-F_1 * l_1^2}{2EI}, when\ l_2 \geq x \geq 0$$

$$v_2(x) = -\frac{F_1 l_1^3}{6EI}\left(2 - 3\frac{(x - l_2)}{l_1} + \frac{(x - l_2)^3}{l_1^3}\right), when\ l_2 \leq x \leq l$$

$$v_2(x) = -\frac{F_1 l_1^3}{3EI} - \sin\varphi_2\ \ (l_2 - x), when\ l_2 \geq x \geq 0$$

When only F_2 / Kun ainoastaan F_2

$$M_1(x) = -F_2 * x$$

$$v_1(x) = \frac{F_2 l^3}{6EI}\left(2 - 3\frac{x}{l} + \frac{x^3}{l^3}\right)$$

$$v_1'(x) = \varphi_1(x) = \frac{F_2 * x^2}{2EI} - \frac{F_2 * l^2}{2EI}$$

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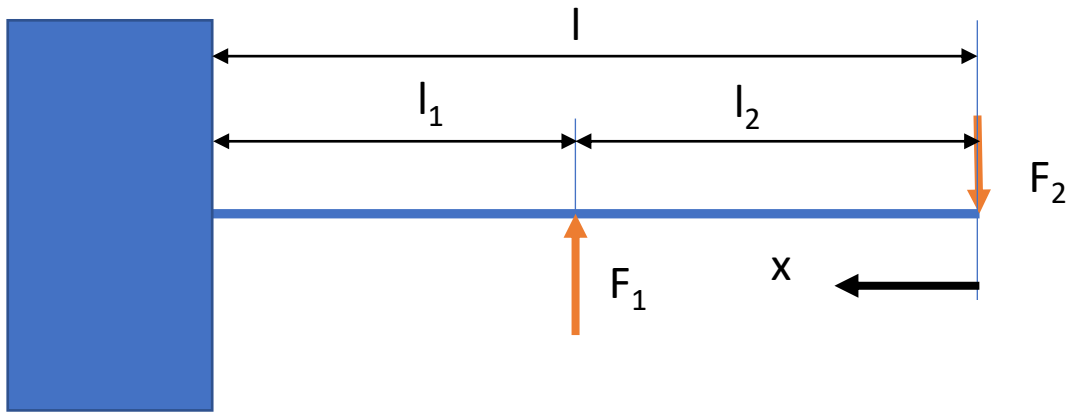
Principle of Superposition



$$v(x) = \frac{F_2 l^3}{6EI}\left(2 - 3\frac{x}{l} + \frac{x^3}{l^3}\right) - \frac{F_1 l_1^3}{3EI} - \sin\left(\frac{F_1 * l_1^2}{2EI}\right)(l_2 - x), when\ l_2 \geq x \geq 0$$

$$v(x) = \frac{F_2 l^3}{6EI}\left(2 - 3\frac{x}{l} + \frac{x^3}{l^3}\right) - \frac{F_1 l_1^3}{6EI}\left(2 - 3\frac{(x-l_2)}{l_1} + \frac{(x-l_2)^3}{l_1^3}\right), when\ l_2 \leq x \leq l$$

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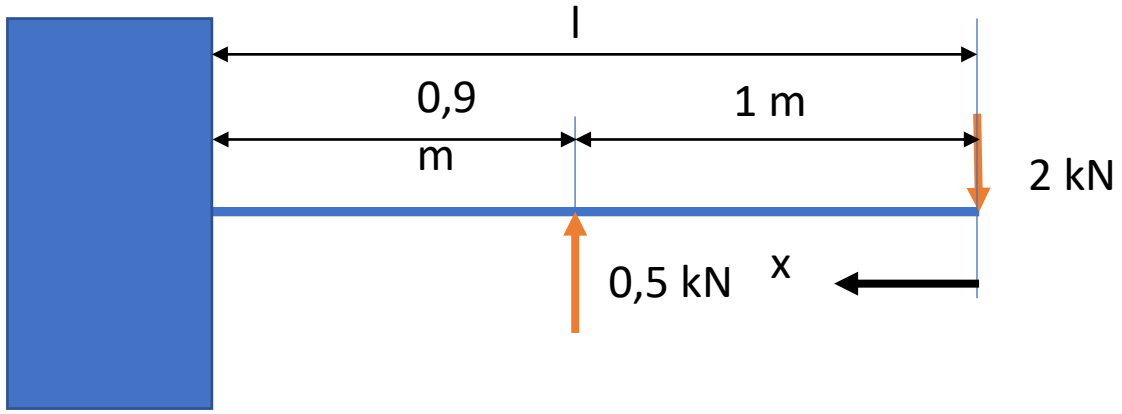
Principle of Superposition

Define the deflection at the free end of the beam in the image



$$v(x) = \frac{F_2 l^3}{6EI}\left(2 - 3\frac{x}{l} + \frac{x^3}{l^3}\right) - \frac{F_1 l_1^3}{3EI} - \sin\left(\frac{F_1 * l_1^2}{2EI}\right)(l_2 - x), when\ l_2 \geq x \geq 0$$

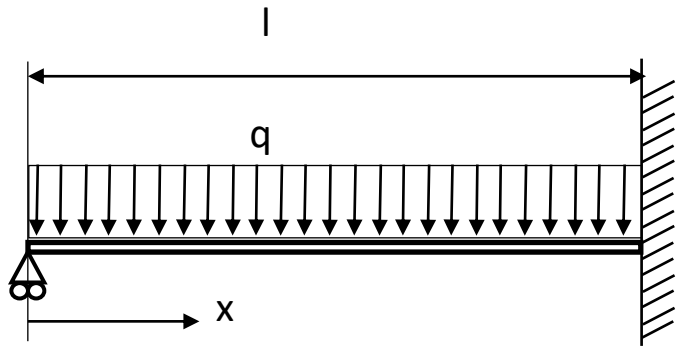
$$v(0) = \frac{F_2 l^3}{3EI} - \frac{F_1 l_1^3}{3EI} - \sin\left(\frac{F_1 * l_1^2}{2EI}\right)(l_2) \Rightarrow v(0) = \frac{1}{3EI}(F_2 l^3 - F_1 l_1^3) - \sin\left(\frac{F_1 * l_1^2}{2EI}\right)(l_2)$$

$$v(0) = \frac{1}{3EI}(F_2 l^3 - F_1 l_1^3) - \sin\left(\frac{F_1 * l_1^2}{2EI}\right)(l_2)$$

$$v(0) = \frac{1}{3*210000\frac{N}{mm^2}*2636719}(2000\ N * (1900\ mm)^3 - 500\ N * (900\ mm)^3) - \sin\left(\frac{500\ N*(900\ mm)^2}{2*210000\frac{N}{mm^2}*2636719\ mm^4}\right)(l_2) = 7{,}67\ mm$$

Deflection of Hyperstatic Beams

Define the deflection curve of the beam in the image



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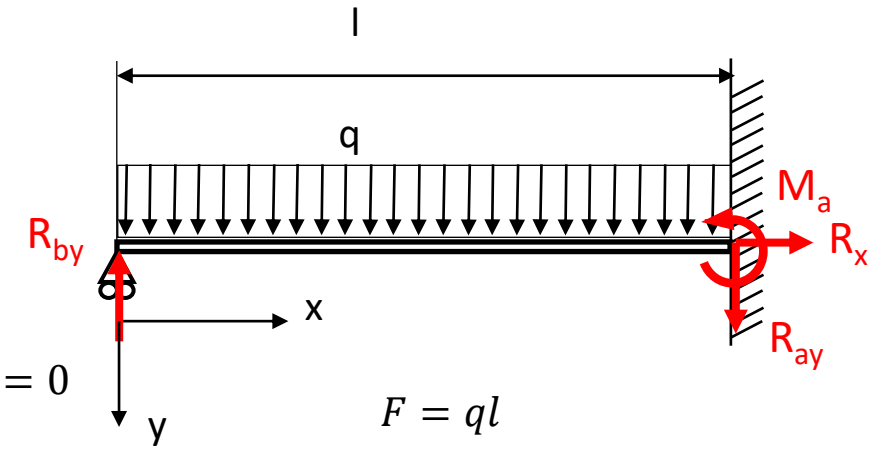
Deflection of Hyperstatic Beams

Define the deflection curve of the beam in the image



$$\leftarrow \sum F_x = 0: R_x = 0 \quad \uparrow \sum F_y = 0: -R_{ay} - F + R_{by} = 0 \quad \circlearrowleft \sum M_A = 0: M_a + \frac{Fl}{2} - R_{by} l = 0$$

$F = ql$

Degree of static indeterminancy is 1

$$M_x = R_{by} x - \frac{Fx^2}{2l}$$

$$v''(x)\left(= \frac{d^2 v(x)}{dx^2}\right) = -\frac{M(x)}{EI}$$

$$\} EI \frac{d^2 v(x)}{dx^2} = -R_{by} x + \frac{Fx^2}{2l}$$

$$EI \frac{dv(x)}{dx} = \frac{-R_{by} x^2}{2} + \frac{Fx^3}{6l} + C_1$$

$$EIv(x) = \frac{-R_{by} x^3}{6} + \frac{Fx^4}{24l} + C_1 x + C_2$$

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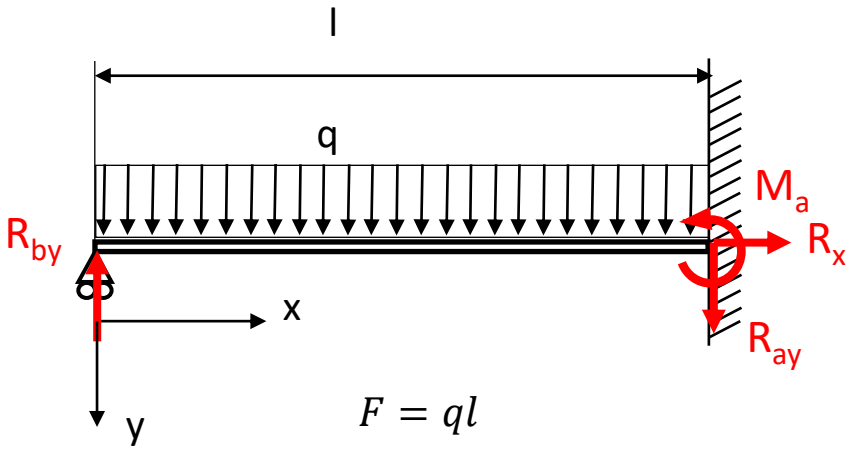
Deflection of Hyperstatic Beams

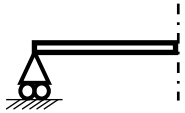
Define the deflection curve of the beam in the image



$$F = ql$$

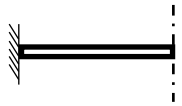
$$EIv(x) = \frac{-R_{by}x^3}{6} + \frac{Fx^4}{24l} + C_1x + C_2$$

$$EI\frac{dv(x)}{dx} = \frac{-R_{by}x^2}{2} + \frac{Fx^3}{6l} + C_1$$



$$M = 0 \Leftrightarrow v'' = 0$$
$$v = 0$$

Pin support / Niveltuki



$$\varphi = 0 \Leftrightarrow v' = 0$$
$$v = 0$$

Rigid support / Jäykkä tuki

$$EIv(0) = \frac{-R_{by}0^3}{6} + \frac{F0^4}{24l} + C_10 + C_2 = 0$$
$$\Longrightarrow C_2 = 0$$

$$EI\frac{dv(l)}{dx} = \frac{-R_{by}l^2}{2} + \frac{Fl^3}{6l} + C_1$$
$$\Longrightarrow C_1 = \frac{R_{by}l^2}{2} - \frac{Fl^2}{6}$$

$$EIv(l) = \frac{-R_{by}l^3}{6} + \frac{Fl^3}{24} + \frac{R_{by}l^3}{2} - \frac{Fl^3}{6}$$

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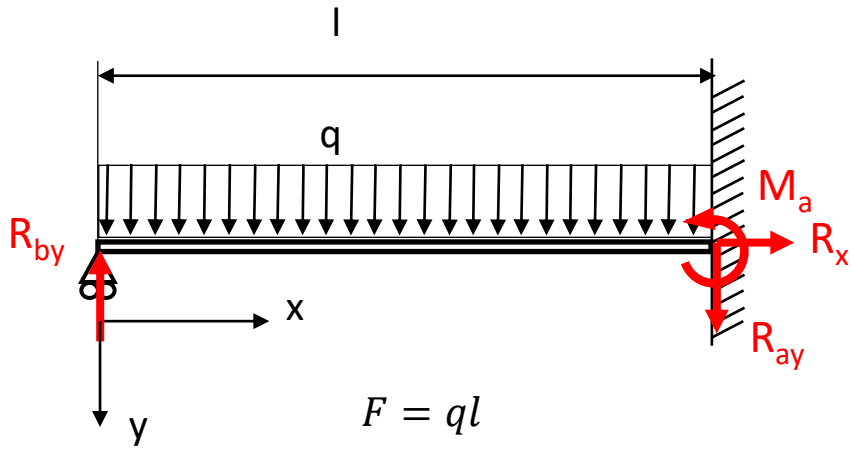
Deflection of Hyperstatic Beams

Define the deflection curve of the beam in the image



$$F = ql$$

$$EIv(l) = \frac{-R_{by}l^3}{6} + \frac{Fl^3}{24} + \frac{R_{by}l^3}{2} - \frac{Fl^3}{6} = 0 \Longrightarrow R_{by} = \frac{3F}{8}$$

$$\uparrow \sum F_y = 0: -R_{ay} - F + R_{by} = 0 \Longrightarrow R_{ay} = -\frac{5F}{8}$$

$$\circlearrowleft \sum M_A = 0: M_a + \frac{Fl}{2} - R_{by}l = 0 \Longrightarrow M_a = -\frac{Fl}{8}$$

$$M_x = R_{by}x - \frac{Fx^2}{2l} = \frac{3Fx}{8} - \frac{Fx^2}{2l} \qquad Q_x = \frac{3F}{8} - \frac{Fx}{l}$$

$$EI\frac{dv(x)}{dx} = \frac{-R_{by}x^2}{2} + \frac{Fx^3}{6l} + C_1 = -\frac{3Fx^2}{16} + \frac{Fx^3}{6l} + \frac{Fl^2}{48} = \frac{Fl^2}{48}\left(\frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1\right)$$

$$EIv(x) = \frac{-R_{by}x^3}{6} + \frac{Fx^4}{24l} + C_1x = -\frac{3Fx^3}{48} + \frac{Fx^4}{24l} + \frac{Fl^2x}{48} = \frac{Fl^3}{48}\left(\frac{2x^4}{l^4} - \frac{3x^3}{l^3} + \frac{x}{l}\right)$$

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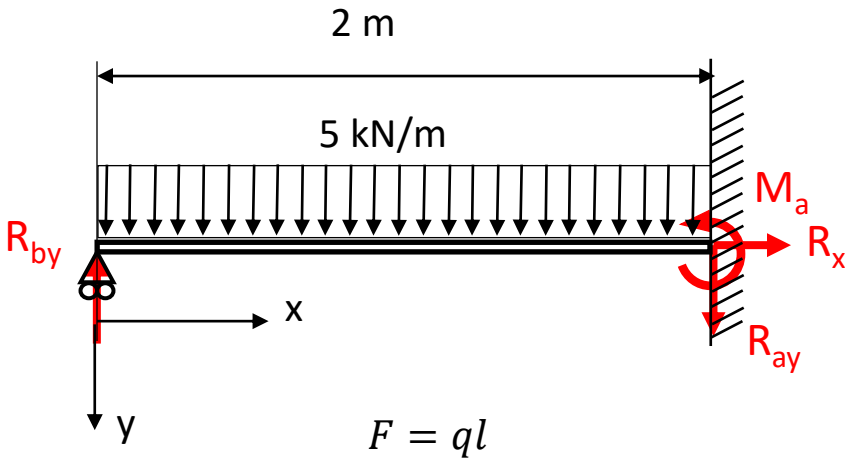
Deflection of Hyperstatic Beams

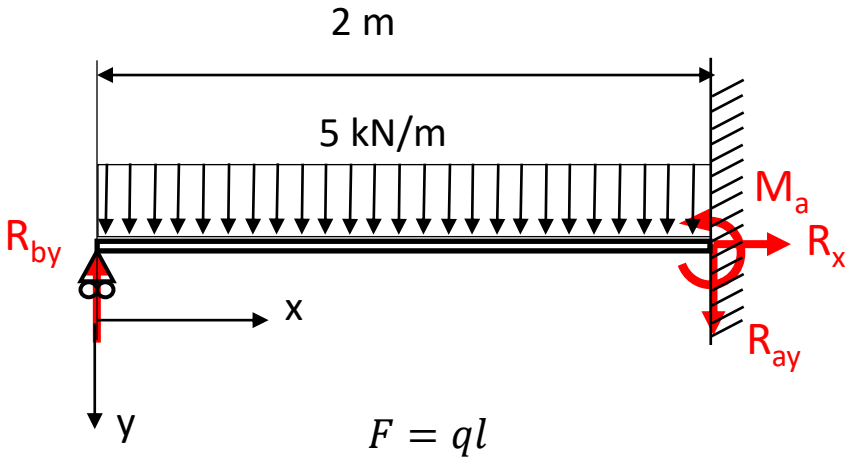
Define max moment and max deflection of the beam in the image



$$F = ql$$

Deflection of Hyperstatic Beams

Define max moment and max deflection of the beam in the image



$$F = ql$$

$$Q_x = \frac{3F}{8} - \frac{Fx}{l} \qquad M_x = \frac{3Fx}{8} - \frac{Fx^2}{2l}$$

$$Q_x = \frac{3F}{8} - \frac{Fx}{l} = 0 \Longrightarrow x = \frac{3}{8}l$$

$$M_x\left(\frac{3}{8}m\right) = \frac{3 * 5\frac{kN}{m} * 2\ m * \frac{3}{8}m}{8} - \frac{5\frac{kN}{m} * 2\ m * \left(\frac{3}{8}m\right)^2}{2 * 2\ m} = 1{,}0546875\ kNm$$

$$M_x(2m) = \frac{3 * 5\frac{kN}{m} * 2\ m * 2\ m}{8} - \frac{5\frac{kN}{m} * 2\ m * (2\ m)^2}{2 * 2\ m} = -2{,}5\ kNm$$

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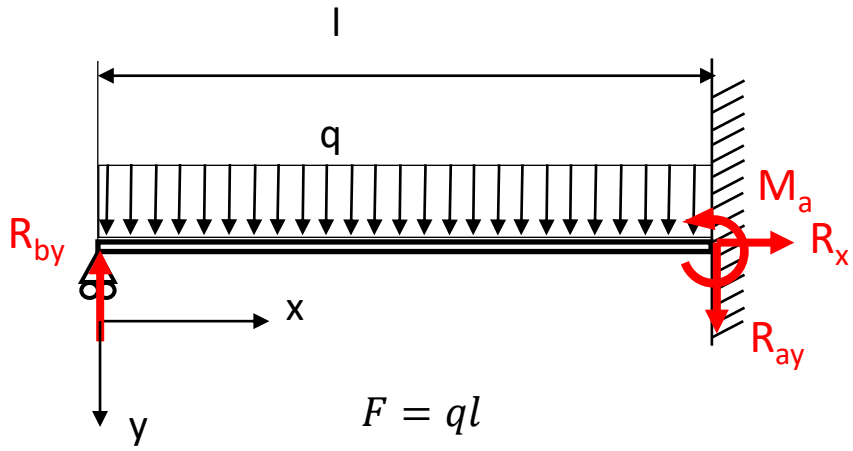
Deflection of Hyperstatic Beams

Define the deflection curve of the beam in the image



$$Q_x = \frac{3F}{8} - \frac{Fx}{l} \qquad M_x = \frac{3Fx}{8} - \frac{Fx^2}{2l}$$

$$EI\frac{dv(x)}{dx} = \frac{Fl^2}{48}\left(\frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1\right) \qquad EIv(x) = \frac{Fl^3}{48}\left(\frac{2x^4}{l^4} - \frac{3x^3}{l^3} + \frac{x}{l}\right)$$

$F = ql$

Degree of static indeterminacy is 1

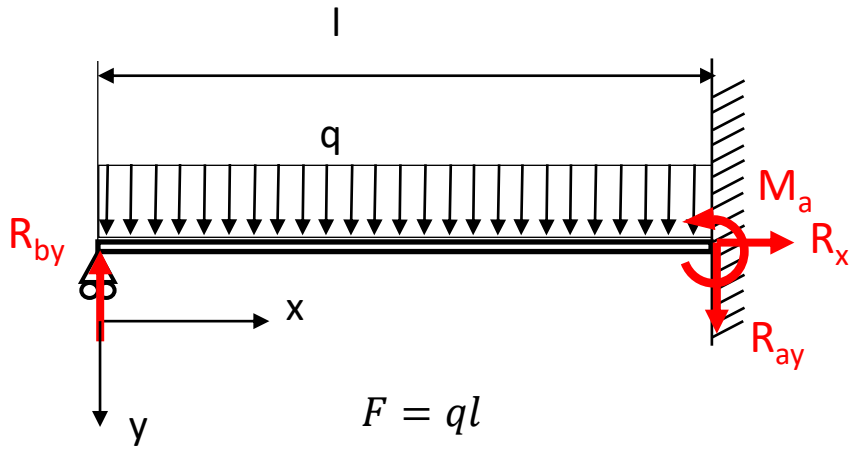
$$EI\frac{dv(x)}{dx} = \frac{Fl^2}{48}\left(\frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1\right) = 0 \Rightarrow \frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1 = 0 \Rightarrow x = l \; or \; x = \frac{l}{16}\left(1 \pm \sqrt{33}\right)$$

$$x = \frac{l}{16}\left(1 + \sqrt{33}\right) \Rightarrow x \approx 0{,}421535l \Rightarrow v_{max} = \frac{78 + 110\sqrt{33}}{2 * 16^4}\frac{Fl^3}{EI} \approx \frac{1}{185}\frac{Fl^3}{EI}$$

$$v_{max} = v(0{,}843m) = \frac{1}{185}\frac{5\frac{N}{mm} * 2000\,mm * (2000\,mm)^3}{210000\frac{N}{mm^2} * 19400000mm^4} = 0{,}000106\,mm$$

Deflection of Hyperstatic Beams

Define the deflection curve of the beam in the image



$$Q_x = \frac{3F}{8} - \frac{Fx}{l} \qquad M_x = \frac{3Fx}{8} - \frac{Fx^2}{2l}$$

$$EI\frac{dv(x)}{dx} = \frac{Fl^2}{48}\left(\frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1\right) \qquad EIv(x) = \frac{Fl^3}{48}\left(\frac{2x^4}{l^4} - \frac{3x^3}{l^3} + \frac{x}{l}\right)$$

$F = ql$

Degree of static indeterminacy is 1

$$EI\frac{dv(x)}{dx} = \frac{Fl^2}{48}\left(\frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1\right) = 0 \Rightarrow \frac{8x^3}{l^3} - \frac{9x^2}{l^2} + 1 = 0 \Rightarrow x = l \; or \; x = \frac{l}{16}\left(1 \pm \sqrt{33}\right)$$

$$x = \frac{l}{16}\left(1 + \sqrt{33}\right) \Rightarrow x \approx 0{,}421535l \Rightarrow v_{max} = \frac{78 + 110\sqrt{33}}{2 * 16^4}\frac{Fl^3}{EI} \approx \frac{1}{185}\frac{Fl^3}{EI}$$

$$v_{max} = v(0{,}843m) = \frac{1}{185}\frac{5\frac{N}{mm} * 2000\,mm * (2000\,mm)^3}{210000\frac{N}{mm^2} * 19400000mm^4} = 0{,}000106\,mm$$

What did we forget?

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C1 – Strength of Materials

M4 – Combining Stresses

Jamk University of Applied Sciences

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Jamk University of Applied Sciences

University of Jaén

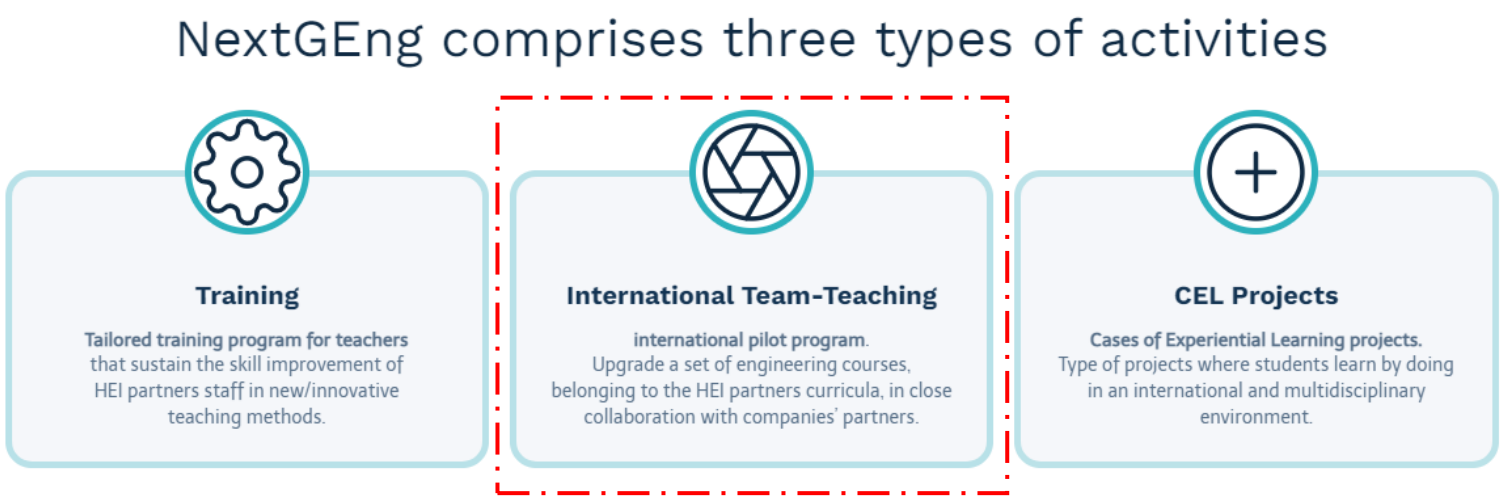
Integracion Sensorial y Robotica

Valmet Technologies Oyj

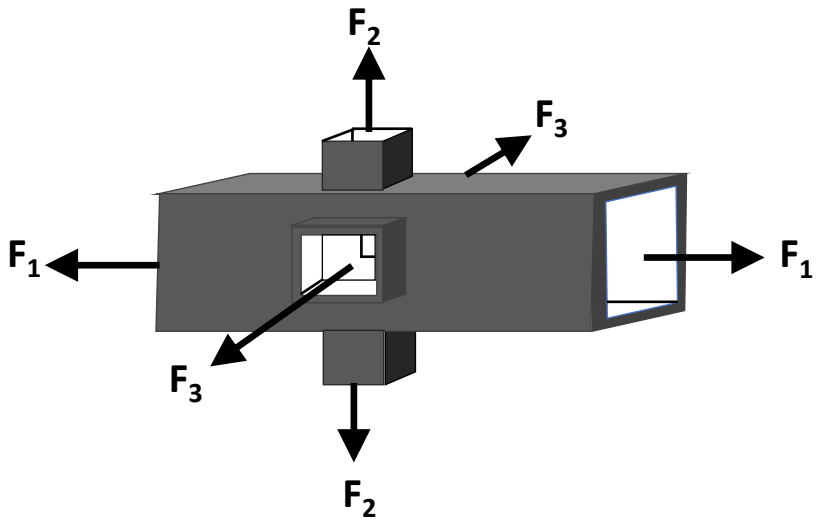
Rober Bosch SRL

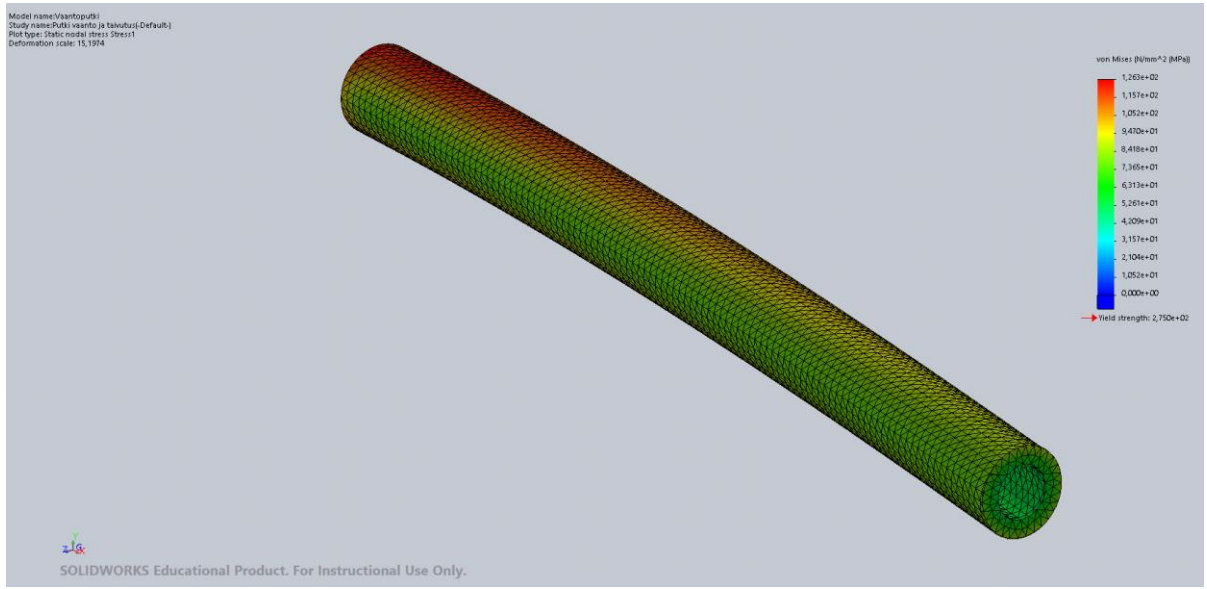
About NextGEng Project

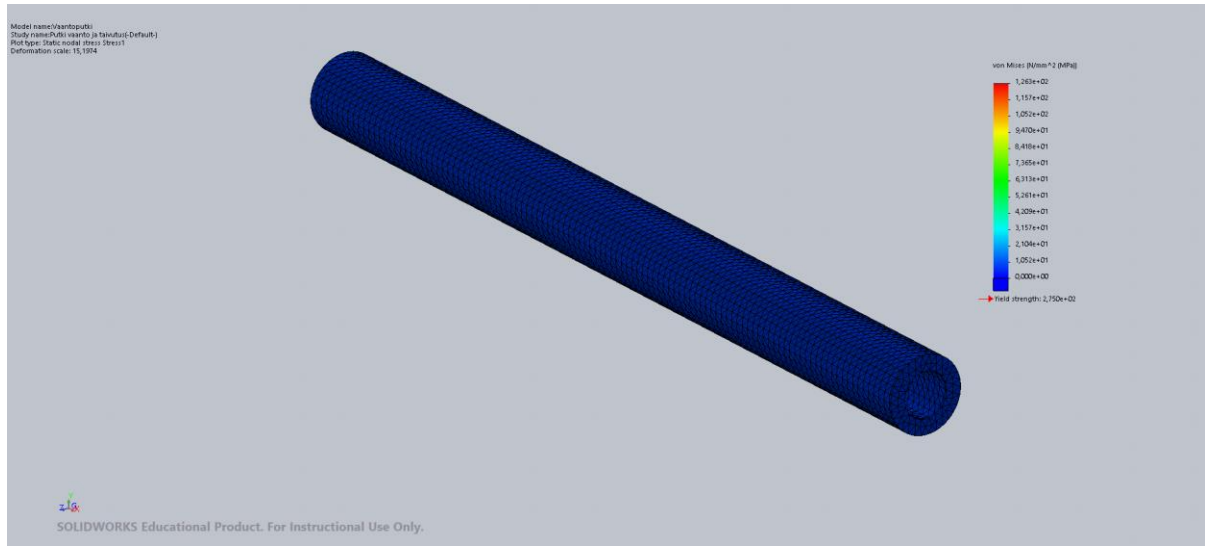
- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



Combining Stresses







Combining Stresses

Upon completion of this module, the student will be able to:

1) Understand the principle of stress types and principle of combining them.
2) Calculate the von Mises stresses in torsional bending.

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Content

- Introduction
- Failure Hypotheses
- Von Mises stress
- Torsional Bending

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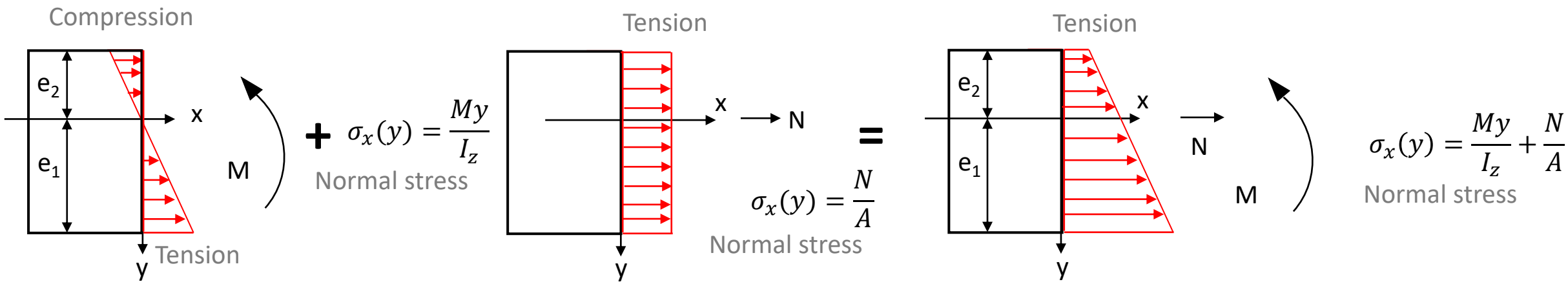
Introduction

Introduction

Stresses

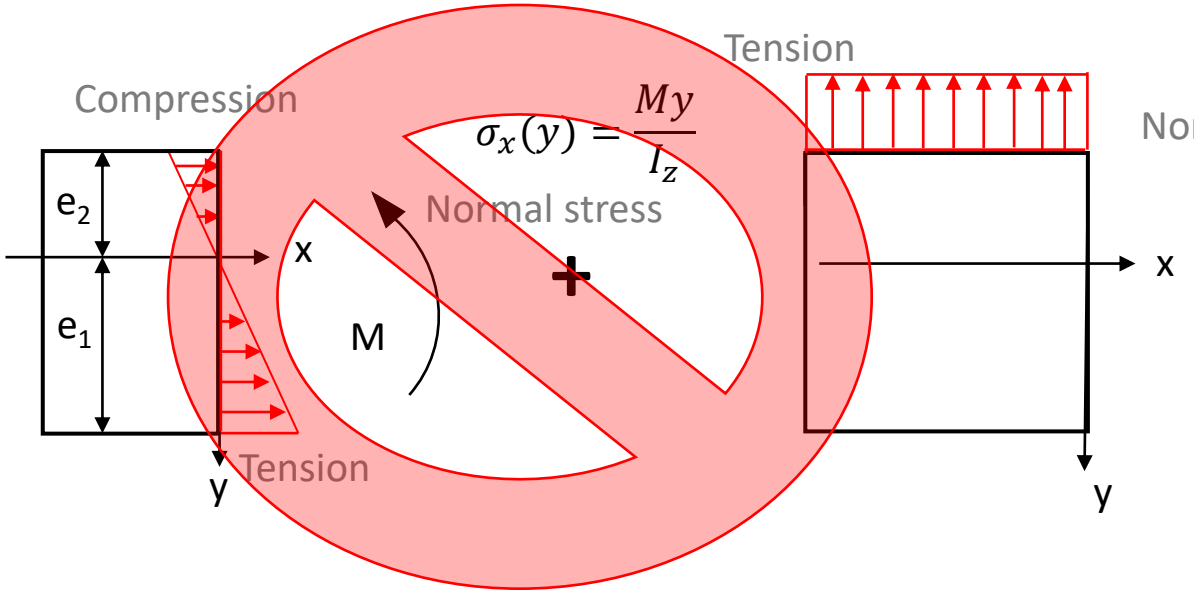
- parallel stresses of the same type interaction by adding up the stresses
- stresses of different types or not parallel interactions with the help of tension hypotheses



Introduction

Stresses

- parallel stresses of the same type interaction by adding up the stresses
- stresses of different types or not parallel interactions with the help of tension hypotheses



$\sigma_x(y) = \frac{N}{A}$

Normal stress

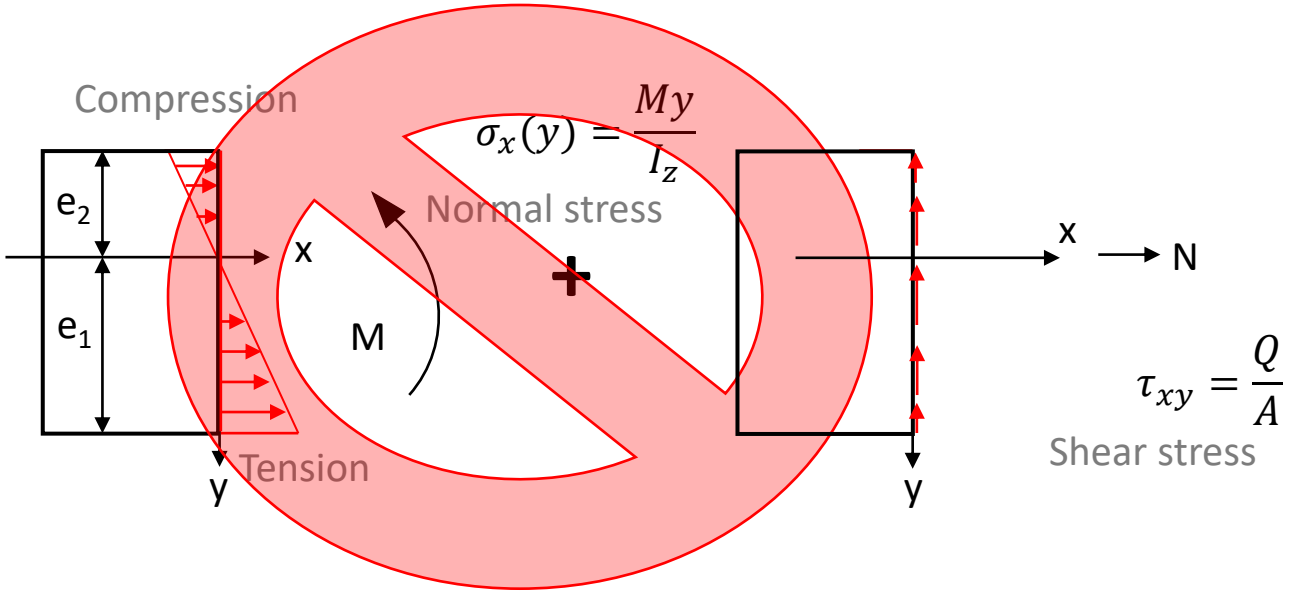
=

Needs tension hypotheses

Introduction

Stresses

- parallel stresses of the same type interaction by adding up the stresses
- stresses of different types or not parallel interactions with the help of tension hypotheses



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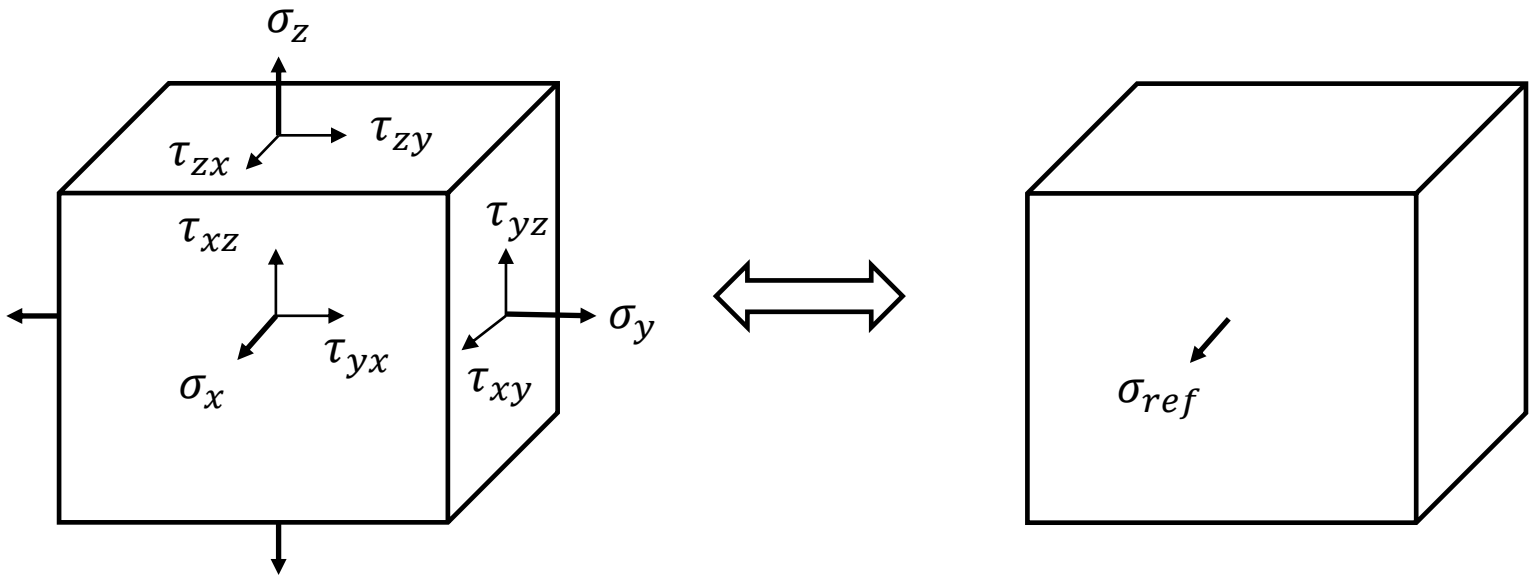
Needs tension hypotheses

Introduction

Reference stress

- Different hypothesis how to combine different type and different direction stresses to one axial stress.
- The goal is that yielding occurs in the same way in multiaxial tension as in axial tension (reference stress).



Topic 1

Failure Hypotheses

Maximum principal stress theory:

- failure by breakage
- brittle materials or all materials under impact load
- RANKINE, MOHR-COULOMB, DRUCKER-PRAGER

Maximum shearing stress theory:

- failure by yielding
- for ductile materials
- compared usually against yield limit
- FEM: stress of Tresca $\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_3) \Longrightarrow \sigma_{ref} = max\{|\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|, |\sigma_1 - \sigma_2|\}$

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Failure Hypotheses

Distortion energy theory:

- failure by yielding
- for ductile materials
- compared usually against yield limit
- FEM: von Mises stresses

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Von Mises Stresses

- 3D stress

$$\sigma_{ref} = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2\right)\right]}$$

- plane stress

$$\sigma_{ref} = \sqrt{\left(\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2\right)}$$

- torsional bending

$$\sigma_{ref} = \sqrt{\left(\sigma_x^2 + 3\tau_{xy}^2\right)}$$

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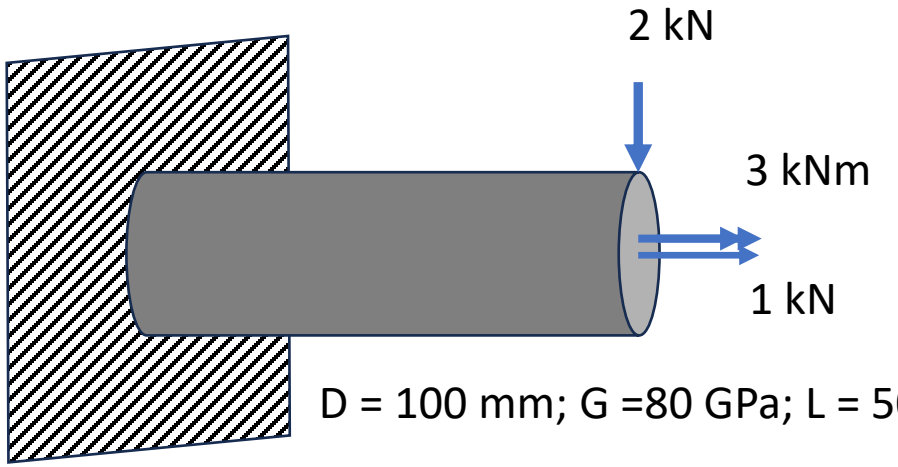
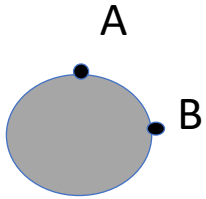
Torsional Bending

Calculate the reference stress (by distortion energy theory), normal stress and shear stress in the cross-section of the support at points A and B



D = 100 mm; G =80 GPa; L = 500 mm.



Cross section

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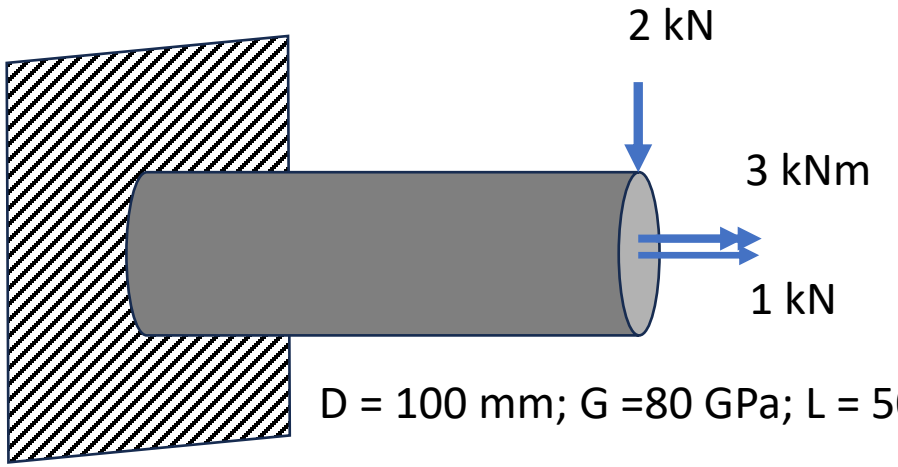
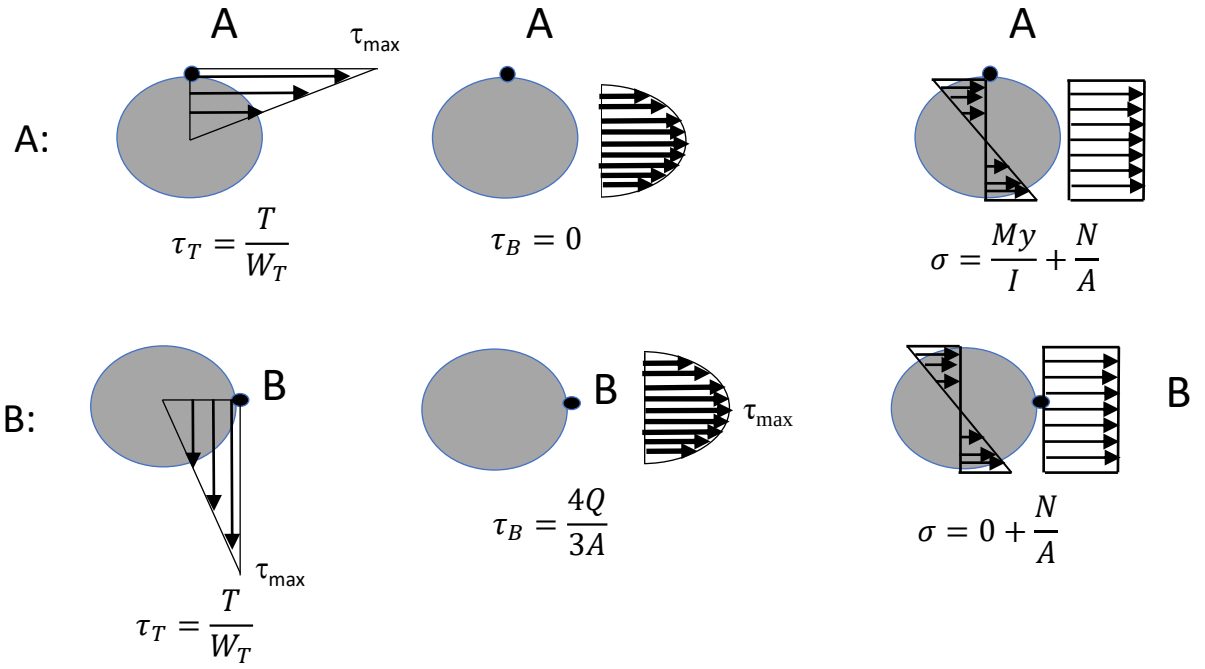
Torsional Bending

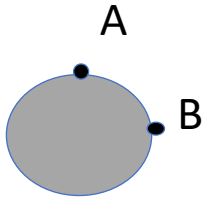


Calculate the reference stress (by distortion energy theory), normal stress and shear stress in the cross-section of the support at points A and B

D = 100 mm; G =80 GPa; L = 500 mm.

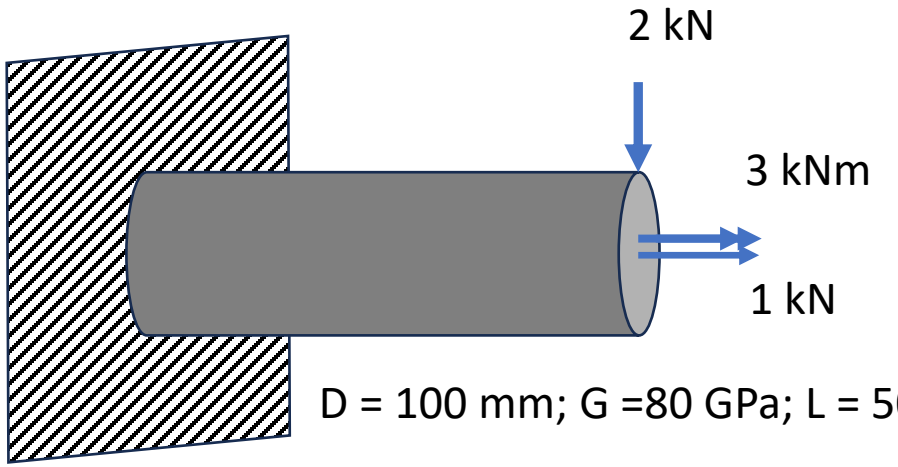
$$\sigma_{ref} = \sqrt{\sigma^2 + 3\tau^2}$$





Cross section

Torsional Bending



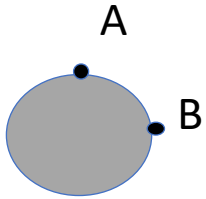
Calculate the reference stress (by distortion energy theory), normal stress and shear stress in the cross-section of the support at points A and B

D = 100 mm; G =80 GPa; L = 500 mm.

$$I = \frac{\pi D^4}{64} = \frac{\pi 100^4 mm^4}{64} = 4900000\ mm^4 \qquad W_T = \frac{\pi 100^3 mm^3}{16} = 196350\ mm^3$$

$$\sigma = \frac{My}{I} + \frac{N}{A} \qquad \tau_T = \frac{T}{W_v} \qquad \tau_B = \frac{4Q}{3A}$$

$$\sigma_{ref} = \sqrt{\sigma^2 + 3\tau^2}$$



Cross section

A: $\tau_B = 0$ $\tau_T = \frac{T}{W_T} = \frac{3000000\ Nmm}{196350\ mm^3} = 15{,}28\ \frac{N}{mm^2}$ $\sigma = \frac{2000\ N * 500\ mm * 50\ mm}{4900000\ mm^4} + \frac{1000\ N}{\pi 50^2 mm^2} = 10{,}3\ \frac{N}{mm^2}$

B: $\tau_B = \frac{4Q}{3A} = \frac{4 * 2000N}{3 * \pi * 50^2 mm^2} = 0{,}34\ \frac{N}{mm^2}$ $\tau_T = \frac{T}{W_T} = \frac{3000000\ Nmm}{196350\ mm^3} = 15{,}28\ \frac{N}{mm^2}$ $\sigma = \frac{1000\ N}{\pi 50^2 mm^2} = 0{,}13\ \frac{N}{mm^2}$

A: $\sigma_{ref} = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{10{,}3^2 + 3(0 + 15{,}3)^2} = 28{,}4 \frac{N}{mm^2}$

B: $\sigma_{ref} = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{0{,}13^2 + 3(0{,}34 + 15{,}3)^2} = 27{,}1\ \frac{N}{mm^2}$

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C1 – Strength of Materials

M5 - General Theory of Bending

Theoretical Aplication

HEI name: University of Jaen (UJA)

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Jamk University of Applied Sciences

University of Jaén

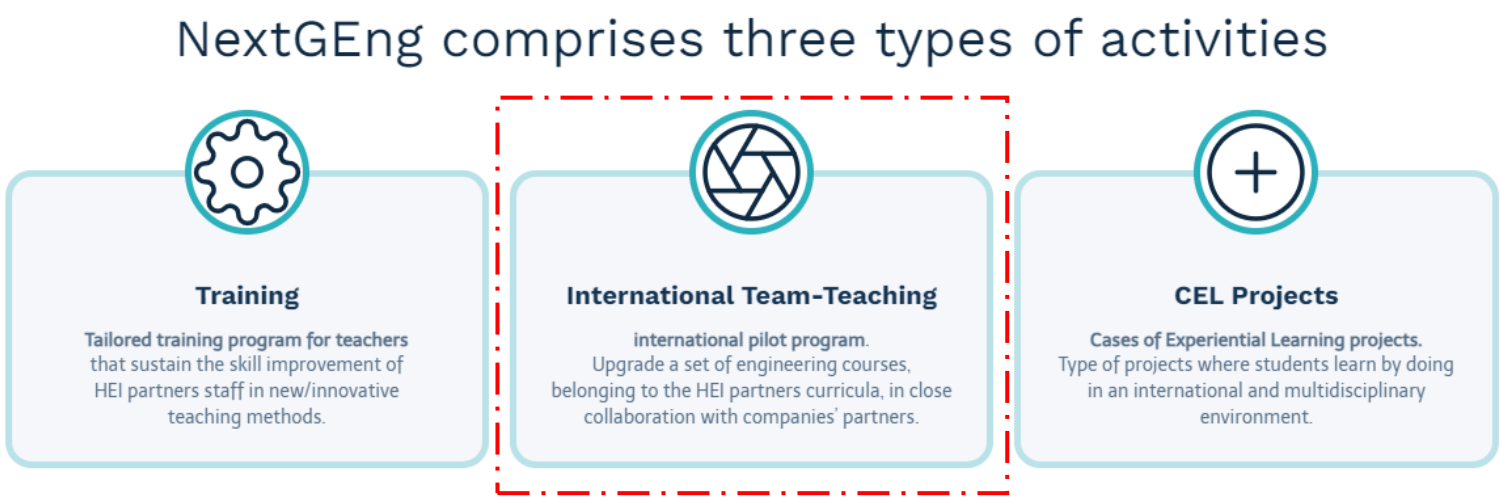
Integracion Sensorial y Robotica

Valmet Technologies Oyj

Rober Bosch SRL

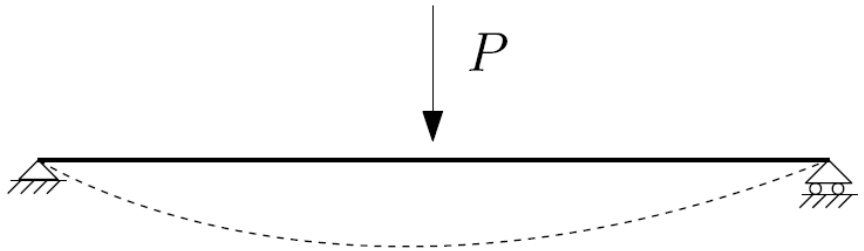
About NextGEng Project

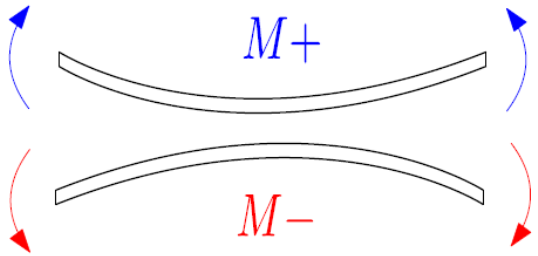
- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



Module 5 - General Theory of Bending

Theoretical Aplication





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Module 5 - General Theory of Bending

Theoretical Aplication

Upon completion of this module, the student will be able to:

1) Calculate the reactions for beams subjected to plane bending
2) Calculate and draw the diagrams for shear forces and bending moments
3) Calculate and draw the diagrams for shear and normal stresses
4) Calculate Von Mises equivalent stress and design a beam
5) To obtain numerical solutions using MDSolids software.

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Content

- Introduction - Theoretical backgrounds
- Topic 1: Von Mises equivalent stress

  Topic 1.1: Cross section resistance criterion

  Topic 1.2: Von Mises equivalent stress in a rectangular cross section and I-shape cross section (*advanced*)
- Topic 2: Simple supported beam subjected to plane bending

  Topic 2.1: Theoretical solution and beam design (rectangular and I-shape cross section)

  Topic 2.2: Numerical solution

Introduction

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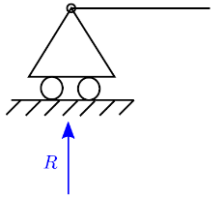
Introduction

Theoretical backgrounds

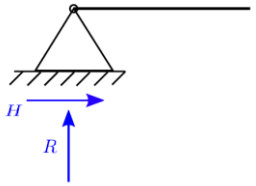
A beam is subjected to plane bending if external forces are applied perpendicular to the longitudinal axis of the beam, or bending moments are in the same plane as the longitudinal axis of the beam, and the deformation occurring in the plane of the forces.

- **Type of supports and reactions**

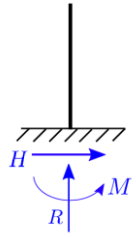
1. Simple support (roller or pinned support) – introduce 1 unknown: Vertical force (R)



2. Articulated support – introduce 2 unknowns: Horizontal (H) and Vertical forces (R)



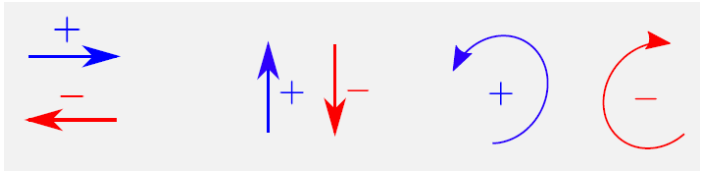
3. Fixed support – introduce 3 unknowns: Horizontal (H) and Vertical forces (R), and bending moment (M)



- **Sign convention for static equilibrium equations**

For the calculation of static equilibrium equations, the following convention presented below is adopted:

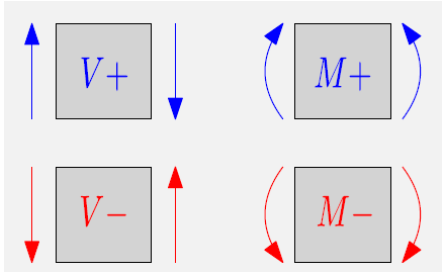
$$\sum F_x = 0; \quad \sum F_y = 0; \quad \sum M_o = 0$$



- **Sign convention for efforts calculus**

It is important to determine the maximum values of efforts in order to calculate the stresses and strains.

For the calculation of efforts (or internal forces and bending moments), the sign convention presented below must be considered.



Sign conventions for shear force *V* and bending moment *M*

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▪ Shear force and bending moments diagrams

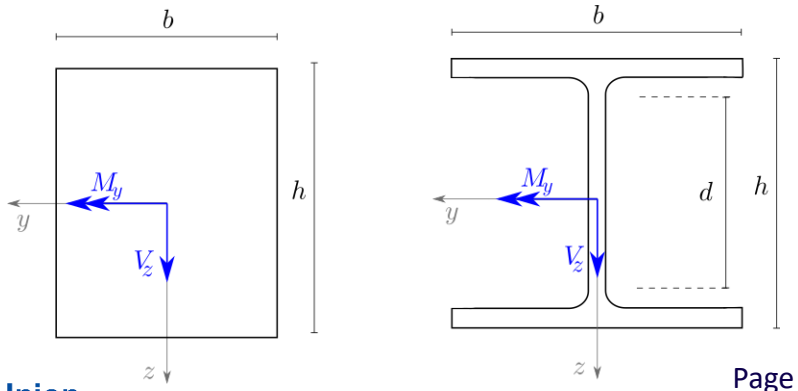
When designing a beam, it is necessary to know how the shear forces and bending moments vary throughout the length of the beam to obtain the maximum and minimum values of these efforts. Information of this kind is usually provided by graphs called **shear-force and bending-moment diagrams**.

*Shear force and bending moment diagrams – **Steps***

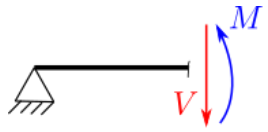
1. A direction of travel of the beam is established
   - From '*left to right*' or from '*right to left*'
2. Enter the plane reference system (O*xy*)
3. The supports are identified, and the reactions related to the type of support are introduced
4. The reactions in the supports are calculated by applying the static equilibrium equations

*Cross section – **Axes and efforts***

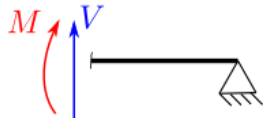
1. Rectangular
2. I-shape



5. The relations of efforts (N, V, M) are written on each interval, considering the convention of the signs of the efforts and applying the static equilibrium equations



Interval from '*left to right*'



Interval from '*right to left*'

6. With the obtained values of the efforts, the shear force and bending moments diagrams are plotted
7. The maximum values of the efforts are noted.

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▪ Normal stress (σ)

Flexural formula (Navier's formula):

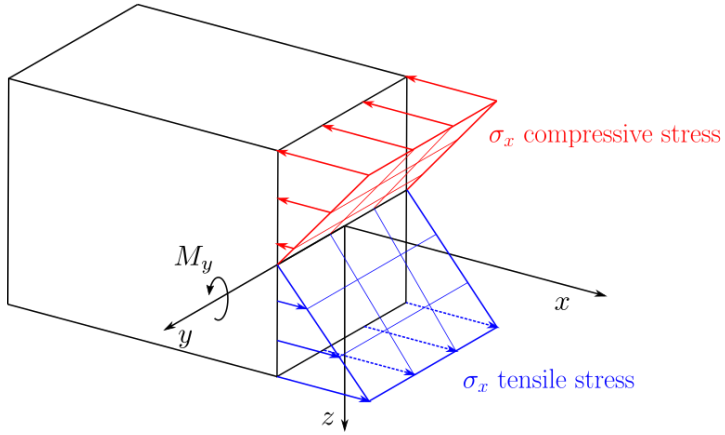
$$\sigma_x = \frac{M_y}{I_y} \cdot z$$

$$\boldsymbol{\sigma_{x,max}} = \frac{M_y}{I_y} \cdot \boldsymbol{z_{max}} = \frac{M_y}{W_{el,y}}$$

where:

- $W_{el,y} = \frac{I_y}{z_{max}}$
- $z_{max} = \pm\frac{h}{2}\ mm$

For a rectangular cross section:



$$I_y = \frac{bh^3}{12}$$

$$W_{el,y} = \frac{bh^2}{6}$$

▪ Shear stress (τ)

Shear formula (Collignon's theorem):

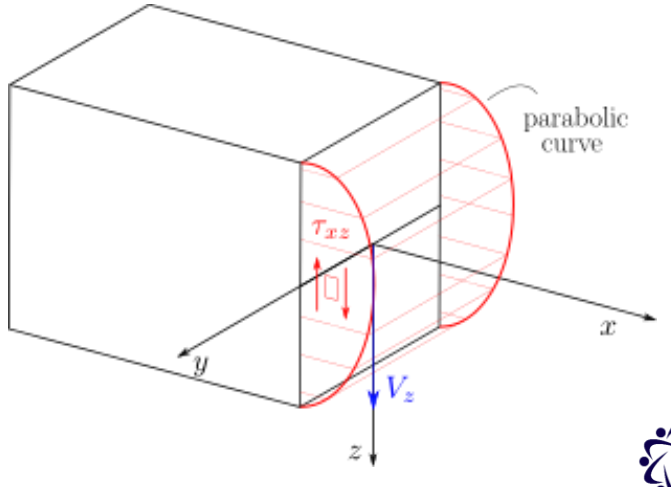
$$\tau_{xz} = \frac{V_z \cdot S}{I_y \cdot b}$$

where:

- $S = \int zdA$, first moment S
- $b =$ width

Note that *S* varies within z-coordinate and *b* is not constant in I-shape cross sections

For a rectangular cross section:



$$S = \frac{b}{2}\left(\frac{h^2}{4} - z^2\right)$$

Topic 1: Von Mises equivalent stress

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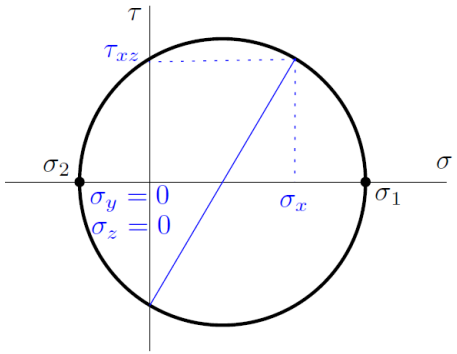
Topic 1.1

Von Mises equivalent stress

The Von Mises stress criterion is a widely used resistance criterion for elastic the analysis of beam cross sections.

- It states that the equivalent stress σ_{eq} should not exceed the allowable stress limit σ_a or plastic behavior may occur.
- Generally, the Von Mises equivalent stress formula is written in terms of the planar principal stresses: $\sigma_{eq} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2}$

However, normal σ_x and shear τ_{xz} stresses obtained in bending **are not principal stresses**. The stress Mohr circle for this state can be plotted as:



Therefore:

$$\begin{cases} \sigma_1 = \dfrac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\dfrac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xz}^2} \\ \sigma_2 = \dfrac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\dfrac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xz}^2} \end{cases}$$

Substituting σ_1 and σ_2 and rearranging:

Navier's and Collignon's formulae can be used → $\sigma_{eq} = \sqrt{\sigma_x^2 + 3\tau_{xz}^2}$

Von Mises resistance criterion:

Every point of the beam cross section should verify:

$$\sigma_{eq} = \sqrt{\sigma_x^2 + 3\tau_{xz}^2} \leq \sigma_a$$

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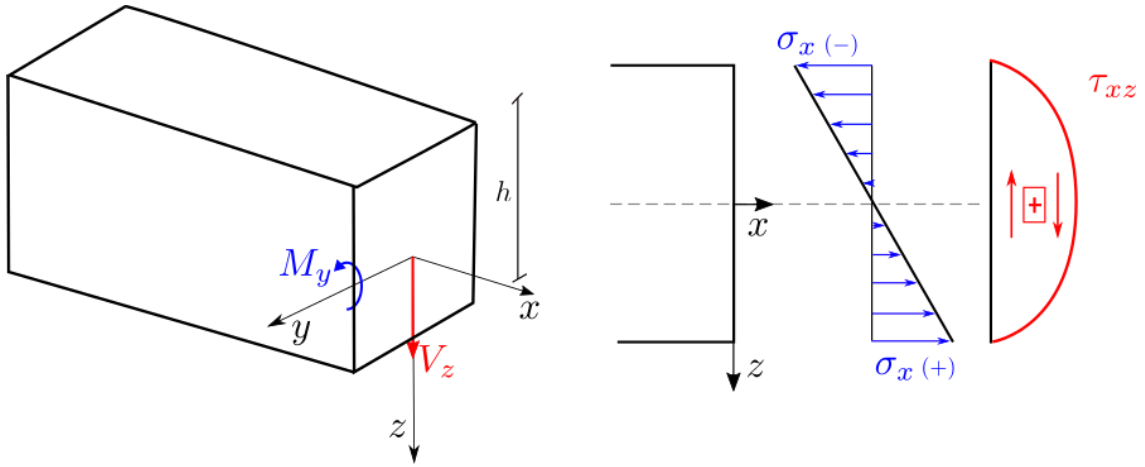
Topic 1.2

Von Mises equivalent stress in a rectangular cross section

It is important to note that maximum normal and shear stresses **do not usually take place** at the same location of the cross section

- The equivalent stress should be calculated at specific locations:
  1. Where maximum σ_x
     - At $z = \pm\frac{h}{2}$
  2. Where maximum τ_{xz}
     - At $z = 0$
  3. Where high combination of σ_x and τ_{xz} occur
     - Not applicable at rectangular cross sections



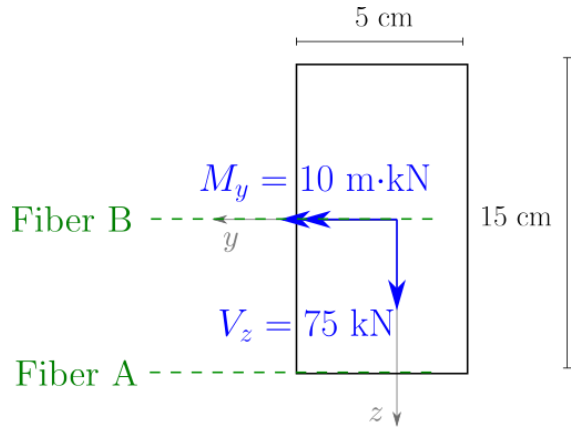
Topic 1.2 (example)

Von Mises equivalent stress in a rectangular cross section

Let us assume a **rectangular** 5x15 cm beam cross section subjected to the following efforts:

$$M_y = 20 \text{ m·kN},\ V_z = 75 \text{ kN}.$$

- Obtain the Von Mises maximum equivalent stress and identify its location within the cross section



$$I_y = \frac{5 \text{ cm} \cdot (15 \text{ cm})^3}{12} = 1406.3 \text{ cm}^4$$

$$S^B = 50 \cdot 75 \cdot \frac{75}{2} \text{mm}^3$$

The equivalent stress is calculated in two locations: fiber A (maximum σ_x) and fiber B (maximum τ_{xz}):

Fiber A:

$$\sigma_x^A = \frac{M_y}{I_y} \cdot z^A = \frac{20 \cdot 10^6 \text{ N} \cdot \text{mm}}{1406.3 \cdot 10^4 \text{ mm}^4} \cdot 75 \text{ mm} = 106.66 \text{ MPa}$$

$$\tau_{xz}^A = \frac{V_z \cdot S^A}{b^A \cdot I_y} = \frac{75 \cdot 10^3 \text{ N} \cdot 0 \text{ mm}^3}{50 \text{ mm} \cdot 1406.3 \cdot 10^4 \text{ mm}^4} = 0 \text{ MPa}$$

$$\sigma_{eq}^A = \sqrt{106.66^2 + 3 \cdot 0^2} = 106.66 \text{ MPa}$$

Fiber B:

$$\sigma_x^B = \frac{M_y}{I_y} \cdot z^B = \frac{20 \cdot 10^6 \text{ N} \cdot \text{mm}}{1406.3 \cdot 10^4 \text{ mm}^4} \cdot 0 \text{ mm} = 0 \text{ MPa}$$

$$\tau_{xz}^B = \frac{V_z \cdot S^B}{b^B \cdot I_y} = \frac{75 \cdot 10^3 \text{ N} \cdot 50 \cdot 75 \cdot 37.5 \text{ mm}^3}{50 \text{ mm} \cdot 1406.3 \cdot 10^4 \text{ mm}^4} = 15.0 \text{ MPa}$$

$$\sigma_{eq}^B = \sqrt{0^2 + 3 \cdot 15^2} = 25.98 \text{ MPa}$$

The maximum equivalent stress is given at Fiber A

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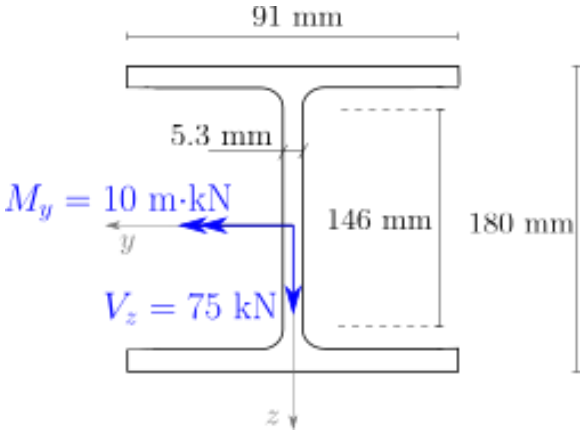
Topic 1.2 (example)

Von Mises equivalent stress in a I-shape cross section (**advanced**)



Let us assume a standard **IPE180** beam subjected to the following efforts:

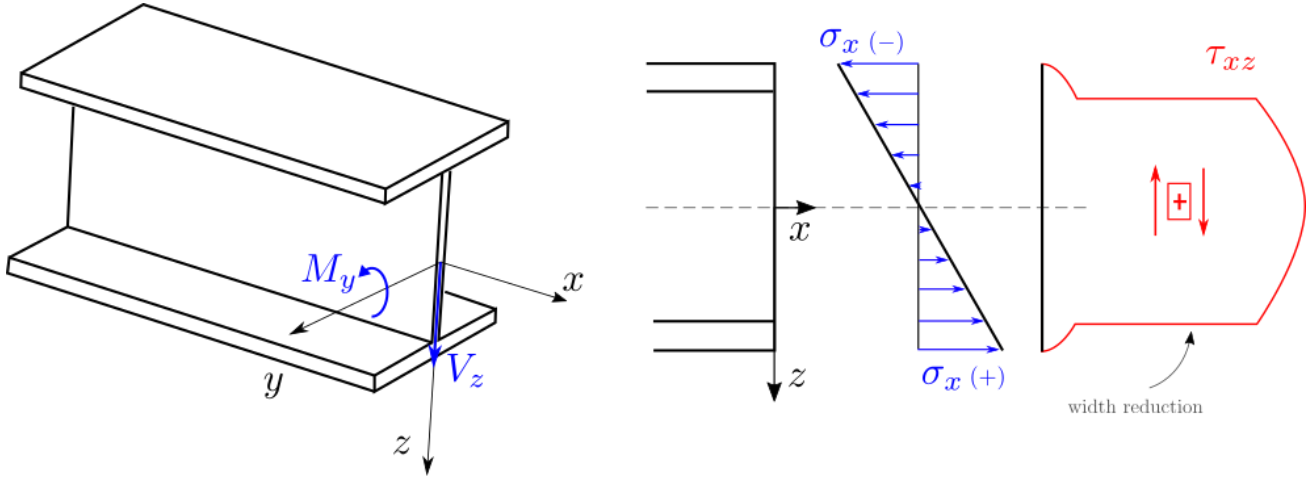
$$M_y = 20 \text{ m·kN},\ V_z = 75 \text{ kN}.$$

- Obtain the Von Mises maximum equivalent stress and identify its location within the cross section

$$I_y = 1320 \text{ cm}^4$$

$$S_{z=0} = \frac{W_{pl,y}}{2} = 83.2 \text{ cm}^3$$

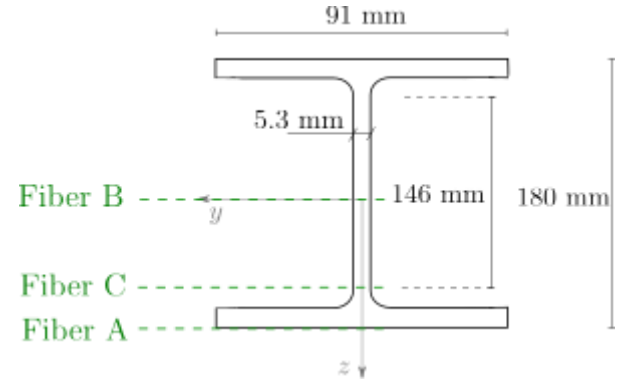
When the cross section has not a constant width, the variable "*b*" in the shear formula varies in z-coordinate



The transition between the web and the flange is a critical fiber!

Topic 1.2 (example)

Von Mises equivalent stress in a I-shape cross section (**advanced**)



Three locations are identified: fiber A (maximum σ_x) and fiber B (maximum τ_{xz}) and fiber C (transition web-flange):

Fiber A:

$$\sigma_x^A = \frac{M_y}{I_y} \cdot z^A = \frac{20 \cdot 10^6 \text{ N} \cdot \text{mm}}{1320 \cdot 10^4 \text{ mm}^4} \cdot 90 \text{ mm} = 136.36 \text{ MPa}$$

$$\tau_{xz}^A = \frac{V_z \cdot S^A}{b^A \cdot I_y} = \frac{75 \cdot 10^3 \text{ N} \cdot 0 \text{ mm}^3}{91 \text{ mm} \cdot 1406.3 \cdot 10^4 \text{ mm}^4} = 0 \text{ MPa}$$

$$\sigma_{eq}^A = \sqrt{136.36^2 + 3 \cdot 0^2} = 136.36 \text{ MPa}$$

Fiber B:

$$\sigma_x^B = \frac{M_y}{I_y} \cdot z^B = \frac{20 \cdot 10^6 \text{ N} \cdot \text{mm}}{1320 \cdot 10^4 \text{ mm}^4} \cdot 0 \text{ mm} = 0 \text{ MPa}$$

$$\tau_{xz}^B = \frac{V_z \cdot S^B}{b^B \cdot I_y} = \frac{75 \cdot 10^3 \text{ N} \cdot 83.2 \cdot 10^3 \text{ mm}^3}{5.3 \text{ mm} \cdot 1320 \cdot 10^4 \text{ mm}^4} = 89.19 \text{ MPa}$$

$$\sigma_{eq}^B = \sqrt{0^2 + 3 \cdot 89.19^2} = 154.48 \text{ MPa}$$

Next slide

Fiber C:

$$\sigma_x^C = \frac{M_y}{I_y} \cdot z^C = \frac{20 \cdot 10^6 \text{ N} \cdot \text{mm}}{1320 \cdot 10^4 \text{ mm}^4} \cdot 73 \text{ mm} = 110.61 \text{ MPa}$$

$$\tau_{xz}^C = \frac{V_z \cdot S^C}{b^C \cdot I_y} = \frac{75 \cdot 10^3 \text{ N} \cdot 69.08 \cdot 10^3 \text{ mm}^3}{5.3 \text{ mm} \cdot 1320 \cdot 10^4 \text{ mm}^4} = 74.06 \text{ MPa}$$

$$\sigma_{eq}^C = \sqrt{110.61^2 + 3 \cdot 74.06^2} = 169.38 \text{ MPa}$$

The maximum equivalent stress is given at Fiber C

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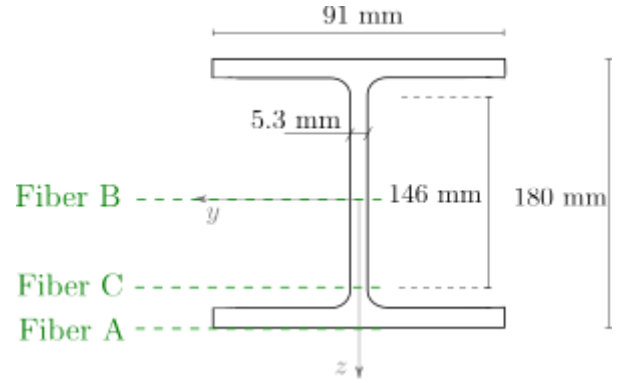
Topic 1.2 (example)

Von Mises equivalent stress in a I-shape cross section (**advanced**)

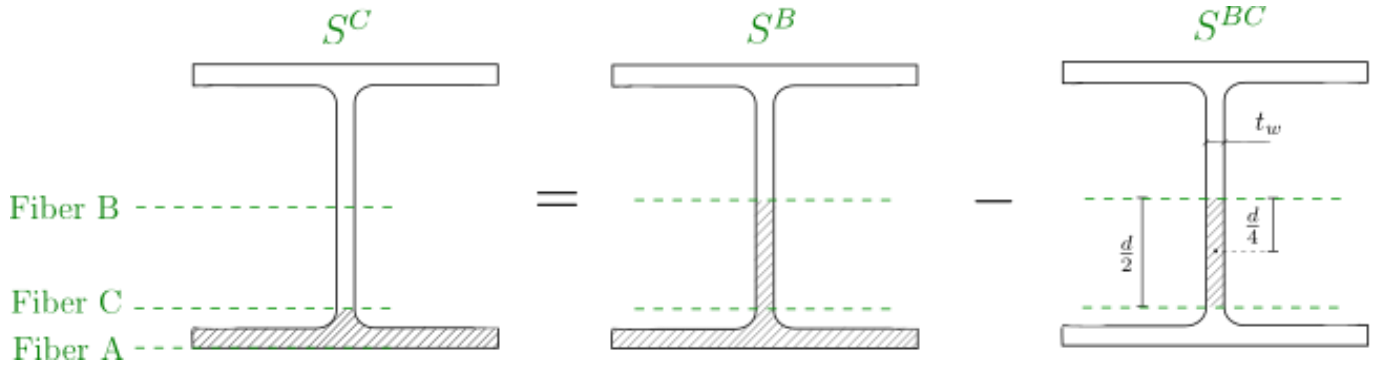


The calculation of the first moment of area in fiber C, S^C, is done by subtracting S^{BC} (the first moment of the area between B and C), from the first moment S^B.

- As the IPE180 is a standard cross section, the first moment of area for the fiber B (when $z = 0$) is:

$$S^B = \frac{W_{pl,y}}{2} = 83.2\ \text{cm}^2$$

- Therefore: $S^C = S^B - S^{BC} = 83200\ \text{mm}^3 - 5.3\ \text{mm} \cdot \frac{146\ \text{mm}}{2} \cdot \frac{146\ \text{mm}}{4} = 69080\ \text{mm}^3 = 69.08\ \text{cm}^3$



Topic 2: Simply supported beam subjected to plane bending

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Topic 2.1

Theoretical calculus

For the given simple supported beam and loaded as in the figure, it is necessary to:

a) Calculate the reactions in the supports;

b) Calculate the internal forces and moments (V and M) in the cross section of the beam.

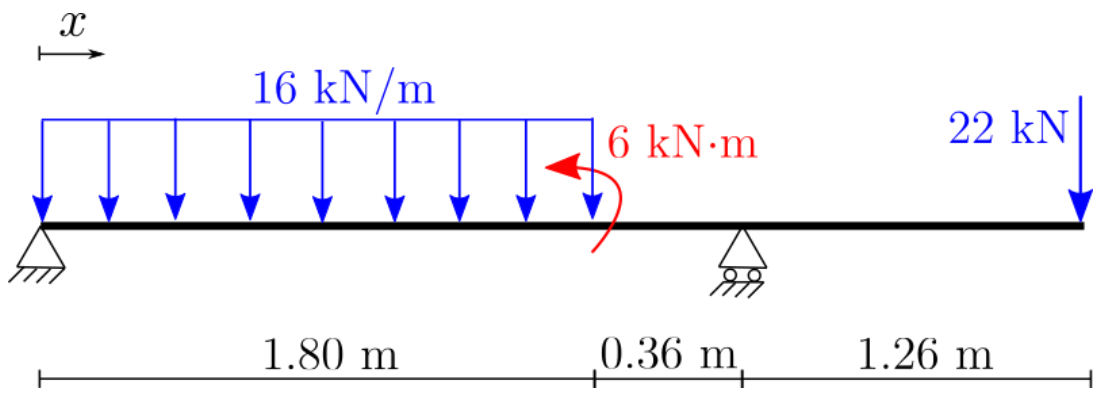
c) Draw the shear force and bending moment diagrams;

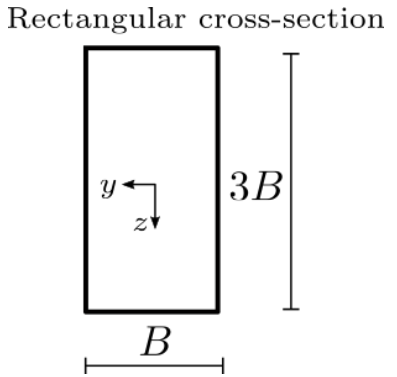
d) Design the beam for the given cross-section assuming σ_a = 145 N/mm^2 and **neglecting** the influence of the shear force

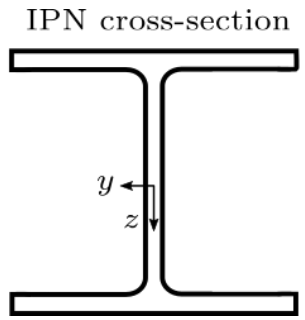
e) Design the beam for a standard IPN cross-section type assuming σ_a = 145 N/mm^2 and **considering** the influence of the shear force;

f) Obtain the stress diagrams for maximum internal forces with MdSolids.

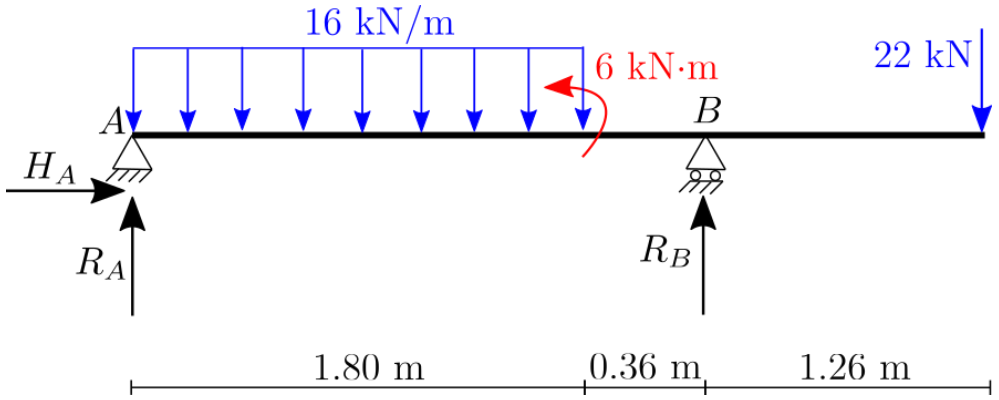
g) Obtain the maximum displacement and slope by using MdSolids.







a) Reactions calculus in the supports



Applying static equilibrium equations:

$$\sum F_H = 0 \rightarrow H_A = 0 \text{ kN}$$

$$\sum F_V = 0 \rightarrow R_A + R_B - 16\text{kN/m} \cdot 1.8\text{m} - 22\text{kN} = 0 \rightarrow R_A + R_B = 50.8 \text{ kN}$$

$$\sum M_A = 0;$$

$$-16\text{kN/m} \cdot 1.8\text{m} \cdot \frac{1.8\text{m}}{2} + 6\text{kN} \cdot \text{m} + R_B(1.8\text{m} + 0.36\text{m}) + 22\text{kN}\,(1.8\text{m} + 0.36\text{m} + 1.26\text{m}) = 0$$

$$\rightarrow R_B = \frac{1}{(1.8\text{m} + 0.36\text{m})}\left[16\text{kN/m} \cdot \frac{(1.8\text{m})^2}{2} - 6\text{kN} \cdot \text{m} + 22\text{kN}(1.8\text{m} + 0.36\text{m} + 1.26\text{m})\right]$$

$$\rightarrow R_B = 44.05 \text{ kN}$$

$$\rightarrow R_A = 50.8\text{kN} - 44.05\text{kN} = 6.74 \text{ kN}$$

Check of the results:

$$\sum F_V = 0 \rightarrow 16\text{kN/m} \cdot 1.80\text{m} + 22\text{kN} - 6.74\text{kN} - 44.05\text{kN} = 0$$

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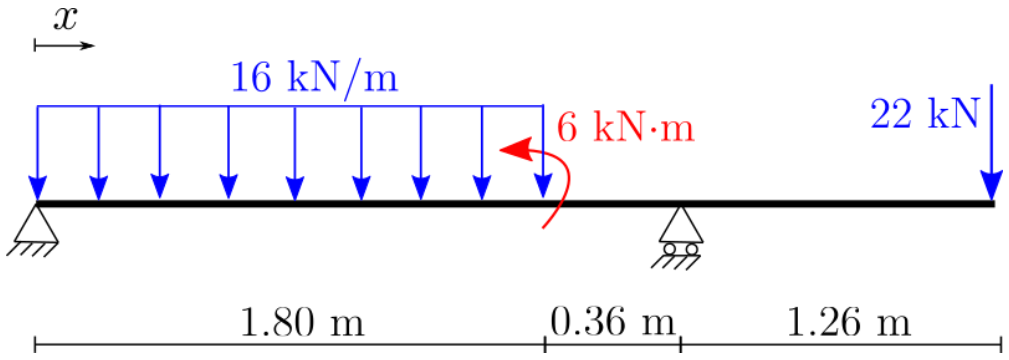
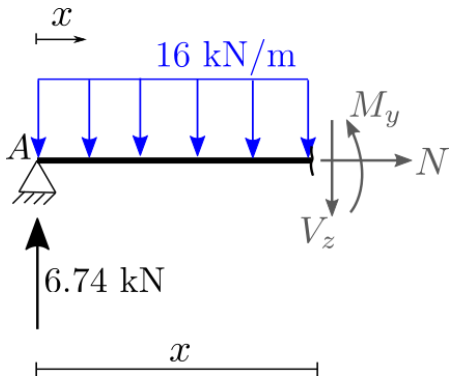
b) Shear forces (V) and bending moments (M) in the cross-section of the beam



Sign convention

$\sum F_x = 0; \quad \sum F_y = 0; \quad \sum M_o = 0$

1st Interval: $0 \leq x < 1.80$ m



Applying static equilibrium equations:

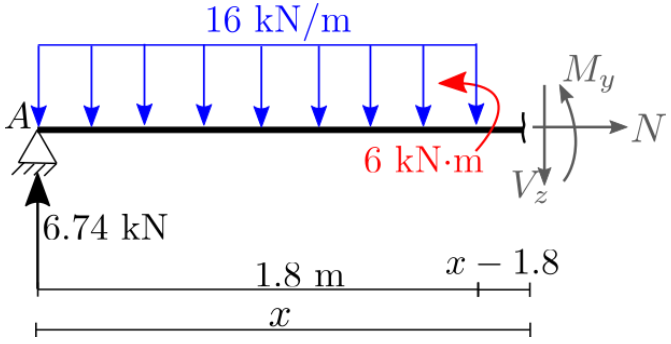
$\sum F_H = 0 \rightarrow \boxed{N = 0 \text{ kN}}$ *Axial force*

$\sum F_V = 0 \rightarrow -V_z - 16 \cdot x + 6.74 = 0$

$\rightarrow \boxed{V_z = -16x + 6.74}$ *Shear force*

$\sum M^x = 0; \quad M_y + 16 \cdot x \cdot \frac{x}{2} - 6.74 \cdot x = 0 \rightarrow \boxed{M_y = -8x^2 + 6.74x}$ *Bending moment*

2nd Interval: $1.80 \leq x < 2.16$ m



Applying static equilibrium equations:

$\sum F_H = 0 \rightarrow \boxed{N = 0 \text{ kN}}$ *Axial force*

$\sum F_V = 0 \rightarrow -V_z - 16 \cdot 1.8 + 6.74 = 0; \quad \rightarrow \boxed{V_z = -22.06 \text{ kN}}$ *Shear force*

$\sum M^x = 0; \quad M_y + 6 + 16 \cdot 1.8 \cdot \left(x - \frac{1.8}{2}\right) - 6.74 \cdot x = 0 \rightarrow \boxed{M_y = -22.06x + 19.92}$ *Bending moment*

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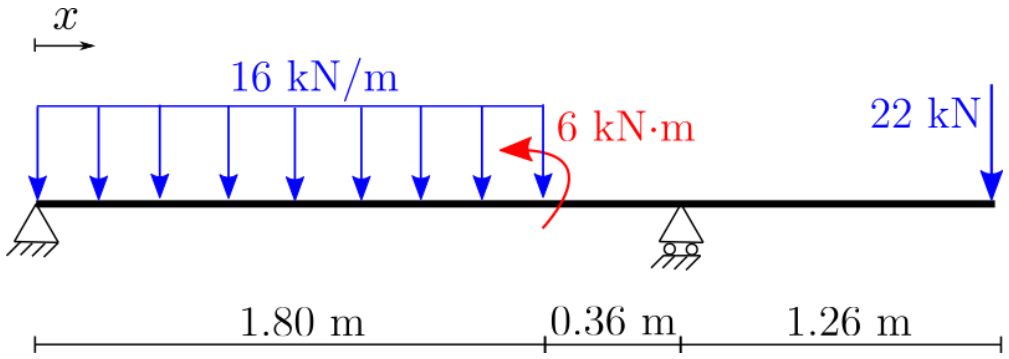
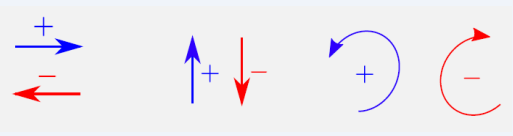
b) Shear forces (V) and bending moments (M) in the cross-section of the beam



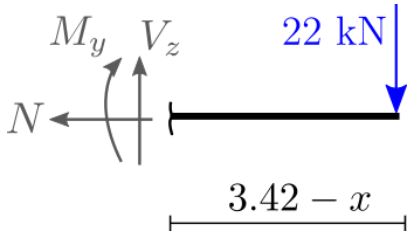
Sign convention

$\sum F_x = 0; \quad \sum F_y = 0; \quad \sum M_o = 0$



3rd Interval: $2.16 \leq x \leq 3.42$ m

SIMPLEST WAY



Applying static equilibrium equations:

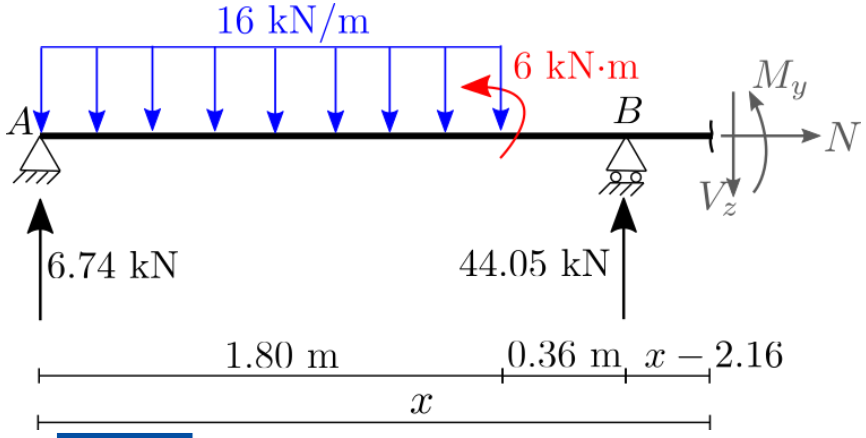
$\sum F_H = 0 \rightarrow \boxed{N = 0 \text{ kN}}$ *Axial force*

$\sum F_V = 0 \rightarrow V_z - 22 = 0$

$\rightarrow \boxed{V_z = 22 \text{ kN}}$ *Shear force*

$\sum M^x = 0; \quad -M_y - 22 \cdot (3.42 - x) = 0 \rightarrow \boxed{M_y = 22x - 75.24}$ *Bending moment*

3rd Interval : $2.16 \leq x \leq 3.42$ m



Applying static equilibrium equations:

$\sum F_H = 0 \rightarrow \boxed{N = 0 \text{ kN}}$ *Axial force*

$\sum F_V = 0 \rightarrow -V_z - 16 \cdot 1.8 + 6.74 + 44.05 = 0; \quad \rightarrow \boxed{V_z = 22 \text{ kN}}$ *Shear force*

$\sum M^x = 0; \quad M_y + 6 + 16 \cdot 1.8 \cdot \left(x - \frac{1.8}{2}\right) - 6.74 \cdot x - 44.05 \cdot (x - 2.16) = 0$

$\rightarrow \boxed{M_y = 22x - 75.24}$ *Bending moment*

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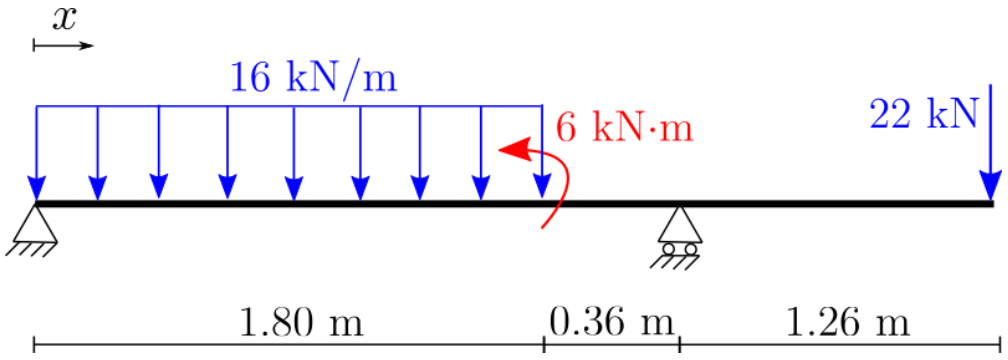
NextGEng

c) Draw the shear force and bending moment diagrams



Efforts equations for this beam:

$$N(x) = 0 \qquad 0 \le x \le 3.42 \text{ m}$$

$$V_z(x) = \begin{cases} -16x + 6.74 & 0 \le x < 1.80 \text{ m} \\ -22.06 & 1.80 \le x < 2.16 \text{ m} \\ 22 & 2.16 \le x \le 3.42 \text{ m} \end{cases}$$

$$M_y(x) = \begin{cases} -8x^2 + 6.74x & 0 \le x < 1.80 \text{ m} \\ -22.06x + 19.92 & 1.80 \le x < 2.16 \text{ m} \\ 22x - 75.24 & 2.16 \le x \le 3.42 \text{ m} \end{cases}$$

To draw the diagrams, the values at the ends of intervals must be computed. Also, if intervals are quadratic or cubic, the maximum effort should also be obtained as it may occur not at the interval ends. The maximum effort takes place when its first derivative equals zero. This happens in the bending moment interval 1 as follows:

$$M_{y\ max\ interval\ 1} \rightarrow \frac{dM_y}{dx} = 0 \rightarrow -16x + 6.74 = 0 \rightarrow x = 0.42\text{m}$$
$$M_y(x = 0.42\text{m}) = -8 \cdot 0.42^2 + 6.74 \cdot 0.42 = 1.42 \text{ kN} \cdot \text{m}$$

The other values to draw the diagram are evaluated at the interval ends as:

$$V_z(x = 0) = 6.74 \text{ kN}$$
$$V_z(x = 1.80^-) = -22.06 \text{ kN}$$
$$V_z(x = 1.80^+) = -22.06 \text{ kN}$$
$$V_z(x = 2.16^-) = -22.06 \text{ kN}$$
$$V_z(x = 2.16^+) = 22 \text{ kN}$$
$$V_z(x = 3.42\ ) = 22 \text{ kN}$$

$$M_y(x = 0) = 0 \text{ kN} \cdot \text{m}$$
$$M_y(x = 1.80^-) = -13.79 \text{ kN} \cdot \text{m}$$
$$M_y(x = 1.80^+) = -19.79 \text{ kN} \cdot \text{m}$$
$$M_y(x = 2.16^-) = -27.72 \text{ kN} \cdot \text{m}$$
$$M_y(x = 2.16^+) = -27.72 \text{ kN} \cdot \text{m}$$
$$M_y(x = 3.42\ ) = 0 \text{ kN} \cdot \text{m}$$

c) Draw the shear force and bending moment diagrams

Summary:

$$N(x) = 0 \qquad 0 \le x \le 3.42 \text{ m}$$

$$V_z(x) = \begin{cases} -16x + 6.74 & 0 \le x < 1.80 \text{ m} \\ -22.06 & 1.80 \le x < 2.16 \text{ m} \\ 22 & 2.16 \le x \le 3.42 \text{ m} \end{cases}$$

$$M_y(x) = \begin{cases} -8x^2 + 6.74x & 0 \le x < 1.80 \text{ m} \\ -22.06x + 19.92 & 1.80 \le x < 2.16 \text{ m} \\ 22x - 75.24 & 2.16 \le x \le 3.42 \text{ m} \end{cases}$$

$V_z(x = 0) = 6.74 \text{ kN}$ $\qquad M_y(x = 0) = 0 \text{ kN} \cdot \text{m}$

$V_z(x = 1.80^-) = -22.06 \text{ kN}$ $\qquad M_y(x = 1.80^-) = -13.79 \text{ kN} \cdot \text{m}$

$V_z(x = 1.80^+) = -22.06 \text{ kN}$ $\qquad M_y(x = 1.80^+) = -19.79 \text{ kN} \cdot \text{m}$

$V_z(x = 2.16^-) = -22.06 \text{ kN}$ $\qquad M_y(x = 2.16^-) = -27.72 \text{ kN} \cdot \text{m}$

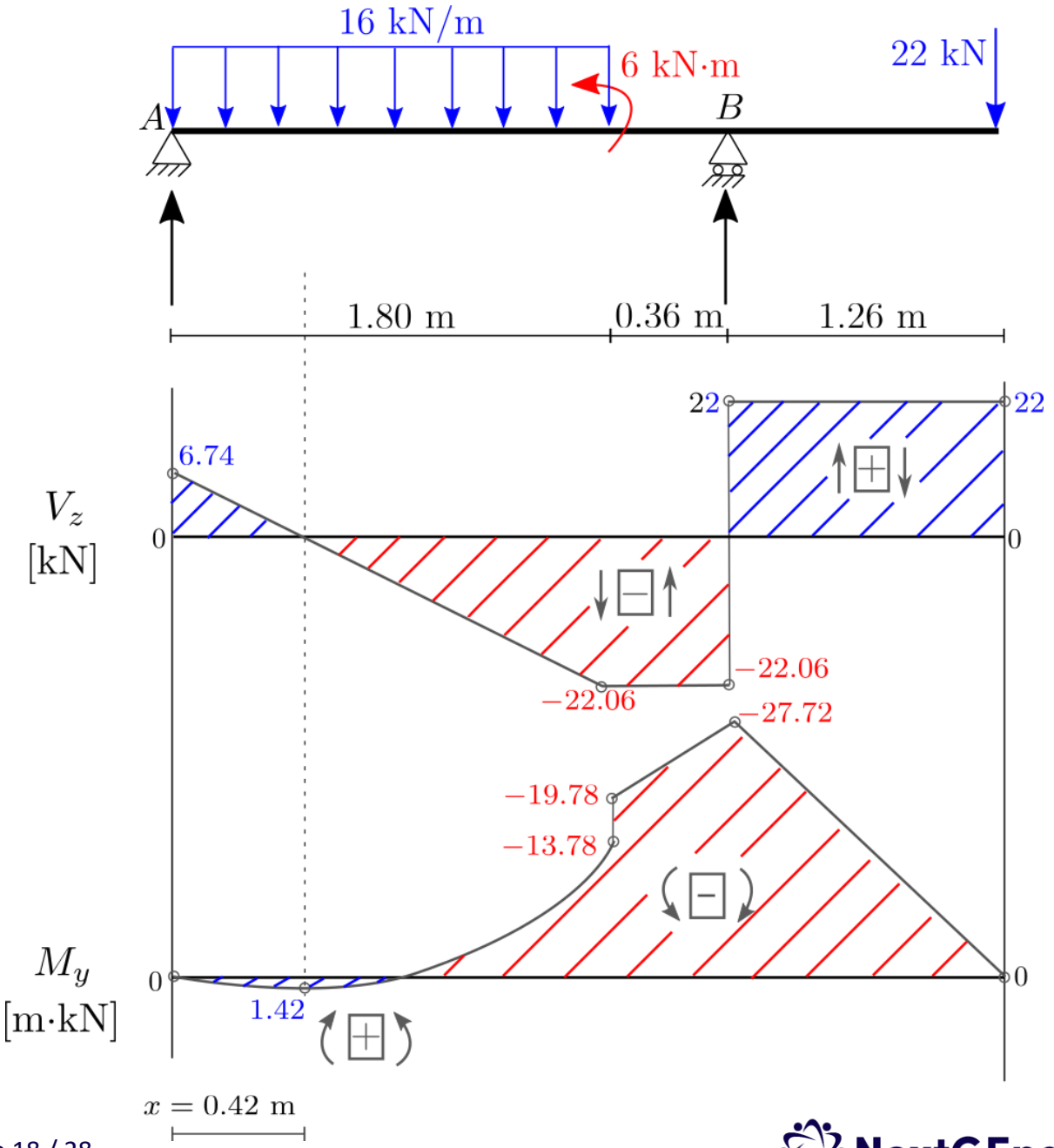
$V_z(x = 2.16^+) = 22 \text{ kN}$ $\qquad M_y(x = 2.16^+) = -27.72 \text{ kN} \cdot \text{m}$

$V_z(x = 3.42\ ) = 22 \text{ kN}$ $\qquad M_y(x = 3.42\ ) = 0 \text{ kN} \cdot \text{m}$

$$M_{y\ max\ interval\ 1} = M_y(x = 0.42\text{m}) = 1.42 \text{ kN} \cdot \text{m}$$

According to the internal forces and moments, the maximum shear force (V_z) and bending moment (M_y) coincide in x=2.16 m and are:

$$V_{z\ max} = -22.06 \text{ kN}$$
$$M_{y\ max} = -27.72 \text{ kN} \cdot \text{m}$$



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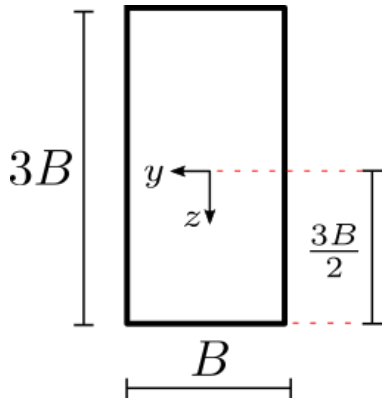
NextGEng

d) Design the beam with rectangular cross-section neglecting the influence of the Shear force

The design of the beam is performed by considering the maximum bending moment $M_{y,max}$ = - 27.72 kN·m, and allowable stress of material σ_a = 145 N/mm^2.



By neglecting the influence of the shear force, the von Mises resistance criterion yields:

$$\sigma_{eq} = \sqrt{\sigma_x^2 + 3\tau_{xz}^2} \rightarrow \sqrt{\sigma_x^2} \rightarrow \sigma_x$$

Therefore, by equaling the maximum normal stress to the allowable stress, one can define the required section modulus:

$$\sigma_{x,max} = \sigma_a \leq \frac{M_{y,max}}{W_y} \rightarrow W_y \geq \frac{M_{y,max}}{\sigma_a} = \frac{27.72 \cdot 10^6 \text{ N} \cdot \text{mm}}{145 \frac{\text{N}}{\text{mm}^2}} = 191172.41 \text{ mm}^3$$

As:
$$W_y = \frac{I_y}{z_{max}} = \frac{\frac{1}{12} B (3B)^3}{\frac{3B}{2}} = 1.5B^3 \geq 191172.41 \text{ mm}^3$$
$$\rightarrow B \geq 50.32 \text{ mm} \rightarrow \boxed{B_{ef} = 51 \text{ mm}}$$

Knowing the dimensions of the cross-section, its properties can be calculated:

- the moment of inertia: $I_{y_ef} = \frac{51 \cdot 153^3}{12} = 15.22 \cdot 10^6 \text{ mm}^4 = 1522 \text{ cm}^4$
- the section modulus: $W_{y_ef} = \frac{I_y}{z_{max}} = \frac{1522 \text{ cm}^4}{7.65 \text{ cm}} = 198.95 \text{ cm}^3$
- the section area: $A_{ef} = 51 \cdot 153 = 7803 \text{ mm}^2 = 78.03 \text{ cm}^2$

VERIFICATION:

$$\sigma_{x,max} = \frac{27.72 \cdot 10^6 \text{ N} \cdot \text{mm}}{198.95 \cdot 10^3 \text{ mm}^3} = 139.33 \text{ N/mm}^2 < \sigma_a$$

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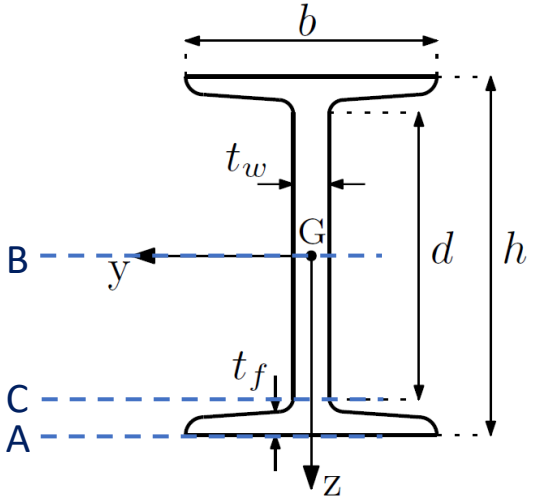
e) Design the beam for a standard IPN cross-section type assuming σ_a = 145 N/mm² and **considering** the influence of the Shear force.



In this case, we have the following efforts: $M_y = -27.72\ \text{m} \cdot \text{kN}; \quad V_z = -22.06\ \text{kN}.$

As in the previous case, we have a required minimum section modulus of 191.17 cm³. Therefore, we can look up the standard profile IPN tables to find:

$$\boldsymbol{IPN\ 200} = \begin{cases} W_y = 214\ \text{cm}^3; & S_y = 125\ \text{cm}^3 \\ I_y = 2140\ \text{cm}^4; \quad b = 90\ \text{mm}; & h = 200\ \text{mm}; \quad d = 159.1\ \text{mm} \\ A = 33.4\ \text{cm}^2; & t_w = 7.5\ \text{mm}; \quad t_f = 11.3\ \text{mm} \end{cases}$$

Considering the influence of the shear force, verification is done in fibers A, B and C as follows:

Fiber A:

$$\sigma_x^A = \frac{M_y}{I_y} \cdot z^A = \frac{-27.72 \cdot 10^6\ \text{N} \cdot \text{mm}}{2140 \cdot 10^4\ \text{mm}^4} \cdot 100\ \text{mm} = -129.53\ \text{MPa}$$

$$\tau_{xz}^A = \frac{V_z \cdot S^A}{b^A \cdot I_y} = \frac{-22.06 \cdot 10^3\ \text{N} \cdot 0\ \text{mm}^3}{90\ \text{mm} \cdot 2140 \cdot 10^4\ \text{mm}^4} = 0\ \text{MPa}$$

Fiber B:

$$\sigma_x^B = \frac{M_y}{I_y} \cdot z^B = \frac{-27.72 \cdot 10^6\ \text{N} \cdot \text{mm}}{2140 \cdot 10^4\ \text{mm}^4} \cdot 0\ \text{mm} = 0\ \text{MPa}$$

$$\tau_{xz}^B = \frac{V_z \cdot S^B}{b^B \cdot I_y} = \frac{-22.06 \cdot 10^3\ \text{N} \cdot 125 \cdot 10^3\ \text{mm}^3}{7.5\ \text{mm} \cdot 2140 \cdot 10^4\ \text{mm}^4} = -17.18\ \text{MPa}$$

Fiber C:

$$\sigma_x^C = \frac{M_y}{I_y} \cdot z^C = \frac{-27.72 \cdot 10^6\ \text{N} \cdot \text{mm}}{2140 \cdot 10^4\ \text{mm}^4} \cdot 79.55\ \text{mm} = -103.04\ \text{MPa}$$

$$\tau_{xz}^C = \frac{V_z \cdot S^C}{b^C \cdot I_y} = \frac{-22.06 \cdot 10^3\ \text{N} \cdot 101.27 \cdot 10^3\ \text{mm}^3}{7.5\ \text{mm} \cdot 2140 \cdot 10^4\ \text{mm}^4} = -13.92\ \text{MPa}$$

Von Mises resistance criterion

$$\sigma_{eq} = \sqrt{\sigma_x^2 + 3\tau_{xz}^2} \leq \sigma_a$$

$$\sigma_{eq}^A = 129.53\ \text{MPa} \leq \sigma_a$$

$$\sigma_{eq}^B = 29.76\ \text{MPa} \leq \sigma_a$$

$$\sigma_{eq}^C = 105.82\ \text{MPa} \leq \sigma_a$$

Topic 2.2

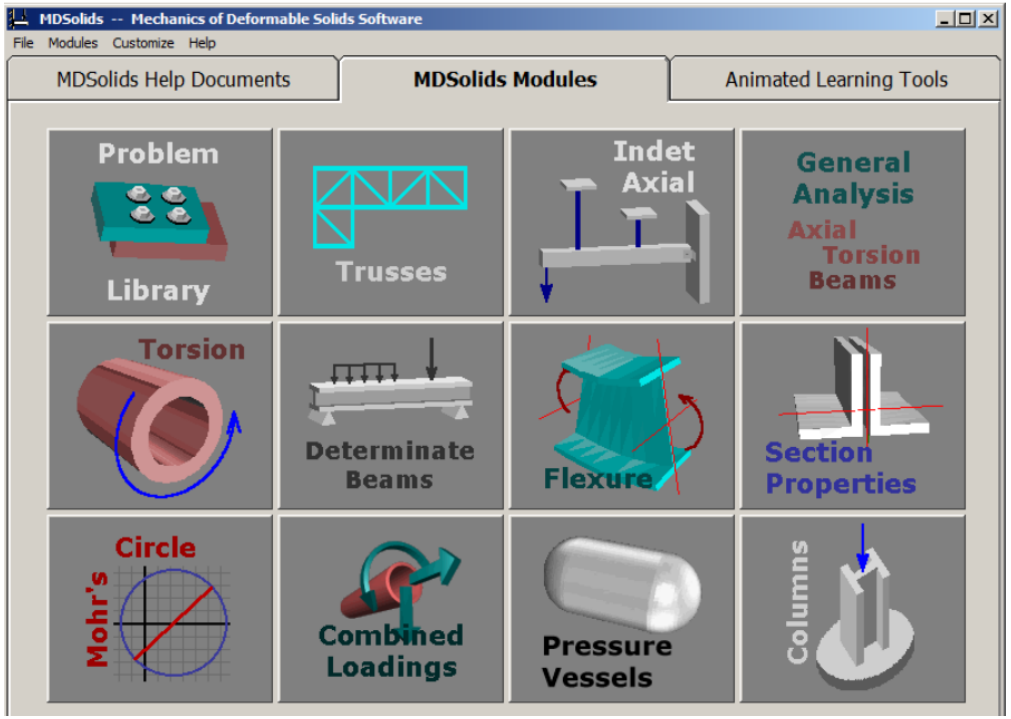
Numerical solution - MdSolids

MDSolids is software for topics taught in the Mechanics of Materials (also commonly called Strength of Materials or Mechanics of Deformable Solids).

MDSolids consists of routines for beams and flexural members, torsional assemblies, axial assemblies, trusses, columns, pressure vessels, section properties, Mohr's circle analysis (including stress transformations and strain transformations), and many more topics.

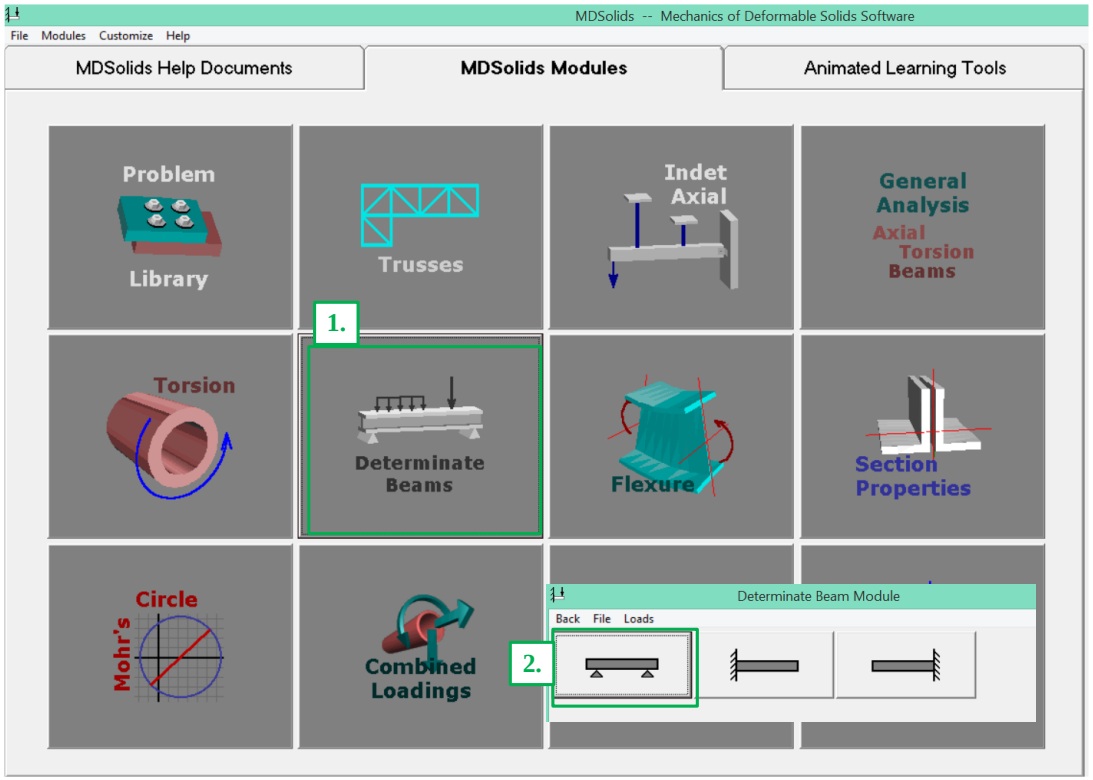
The MDSolids software can be free downloaded from:

https://web.mst.edu/mdsolids/

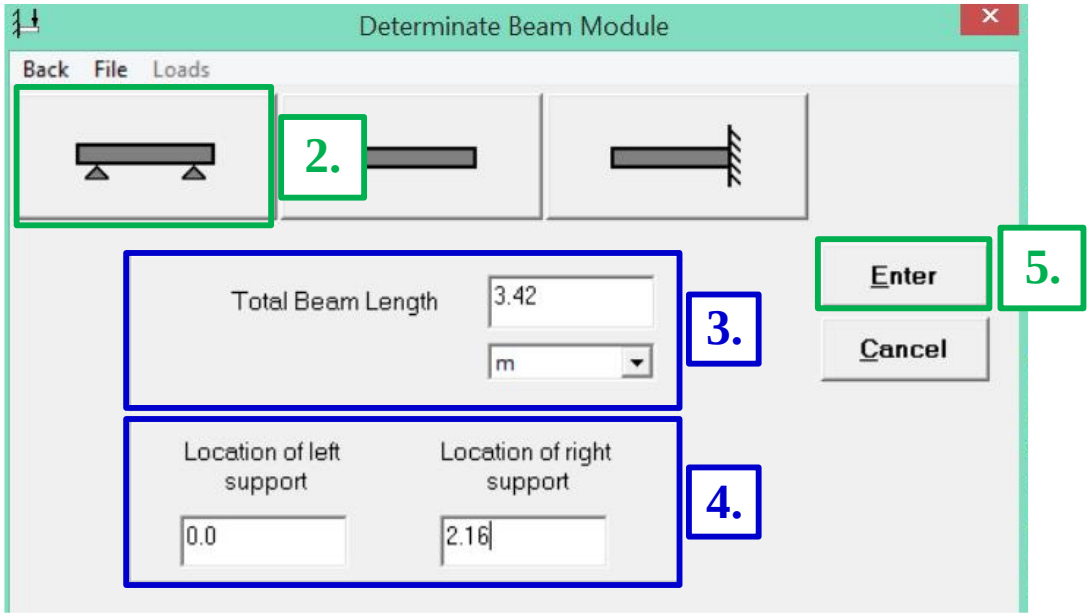


For the numerical solution of the proposed problem, the MDSolids program is used, respectively the Determinate Beams module. The following slides shows step by step numerical modeling of the proposed problem.

STEP 1. Open *Determinate Beams* module
STEP 2. It is selected the type of beam's supports (simple supports for this application)

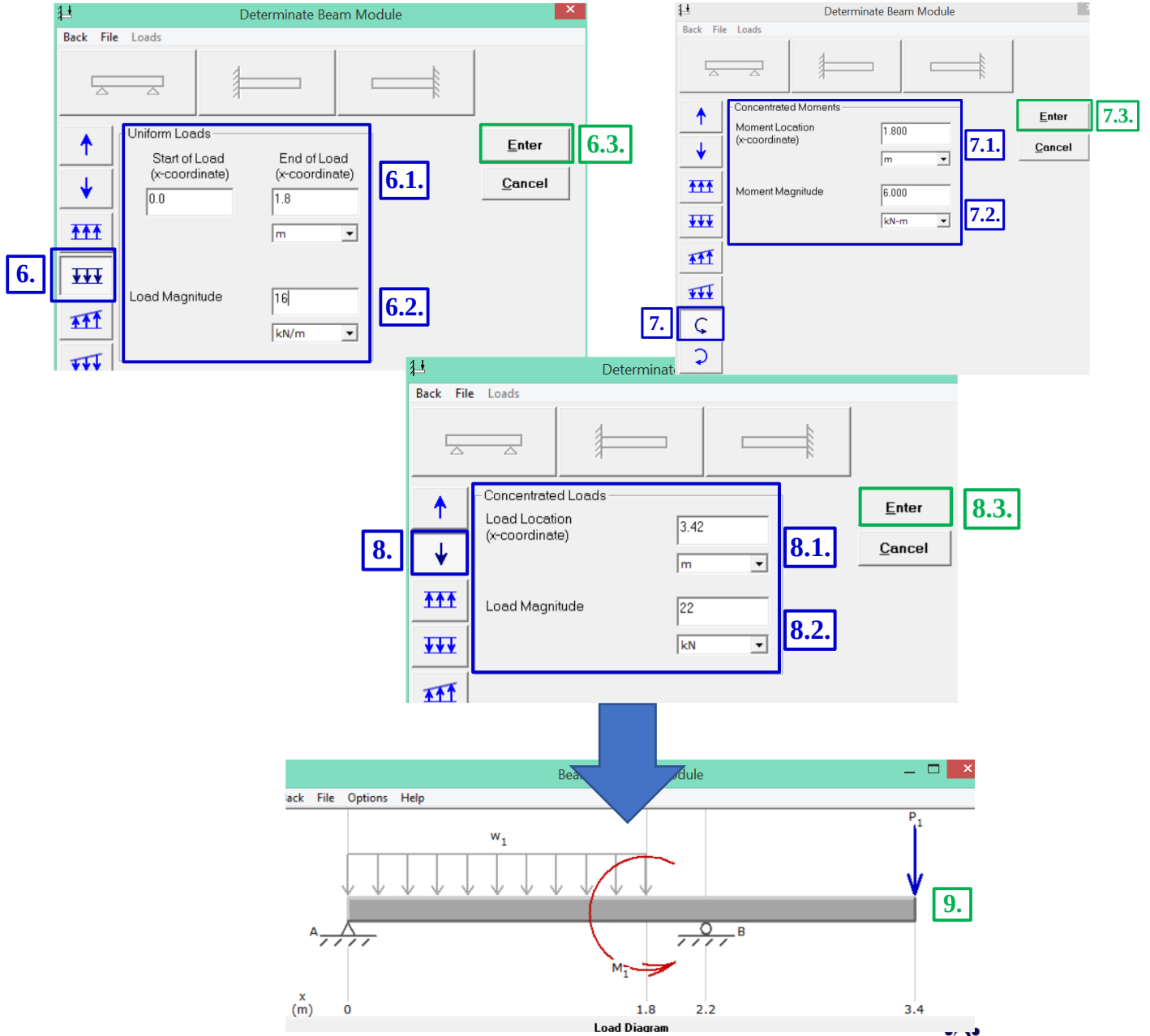


STEP 3. It's introduced the beam's length in *Total beam length* space
STEP 4. Are defined the x coordinates of each support in *Location of left/right support* spaces
STEP 5. Press ENTER



External loads are defined and introduced, thus:

STEP 6. Uniformly distributed load (q), [kN/m]:
6.1. Start/End of Load (x – coordinate)
6.2. Load Magnitude
6.3. Press ENTER.
STEP 7. Mending moment (M), [kN·m]:
7.1. Moment location (x – coordinate)
7.2. Moment Magnitude
7.3. Press ENTER.
STEP 8. Concentrated force (F), [kN]:
8.1. Load location (x – coordinate)
8.2. Load Magnitude
8.3. Press ENTER.
STEP 9. The simple supported beam with external loads is obtained.



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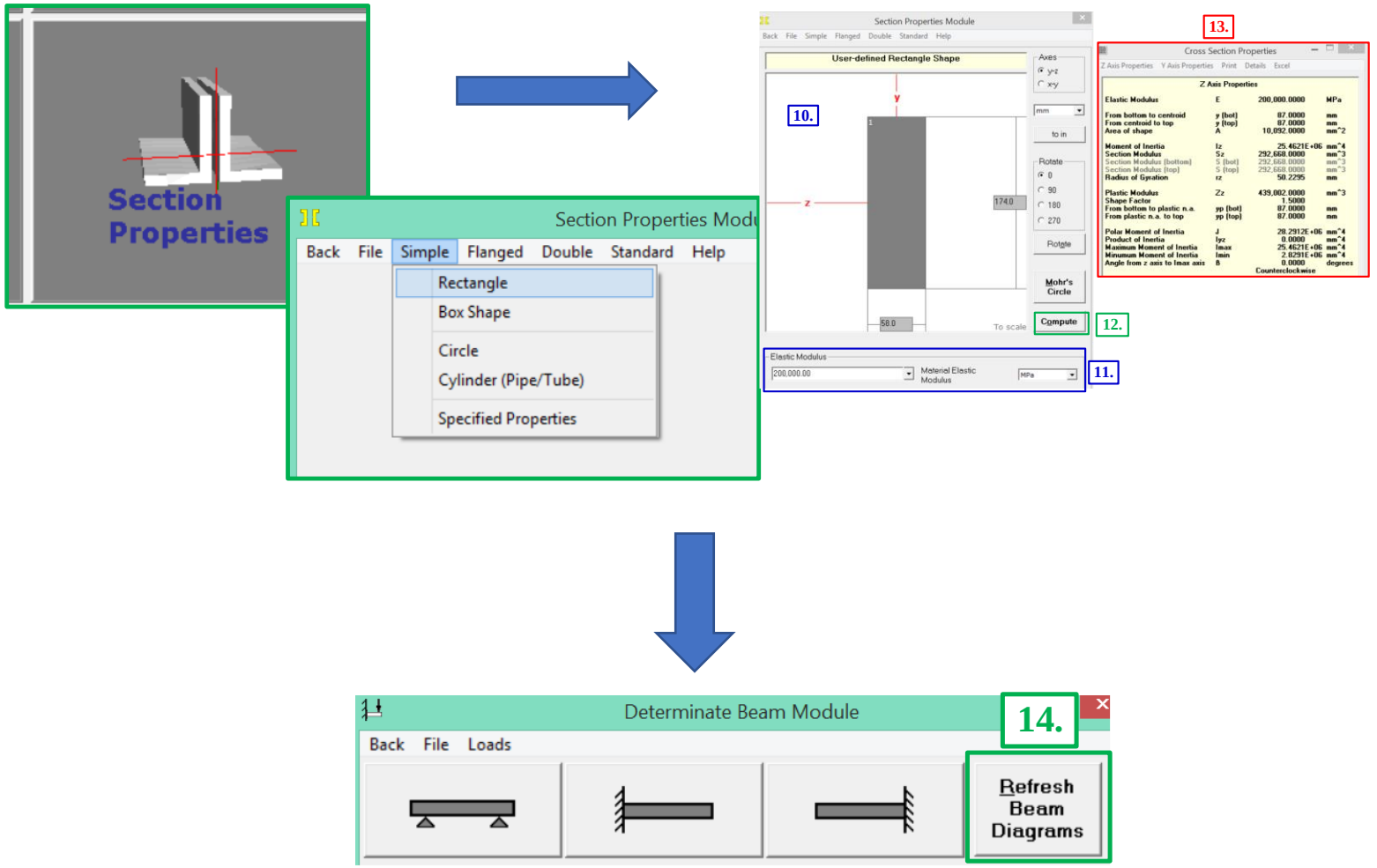
Defining the rectangular cross-section:

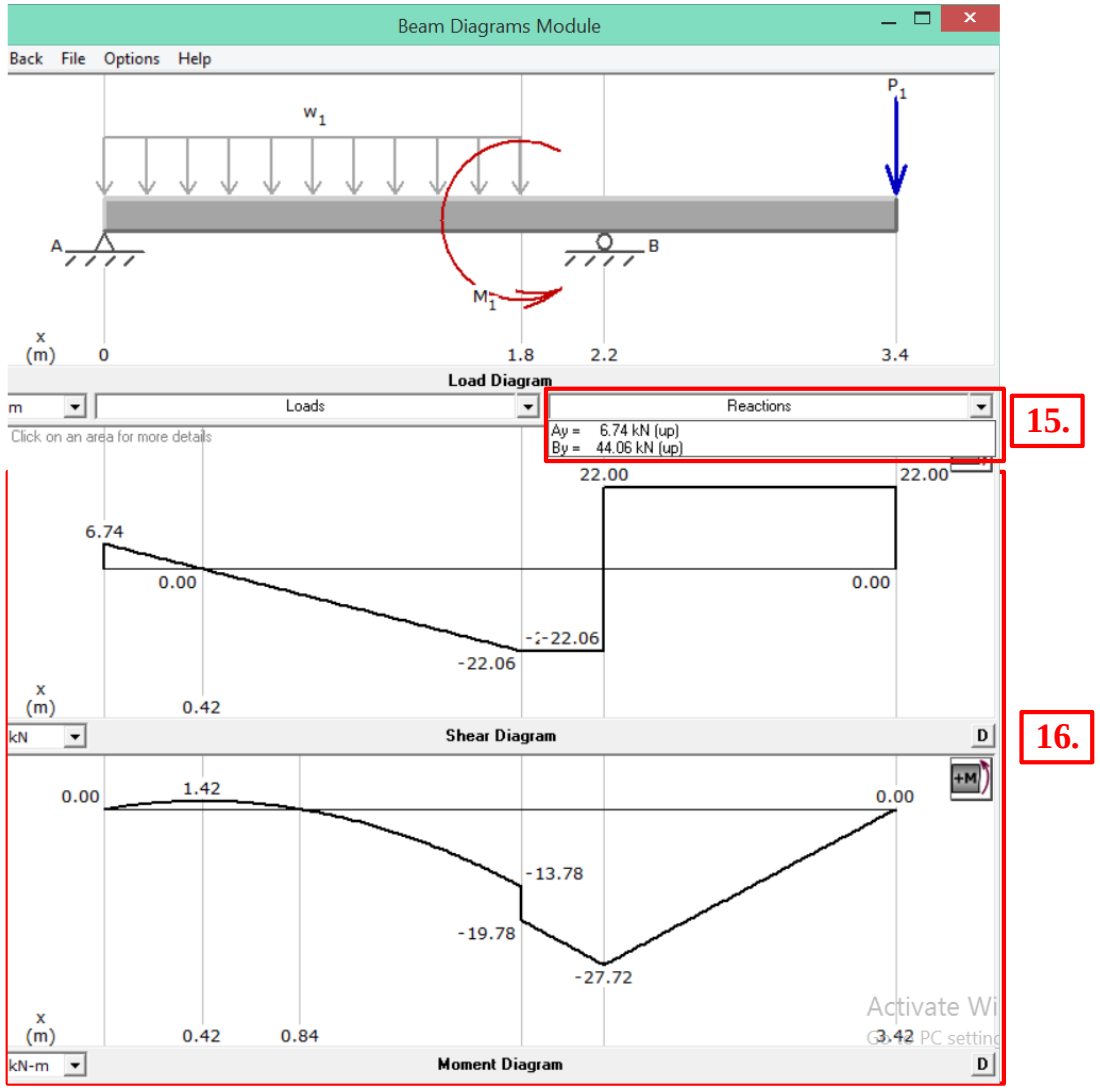
Without closing the Determine Beams mode, Back from the main menu bar returns to the initial interface of the program and launches the Section Properties module.
From the main menu bar, Simple -> Rectangle is selected.
STEP 10. Dimensions of the cross-section are introduced
STEP 11. Elastic modulus (or Young's modulus) is introduced
STEP 12. Press COMPUTE
STEP 13. The z and y cross-section properties are obtained
STEP 14. Without closing the windows in the Section Properties module, with Back you return to the initial Determine Beams interface and press the Refresh Beam Diagrams button - this means that the previously defined cross section has been considered



Numerical results: Reactions forces and diagrams

STEP 15. *Reactions* – The values of the reactions from the two supports are obtained

STEP 16. *Shear Diagram, Moment Diagram*



Numerical results: Stresses and displacements

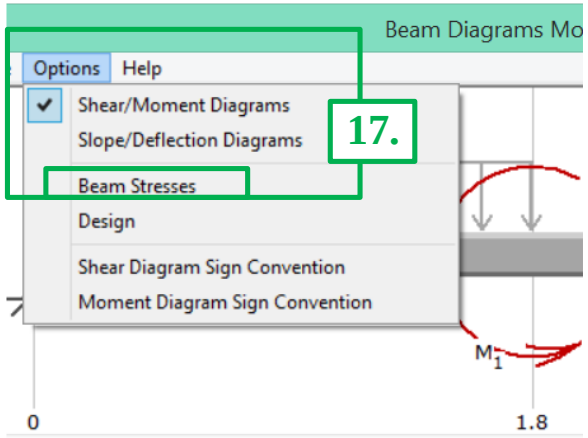
▪ **Normal (σ) and shear (τ) stresses**

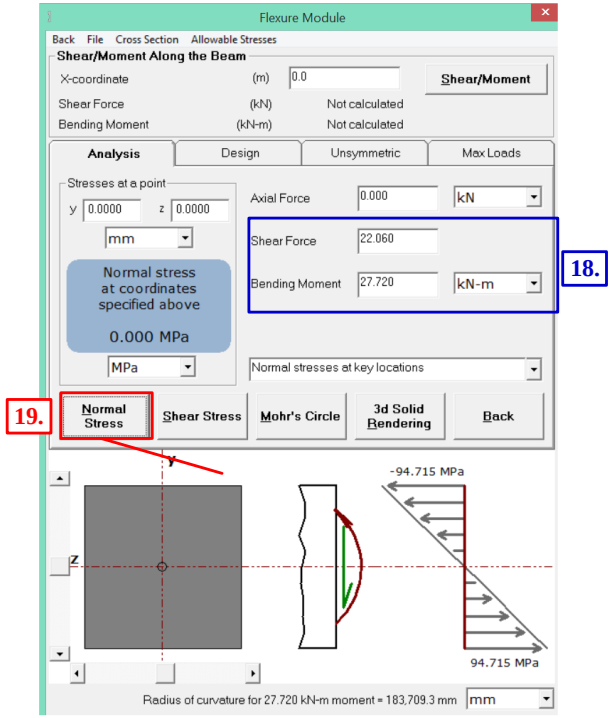
STEP 17. In the main menu bar of the internal forces and moments diagrams window select *Options → Beam Stresses*

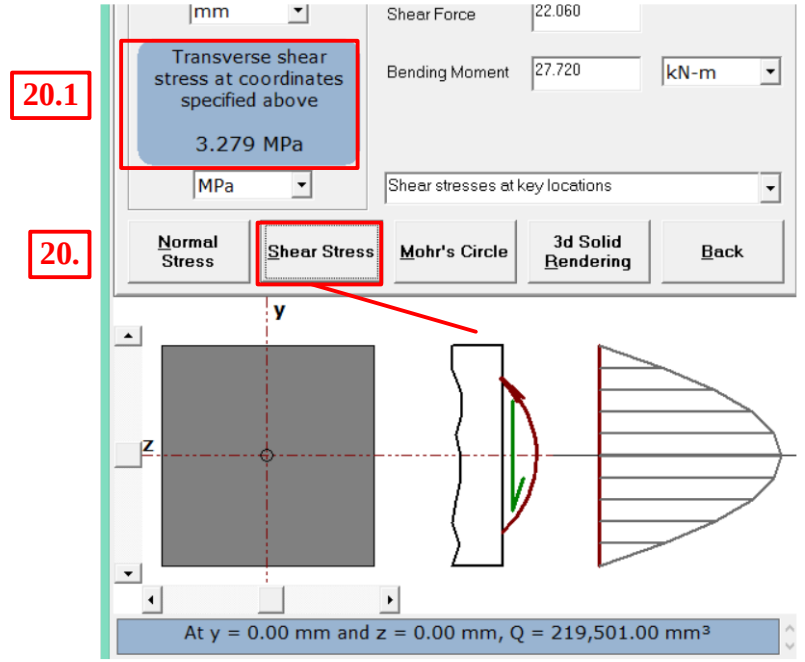
STEP 18. Maximum shear force and bending moment are introduced

STEP 19. Press *Normal Stress* – The maximum normal stresses diagram are illustrated

STEP 20&20.1. Press *Shear Stress* – The maximum shear stress diagram is illustrated (see STEP 20.1)



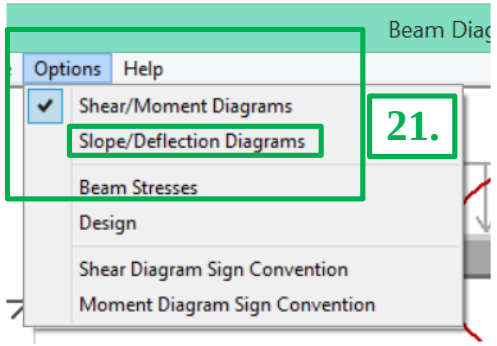


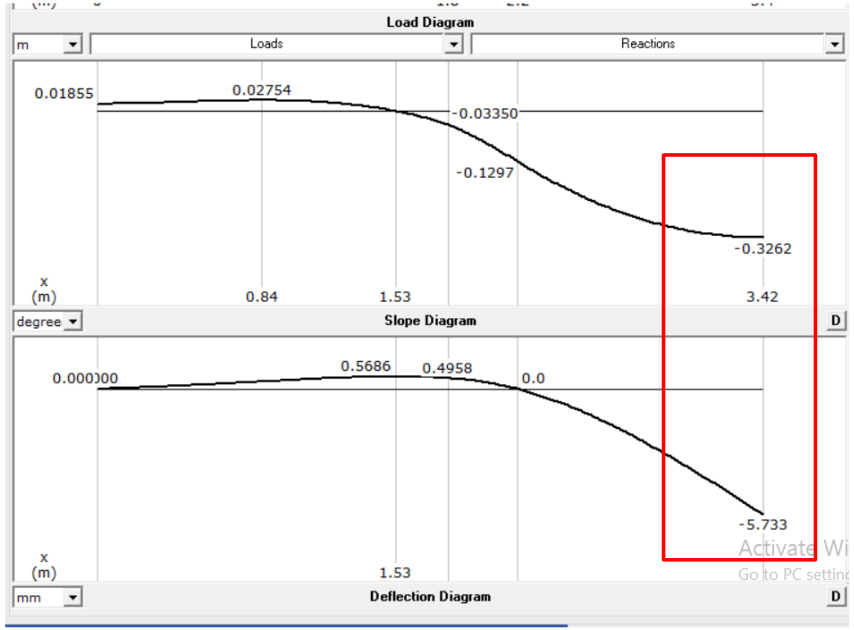


Numerical results: Stresses and displacements

- **Displacement and slope**

STEP 21. In the main menu bar of the internal forces and moments diagrams window select *Options → Slope/Deflection Diagrams*
STEP 22.1. The slope diagram is obtained, in [°].
STEP 22.2. The displacement diagram is obtained, in [mm]





e) Obtain the maximum displacement and slope by using MdSolids.

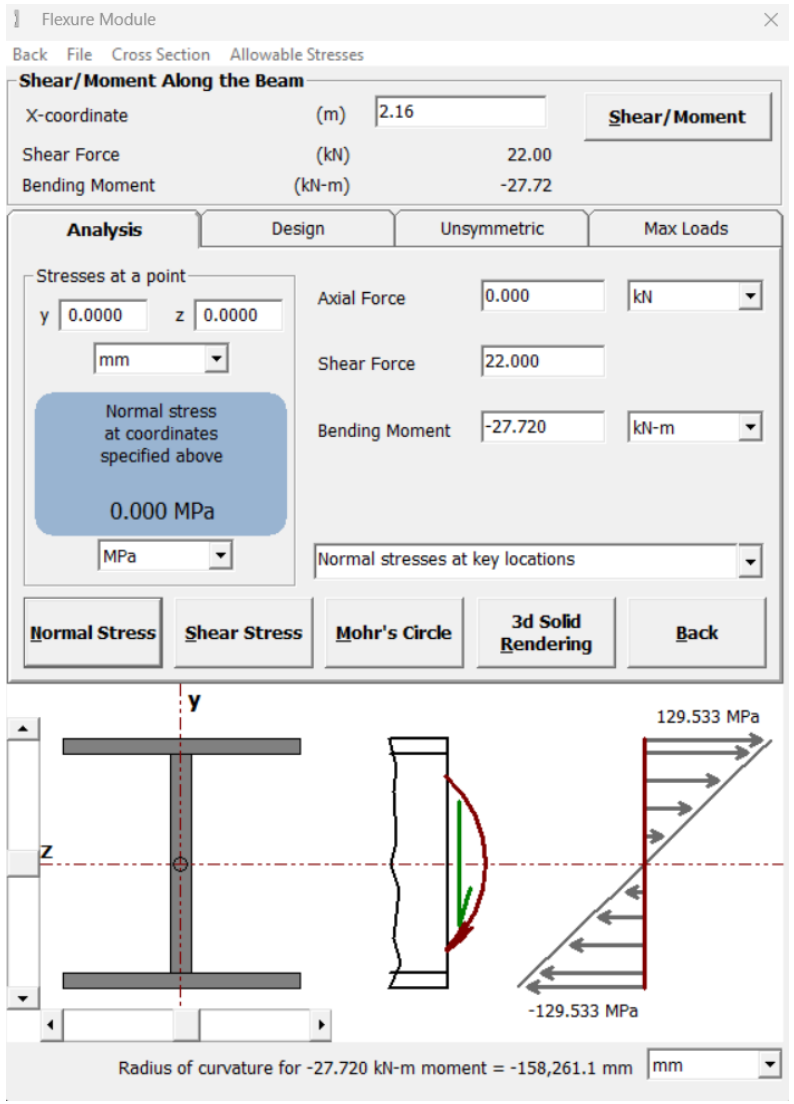
According to the numerical diagrams, the maximum displacement and slope are in the free end of the beam:

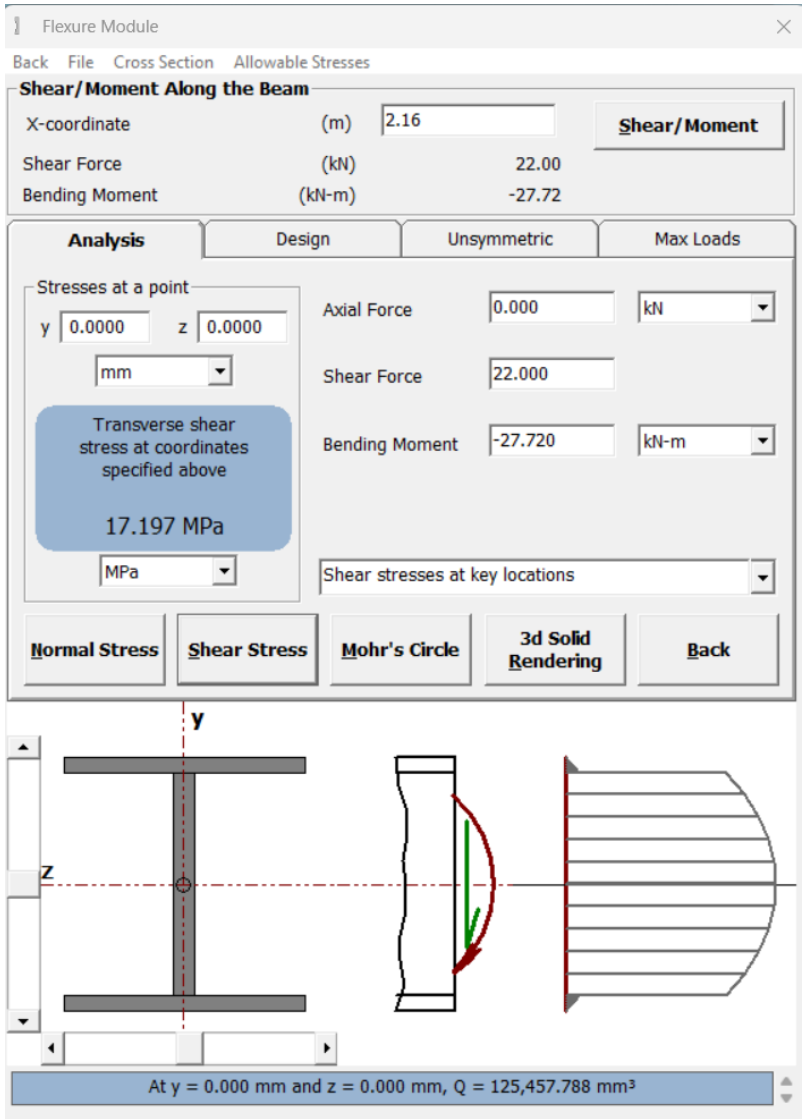
δ_{max} = - 0.5733 mm; φ_{max} = - 0.03262 [°]

Standard IPN 200

Numerical results:

- **Normal (σ) and shear (τ) stresses**





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C1 – Strength of Materials

M6 - Buckling

Theoretical and Experimental Aplication

HEI name: University of Jaen (UJA)

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

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Integracion Sensorial y Robotica

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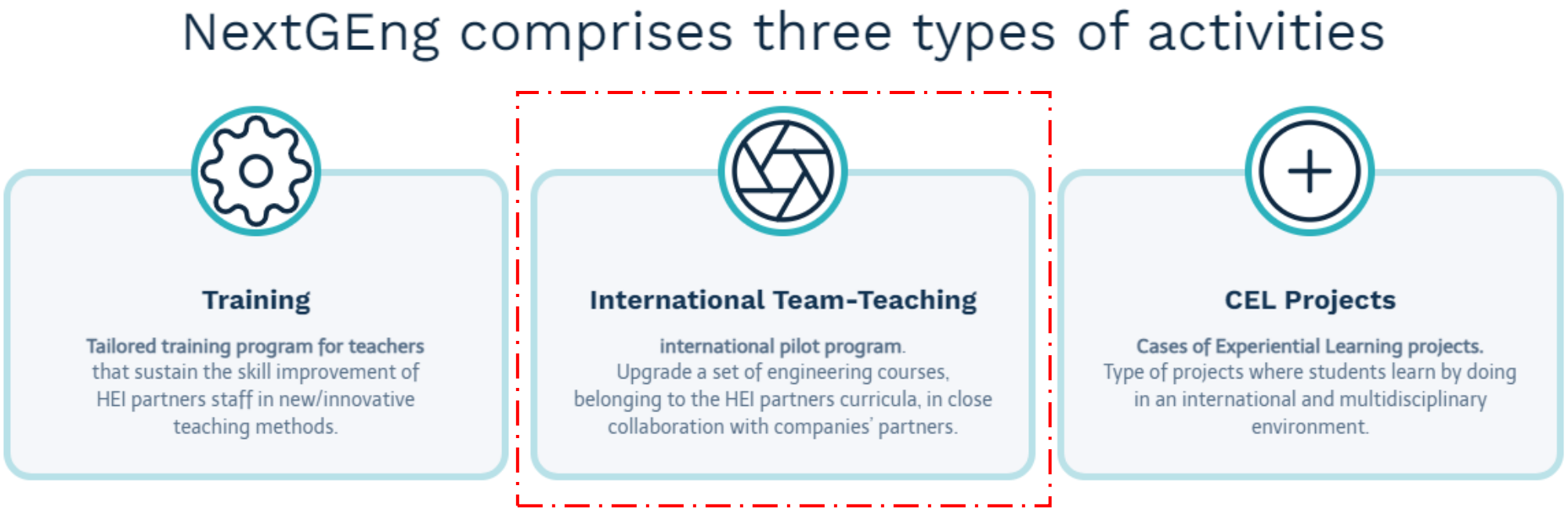
About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



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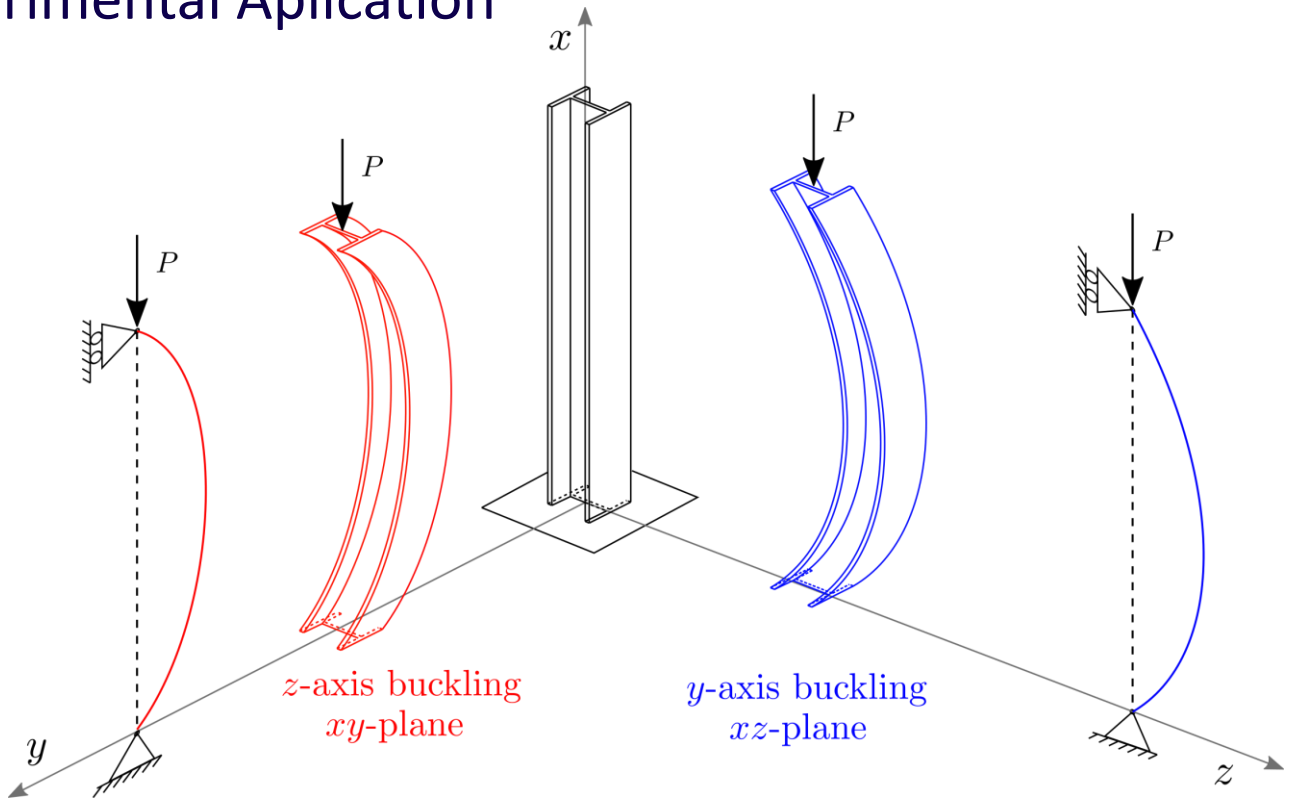
Module 6 - Buckling

Theoretical and Experimental Aplication



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Module 6 - Buckling

Theoretical and Experimental Aplication

Upon completion of this module, the student will be able to:

1) Understand the concept of Euler critical buckling force and its limitations
2) Calculate the critical buckling force for different type of supports
3) To perform experimental measurements of critical buckling force for different type of supports.

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Content

- Introduction - Theoretical backgrounds
- Topic 1: Euler critical buckling force

  Topic 1.1: Euler formula (advanced)

  Topic 1.2: Limitations of the Euler critical buckling force
- Topic 2: Critical buckling force determination of straight bars (Experimental Application)

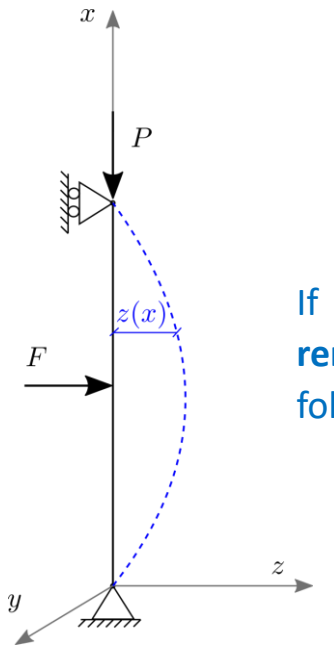
  Topic 2.1: Plane bars with different lengths and type of supports subjected to axial loading

Introduction

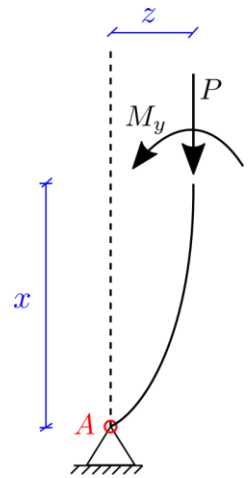
Introduction

Theoretical backgrounds

When a beam is subjected to two concentrated loads P (axial) and F (transverse), it experiences the following deformation shape:



If load F vanishes and the beam **remains in equilibrium**, one has the following equilibrium condition:



$$\sum M^A = 0$$

$$M_y - P \cdot z = 0$$

- **Depending on the value of the force P, we have three scenarios**

1. *If* $P \cdot z = M_y$ → Equilibrium condition

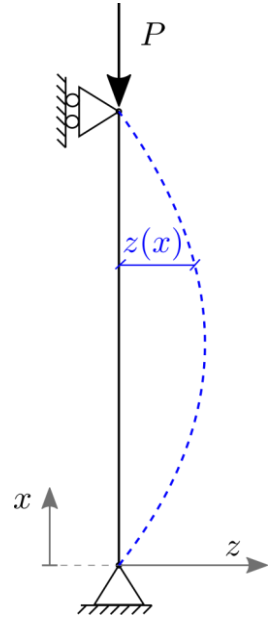
2. *If* $P \cdot z < M_y$ → Stable. The beam returns to its original state

3. *If* $P \cdot z > M_y$ → Unstable. Deformation grows → *Buckling*

Determining **P** in this scenario is the maximum axial load for the beam before buckling → Euler critical buckling force P_{cr}

Topic 1: Euler critical buckling force

Topic 1.1 Euler formula (advanced)



▪ **Using the differential equation of the elastic curve of a beam, we know:**

$$\frac{d^2z}{dx^2} + \frac{\boldsymbol{M_y}}{E \cdot I_y} = 0 \quad \textit{Substituting the equilibrium condition} \rightarrow \boxed{\frac{d^2z}{dx^2} + \frac{\boldsymbol{P}}{E \cdot I_y} \cdot \boldsymbol{z} = 0}$$

Second order ordinary differential equation with constant coefficients (**ODE**)

The solution of this ODE $z(x)$ is known if the coefficients are positive $\left(\frac{P}{EI_y} > 0\right)$ →

$$z(x) = C_1 \cdot \sin\left(\sqrt{\frac{P}{EI_y}} \cdot x\right) + C_2 \cdot \cos\left(\sqrt{\frac{P}{EI_y}} \cdot x\right)$$

General solution

*Applying **boundary conditions**:*

- Deflection at end supports is zero:

1. $z(x = 0) = 0;$ → $\boxed{C_2 = 0}$

2. $z(x = L) = 0;$ → $\boxed{C_1 \sin\left(\sqrt{\frac{P}{EI_y}} \cdot x\right) = 0}$

Therefore, the “sin” argument must equal π.
Thus, we can extract the load **P** that fulfills the beginning of the buckling condition:

$$\sqrt{\frac{P}{EI_y}} \cdot L = \pi \rightarrow \boxed{P_{cr} = \left(\frac{\pi}{L}\right)^2 EI_y}$$

Euler critical buckling force

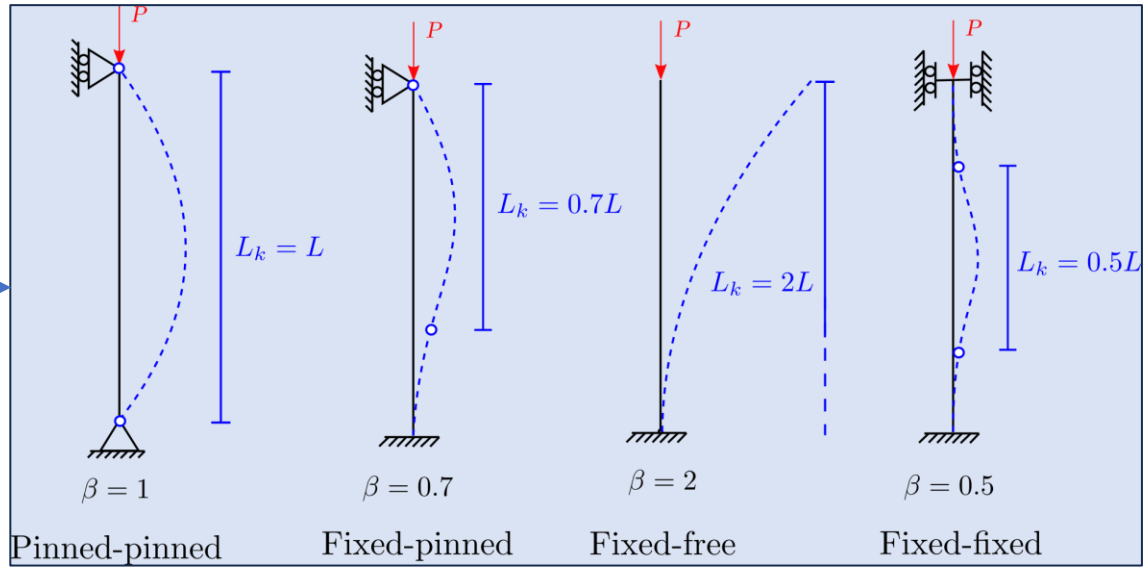
Topic 1.1 Euler formula (advanced)

- **Types of supports:**

The previous Euler formula is obtained based on a simply supported beam. What happens in other types of support?

Same formula is used but the beam length is updated as an "effective length" L_k:

$$L_k = \beta \cdot L$$



$$P_{cr,y} = \left(\frac{\pi}{L_{k,y}}\right)^2 EI_y \qquad P_{cr,z} = \left(\frac{\pi}{L_{k,z}}\right)^2 EI_z$$

- **Buckling axis:**

Buckling may happen along an axis perpendicular to the longitudinal direction of the beam. Therefore:

Y-axis buckling $P_{cr,y} = \left(\frac{\pi}{L}\right)^2 EI_y$

Z-axis buckling $P_{cr,z} = \left(\frac{\pi}{L}\right)^2 EI_z$

The minimum of P_{cr} determines the beginning of buckling

$$P_{cr} = \min\left(P_{cr,y}, P_{cr,z}\right)$$

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Topic 1.1 Euler formula (advanced)

- **Euler formula using slenderness factor λ:**

The slenderness factor is a dimensionless parameter that is usually used in the Euler critical formula. It is defined as follows:

$$\lambda = \frac{L_k}{i}$$

$L_k = \beta \cdot L$ is the effective length

$i = \sqrt{\frac{I}{A}}$ is the radius of gyration where A is the beam cross section

Considering buckling axes, it yields: $\lambda_y = \frac{L_{k,y}}{i_y}$ $\lambda_z = \frac{L_{k,z}}{i_z}$

And the Euler critical formula:

$$P_{cr,y} = \left(\frac{\pi}{\lambda_y}\right)^2 EA \qquad P_{cr,z} = \left(\frac{\pi}{\lambda_z}\right)^2 EA$$

where A is the beam cross section

Consequently, buckling occurs within the axis of **maximum slenderness**

$$P_{cr} = \left(\frac{\pi}{\lambda_{max}}\right)^2 EA$$

Topic 1.2 Limitations of the Euler critical buckling force

Euler formula is derived adopting the following assumptions:

- Elastic material: Hooke's law and Navier hypothesis
- Beam axis is mathematically straight, and the axial force is perfectly aligned
- Beam cross section is constant
- The stress state of the beam is neutral

However, there is no perfect beam in real world:

- There are geometric and material imperfections
- Loads are not perfectly aligned
- Residual stresses can appear, etc.

All these reasons make the beam to buckle with an axial load **lower** than the one predicted by Euler

$$P_{cr,real} < P_{cr,Euler}$$

- Consequently, Euler critical buckling force **should not be directly** used
- The standard regulations assume these concerns and predict a column buckling force using the Euler formula but applying a set of detailed safety coefficients

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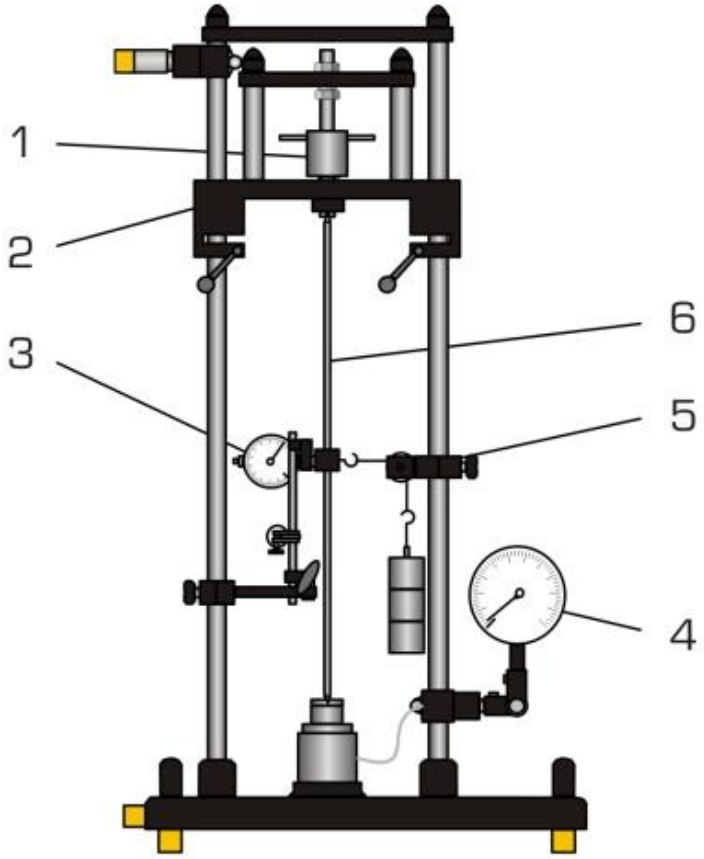
Topic 2: Critical buckling force determination of straight bars (Experimental application)

Topic 2.1 Plane bars with different lengths and supports subjected to axial loading

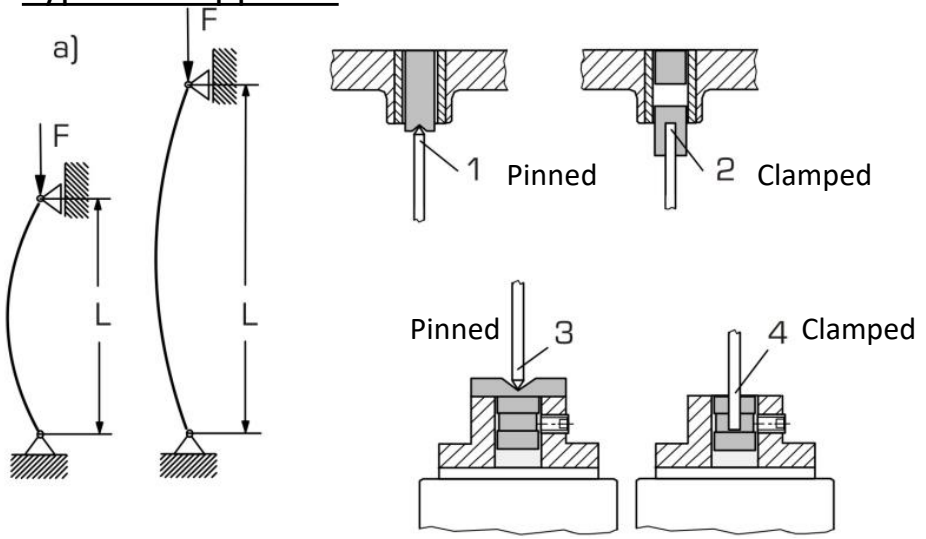
Equipment: GUNT WP-120

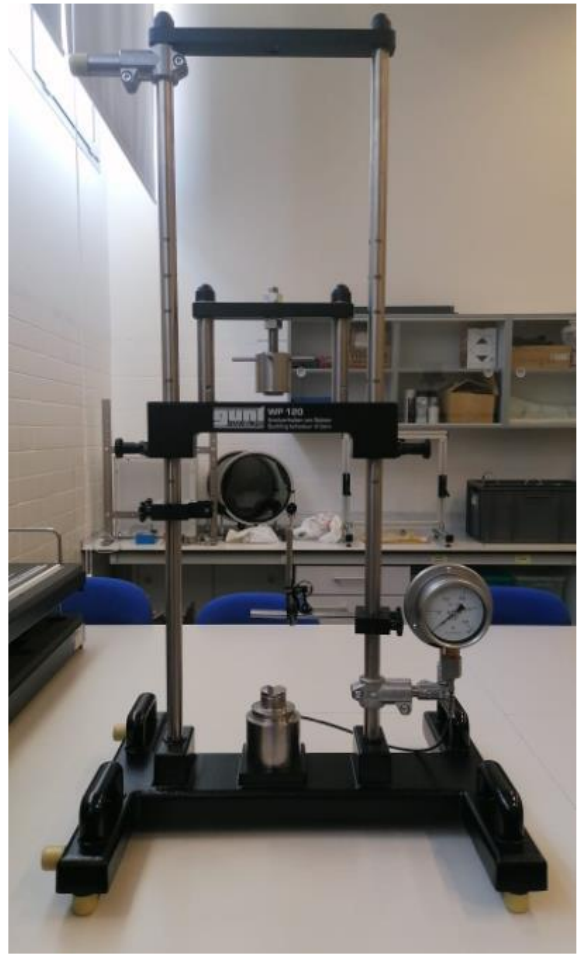


Details:

1. Spindle
2. Height-adjustable load member
3. Dial gauge for lateral deflection of the test bar
4. Dynamometer
5. Mechanism for generating a lateral load
6. Test bar

Types of supports:





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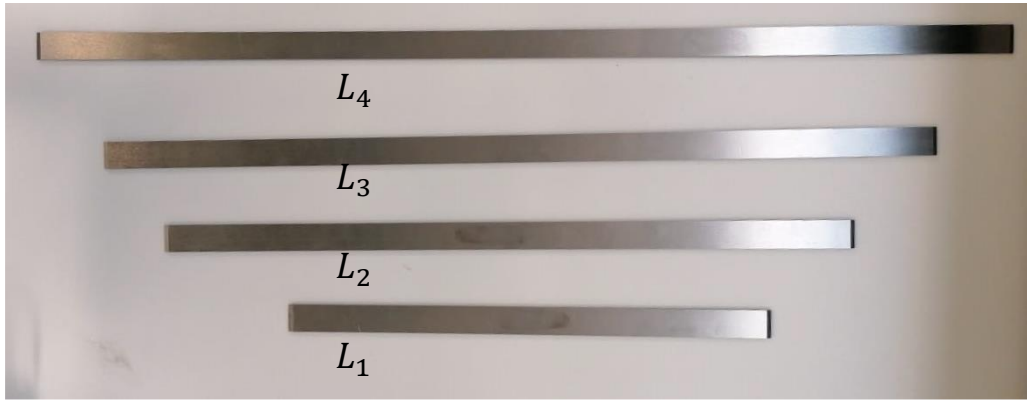
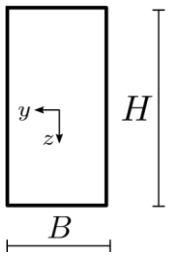
Experiment

Laboratory Aim: Experimental determination of critical buckling force for straight bars with different lengths and type of supports, and comparison with the calculated (theoretical) values.

Pinned-pinned bars to study the influence of length bar:



Rectangular cross-section



$L_1 = 350$ mm
$L_2 = 500$ mm
$L_3 = 600$ mm
$L_4 = 700$ mm

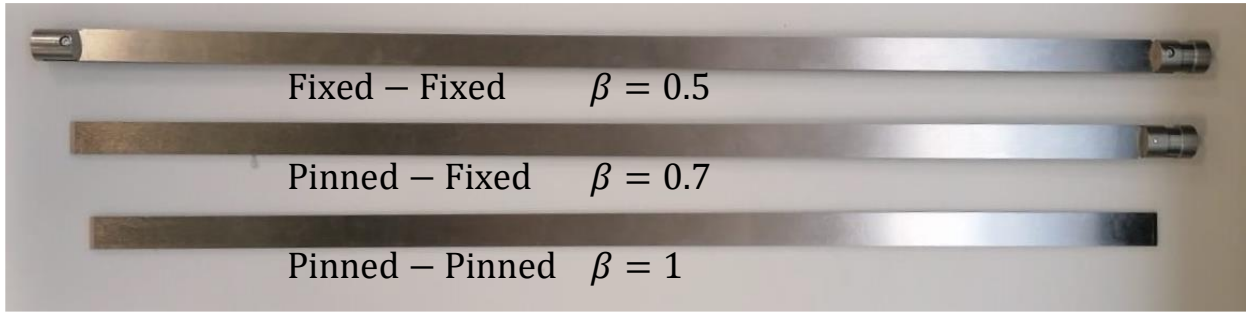
$B = 4$ mm
$H = 20$ mm

Steel: $E = 2.1 \cdot 10^5$ MPa

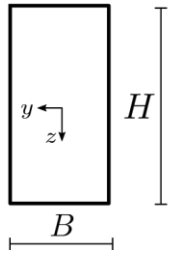
$I_z = \frac{HB^3}{12}$ mm^4

$i_z = \sqrt{\frac{I_z}{A}}$ mm

Bars to study the influence of the type of support:



Rectangular cross-section



$L = 650$ mm

$B = 4$ mm
$H = 20$ mm

Steel: $E = 2.1 \cdot 10^5$ MPa

Buckling axis is ***z***-axis

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- The following steps will be taken to perform the experimental measurements:

1. In order to obtain the pinned supports, the bar free ends are connected to the adapters shown in the figures and installed on the WP-120 GUNT equipment:
2. The bar is adjusted in the WP-120 with the height adjustable load member;
3. The dial gauge is installed at the mid position of the bar and set to zero, to start measuring the bar lateral deflection.
4. Load is applied with the spindle which compresses the bar;
5. The force transducer, which is installed at the bottom, is connected to the dynamometer display and shows the force transmitted by the spindle;
6. The bar lateral displacement measured by the dial gauge is registered with the load applied by the spindle and showed in the dynamometer;
7. The experiment finishes when load remains constant while the spindle rotates. Thus, the critical buckling load is obtained.

Pinned support (top)

Pinned support (bottom)

Bar with fixed end

Fixed support (top)

Fixed support (bottom)

1. Experimental critical buckling force for different type of supports

Known data:

$L = 650$ mm; $E = 2.1 \cdot 10^5$ MPa

$H = 2$ mm; $B = 20$ mm; $\beta = 1$

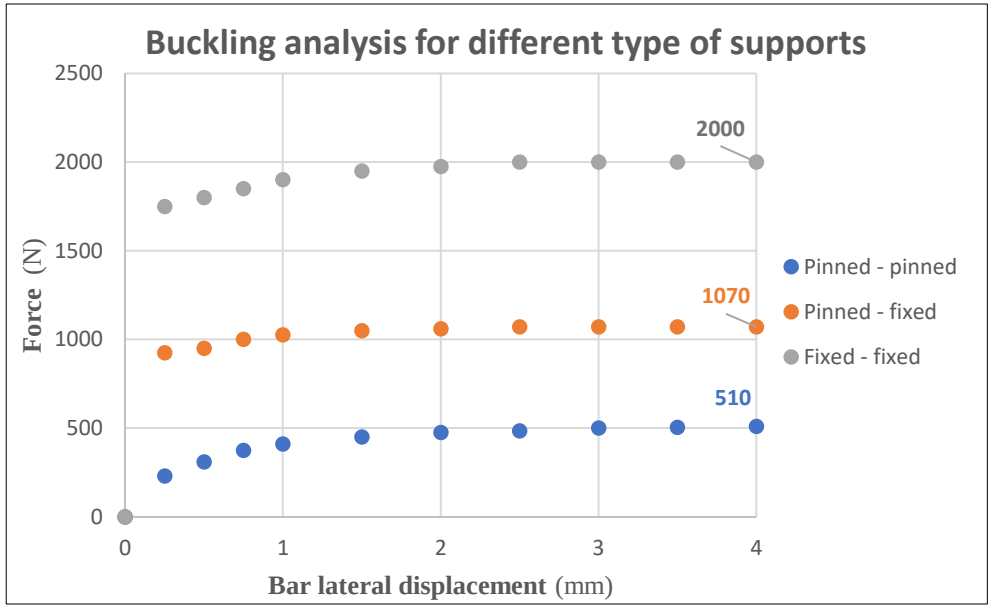
$\beta = 0.5$ for *fixed-fixed* support

$\beta = 0.7$ for *pinned-fixed* support

$\beta = 1$ for *pinned-pinned* support

$$P_{cr,theo} = \left(\frac{\pi}{\lambda_{max}}\right)^2 EA \qquad \lambda = \frac{L_k}{i}; \quad L_k = \beta \cdot L; \quad i = \sqrt{\frac{I}{A}};$$

$$Rel.dev. = \left|\frac{|P_{cr.\,exp}| - |P_{Cr\,theoretic}|}{|P_{cr.\,exp}|}\right| \cdot 100 \rightarrow [\%]$$



The experimental buckling force, $P_{cr.\,exp.}$ is the maximum value indicated by the graphs. When the force does not increase with displacement

Type of support	Bar length L [mm]	Bar effective length L_k [mm]	Slenderness factor λ	Critical buckling force		Relative deviation [%]
				$P_{cr,\,theoret}$ [N]	$P_{cr,\,exp}$ [N]	
Pinned - pinned						
Pinned - fixed						
Fixed - fixed						

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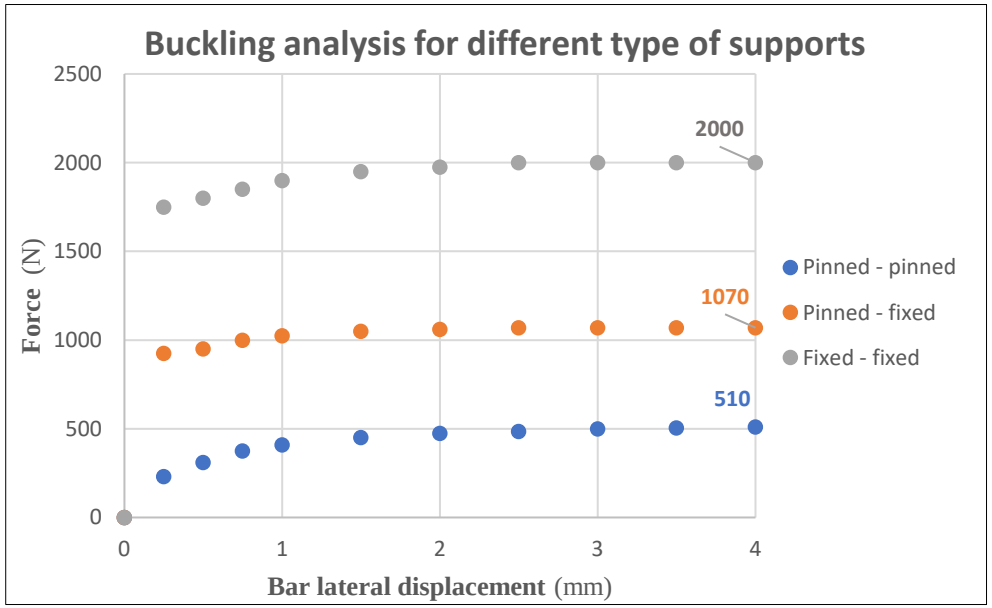
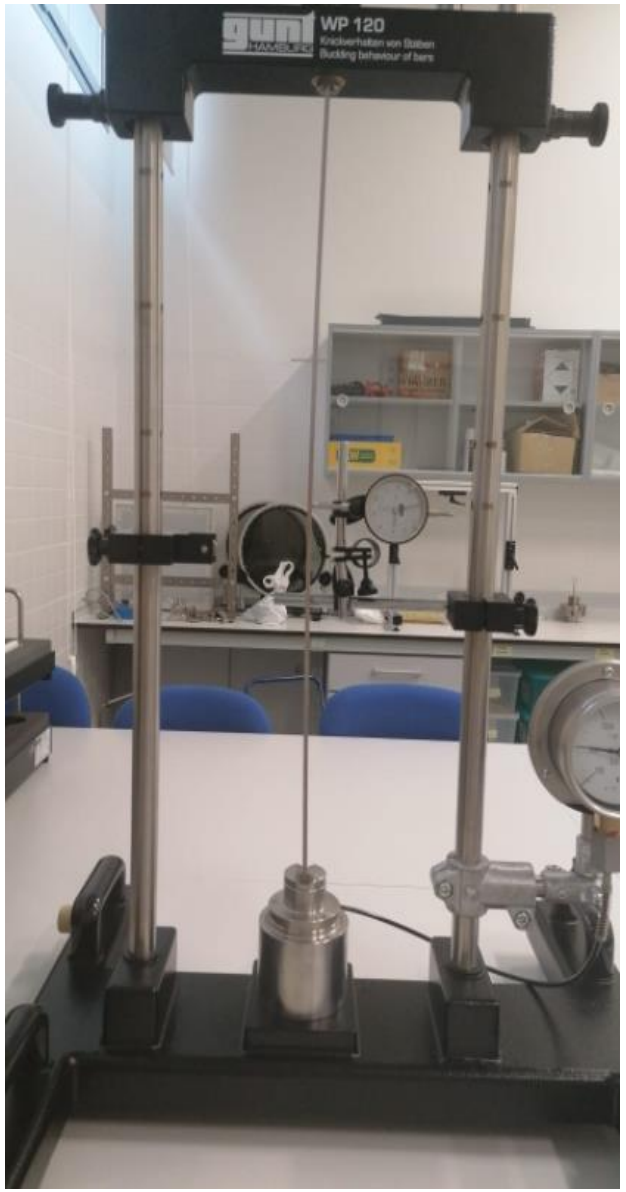
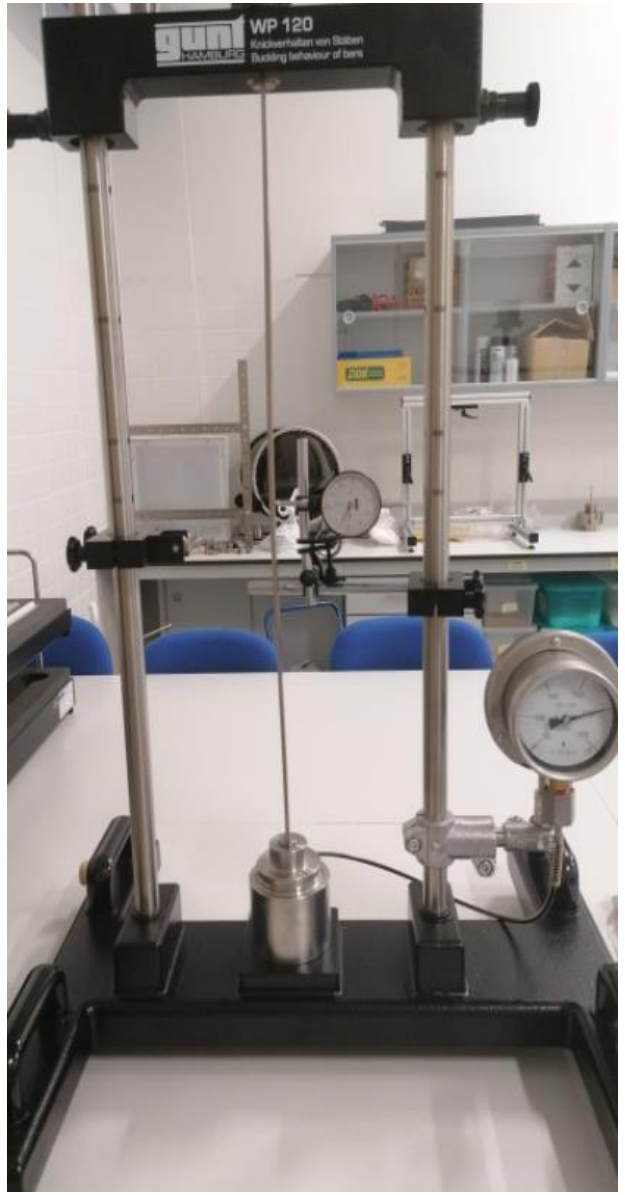
1. Experimental critical buckling force for different type of supports

Buckling scenarios:





Pinned-pinned



Fixed-Fixed

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2. Experimental critical buckling force for different bar lengths

Known data:

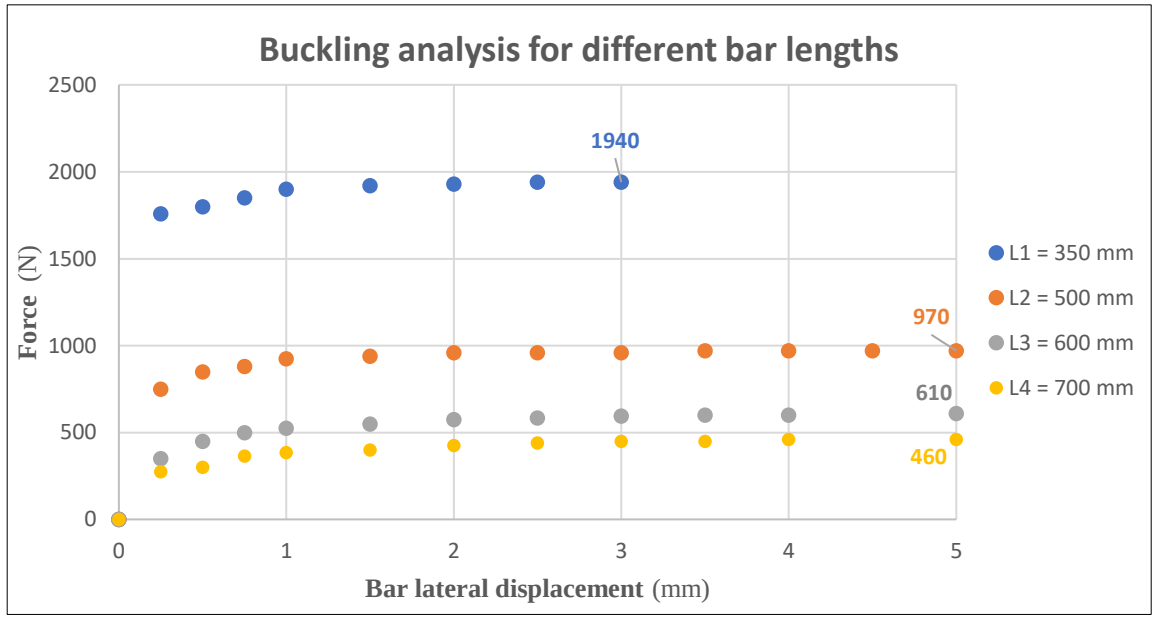
$H = 2$ mm; $B = 20$ mm; $E = 2.1 \cdot 10^5$ MPa; $\beta = 1$

$L_1 = 350$ mm; $L_2 = 500$ mm; $L_3 = 600$ mm; $L_4 = 700$ mm.

$$P_{cr,theo} = \left(\frac{\pi}{\lambda_{max}}\right)^2 EA$$

$$\lambda = \frac{L_k}{i}; \qquad L_k = \beta \cdot L; \qquad i = \sqrt{\frac{I}{A}};$$

$$Rel.\,dev. = \left|\frac{|P_{cr.\,exp}| - |P_{Cr\,theoretic}|}{|P_{cr.\,exp}|}\right| \cdot 100 \rightarrow [\%]$$



The experimental buckling force, $P_{cr.\,exp.}$ is the maximum value indicated by the graphs. When the force does not increase with displacement

Bar length [mm]	Type of support	Bar effective length L_k [mm]	Slenderness factor λ	Critical buckling force		Relative deviation [%]
				$P_{cr,\,theoret}$ [N]	$P_{cr,\,exp}$ [N]	
350	*Pinned-pinned*					
500	*Pinned-pinned*					
600	*Pinned-pinned*					
700	*Pinned-pinned*					

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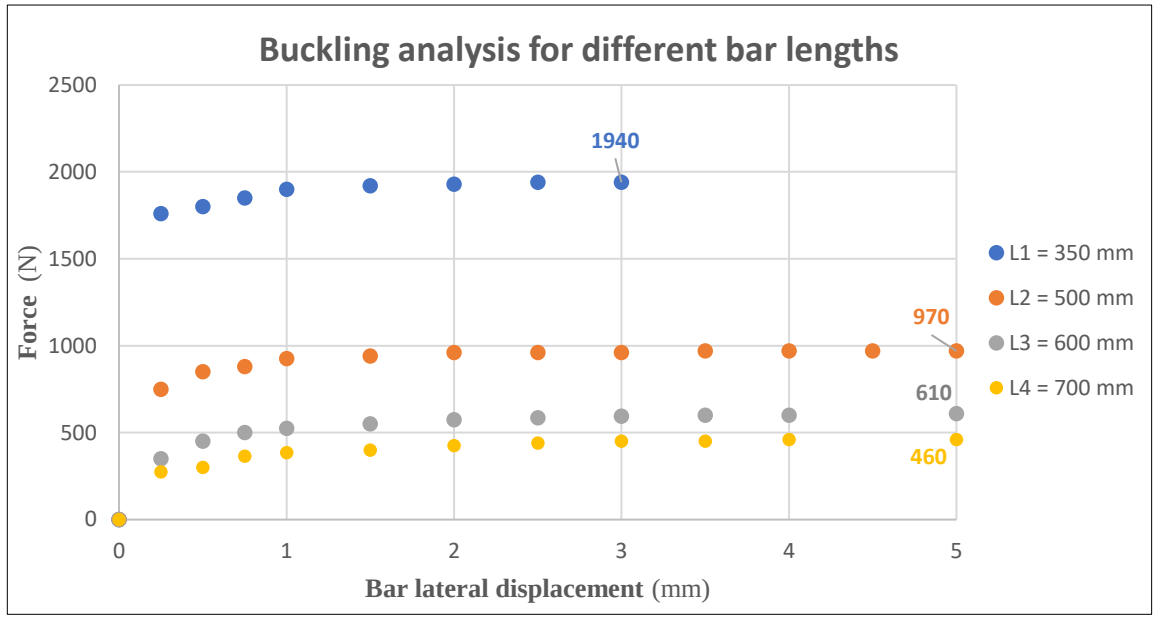
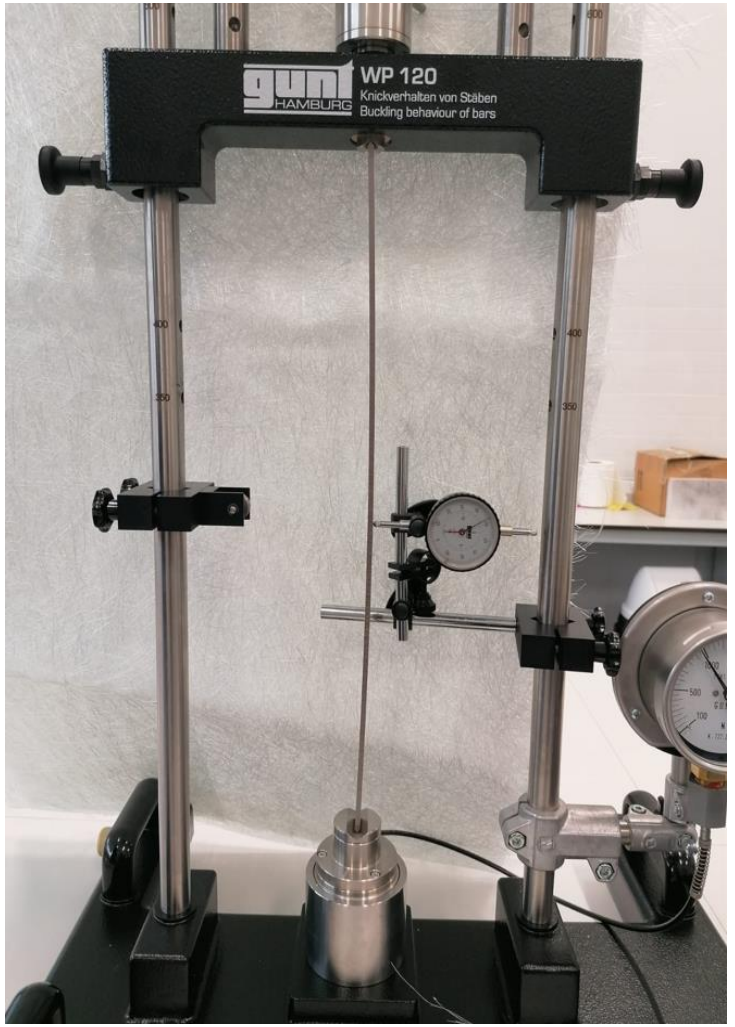
2. Experimental critical buckling force for different bar lengths

Buckling scenarios:



$L_2 = 500$ mm;



$L_3 = 600$ mm;

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C2 – Industrial Automation

M1 - Industrial Control Systems. Industrial Programming Languages

CO - Technical University of Cluj-Napoca

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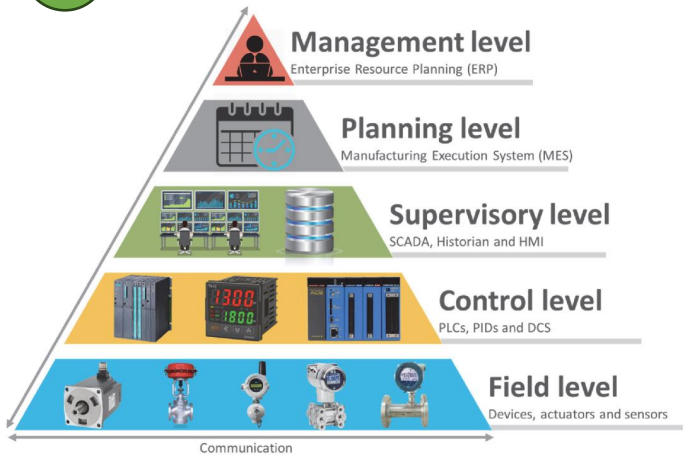
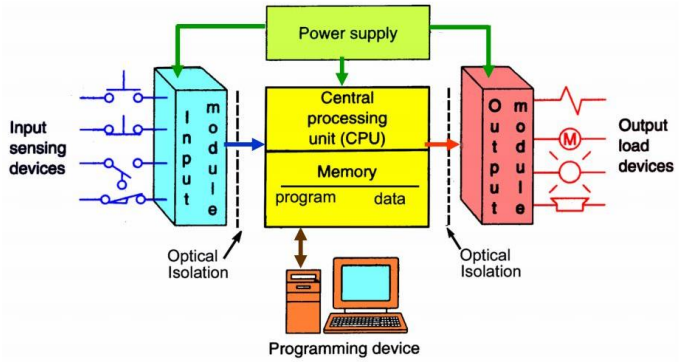
M1 - Industrial Control Systems. Industrial Programming Languages

1 Industrial Control System



3 PLC System



Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.

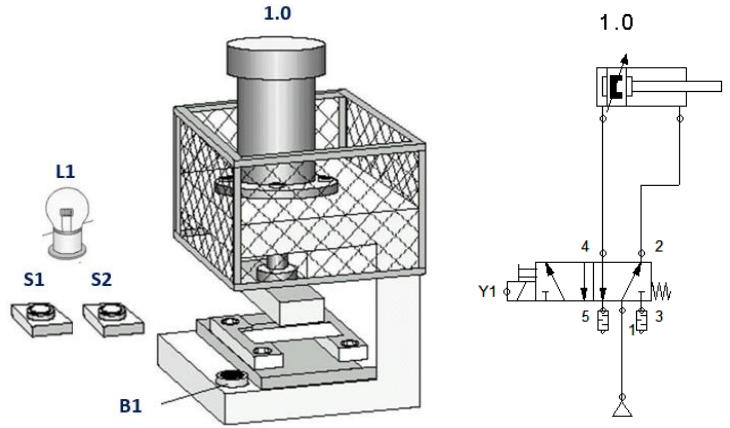
2

4 IEC 61131-3

IEC 61131-3

- **Ladder Logic Diagram (LD)**
- Function Block Diagram (FBD)
- Instruction List (IL)
- Structured Text (ST)
- Sequential Function Chart (SFC)

5 Industry case study – pneumatic press



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M1 - Industrial Control Systems. Industrial Programming Languages

Upon completion of this module, the student will be able to:

1) Understand the architecture of a modern ***Industrial Control System (ICS)*** in the context of ***Industry 4.0***
2) Understand what ***eco-friendly concepts*** are addressed by ***Industry 4.0***
3) Understand the structure of a ***Programmable Logic Controller (PLC)***
4) Understand standardized PLC programming according to ***IEC 61131-3***
5) Design basic and intermediate ***Ladder Logic Diagrams (LD)*** for an ***industrial pneumatic press***

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Content

- Industrial Control Systems
- Sustainable development through Industry 4.0
- Programmable Logic Controllers
- IEC 61131-3
- Industry case study – pneumatic press
- Summary

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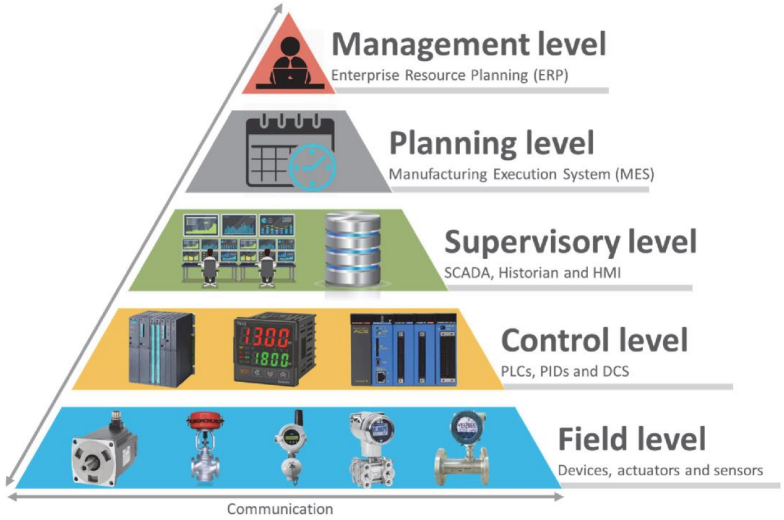
1 **Industrial Control System**



Industrial Control Systems

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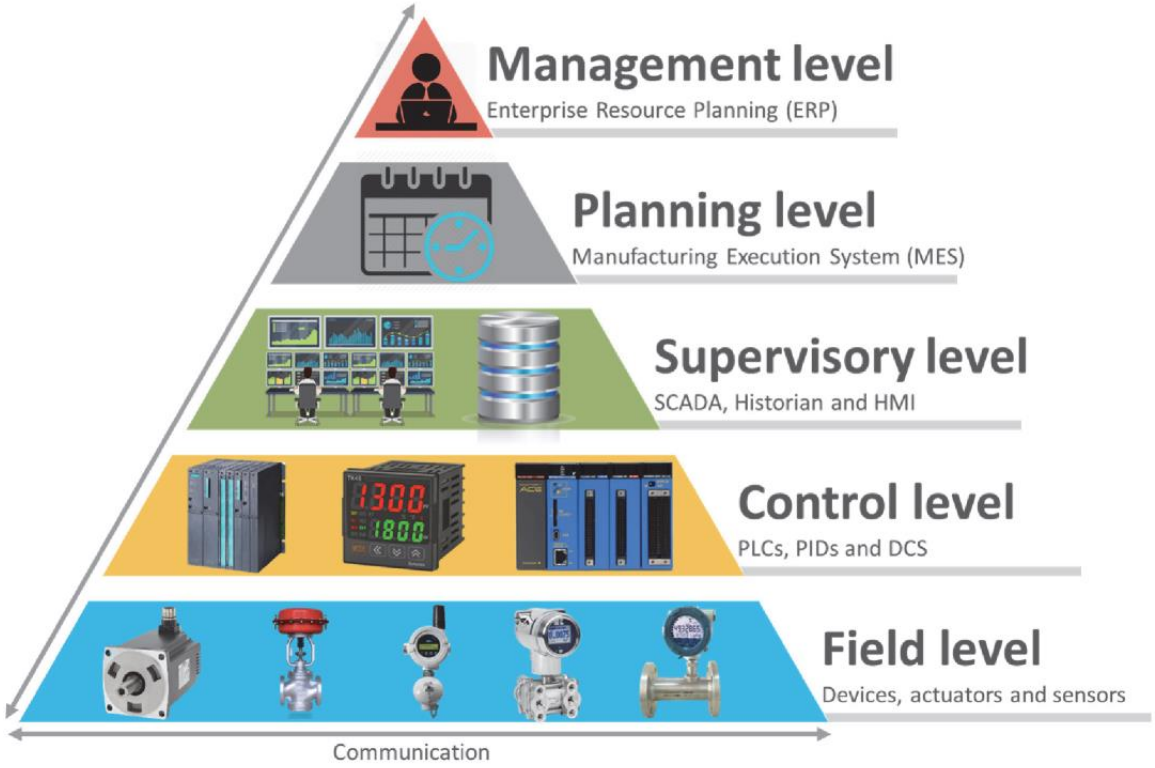
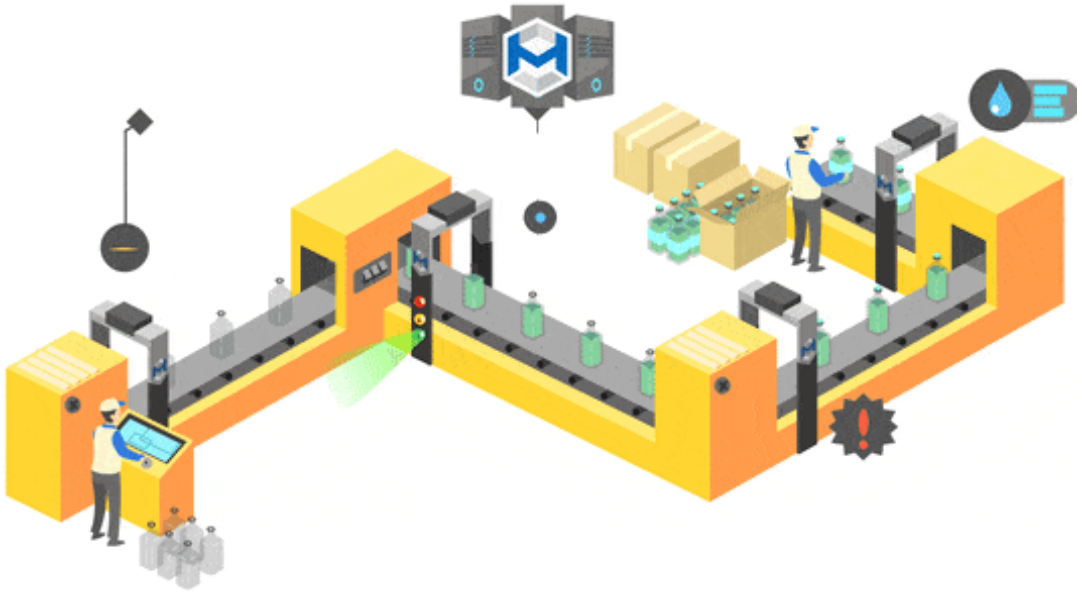
Industrial Automation Pyramid



The automation pyramid of a typical industrial control system.

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.



Example of industrial control system.

Source: https://heliconia.io/blog/industry-2/what-is-industry-4-0-1

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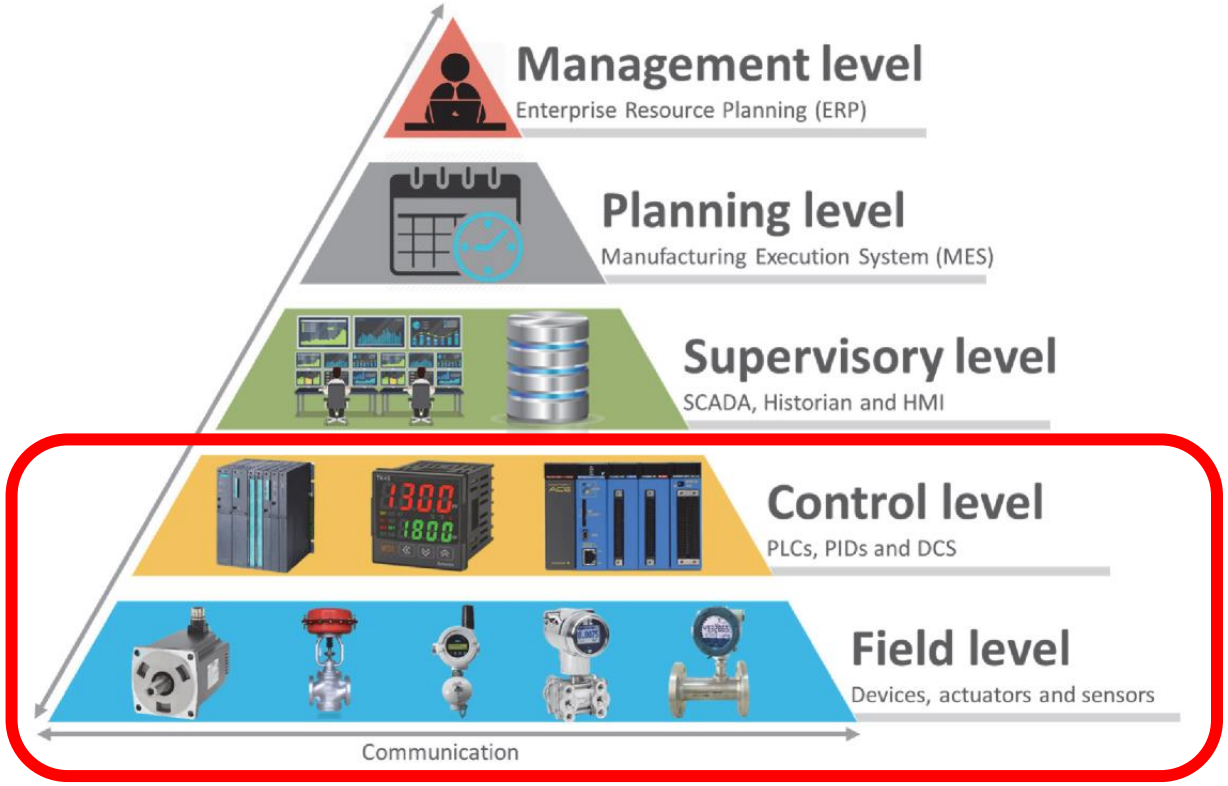
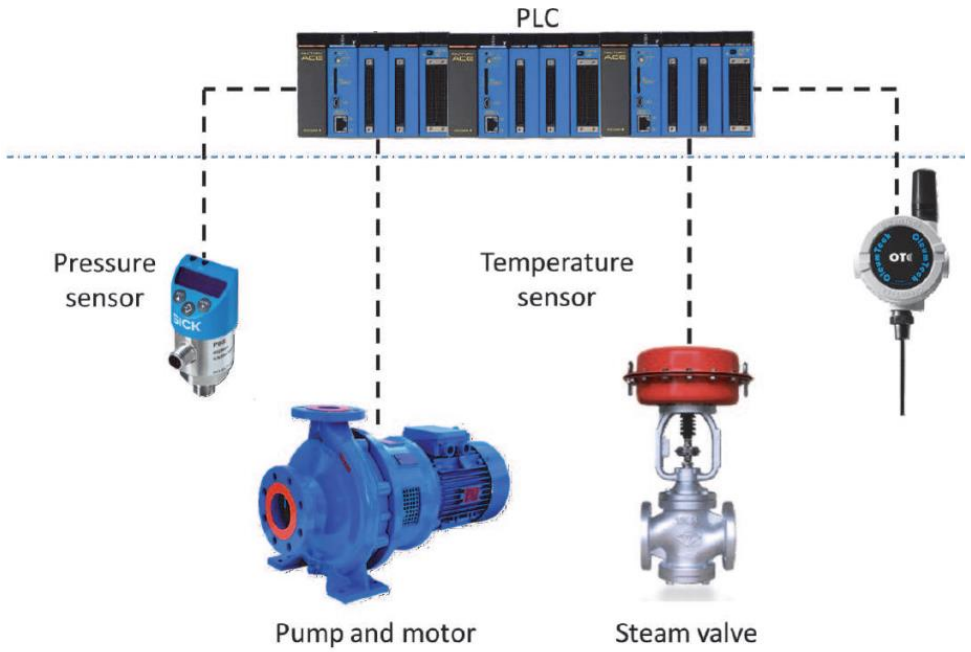
Industrial Automation Pyramid



The automation pyramid of a typical industrial plant.

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.



Example of the integration between field and control level.

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.

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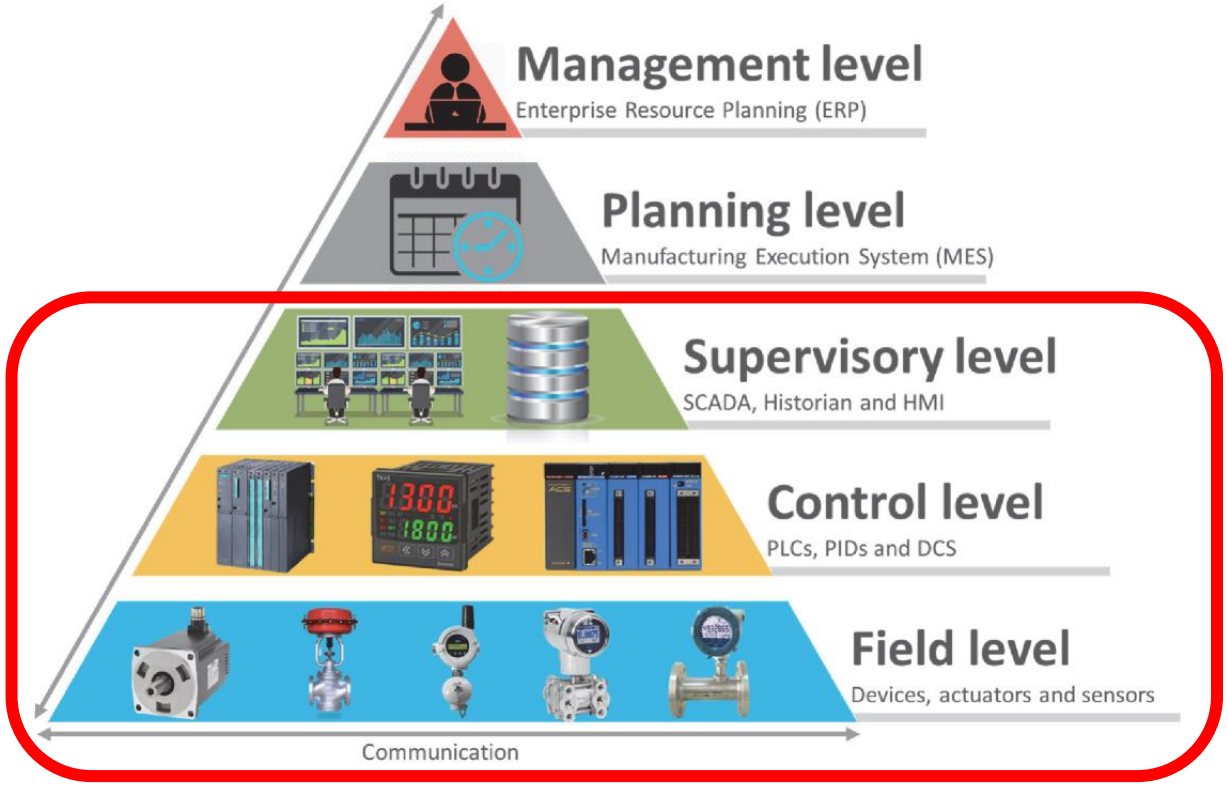
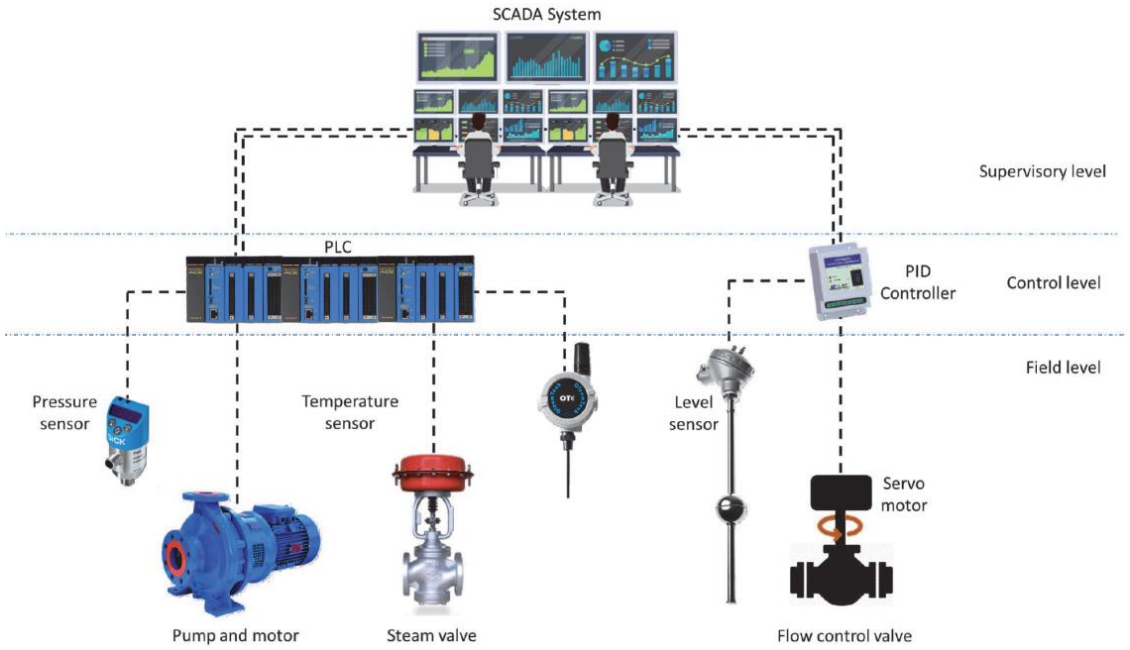
Industrial Automation Pyramid



The automation pyramid of a typical industrial plant.

Soure: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.



Relation between supervisory and control level.

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.

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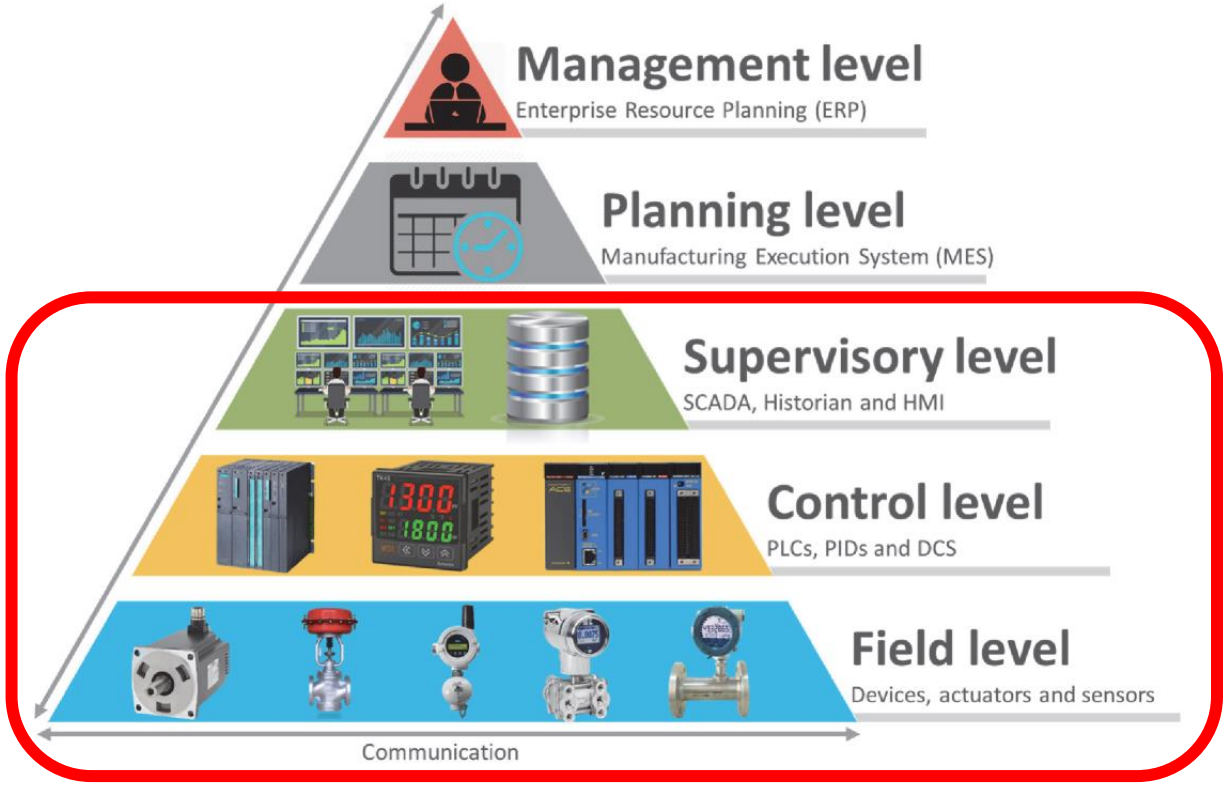
Industrial Automation Pyramid



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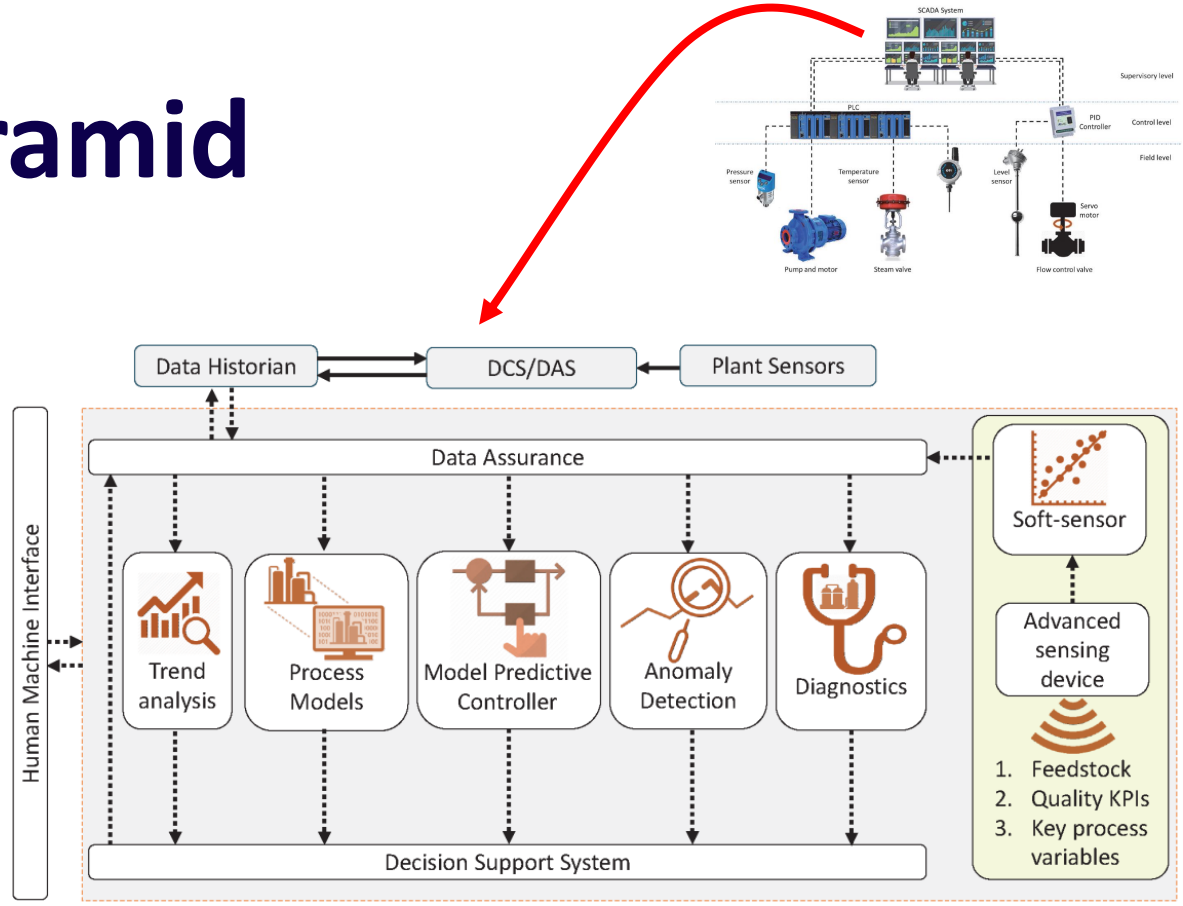

Example of an integrated framework for transforming acquired data into useful information to make/take good decisions

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.

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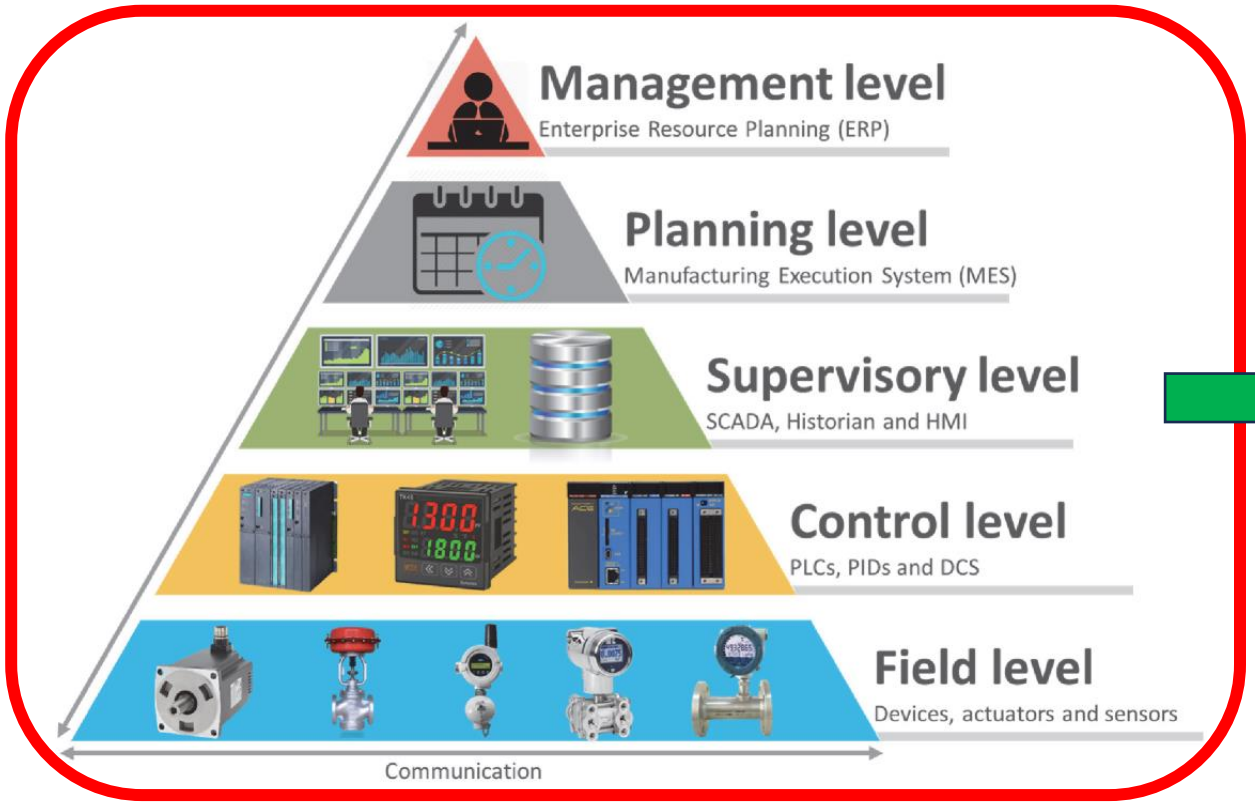
Industrial Automation Pyramid



The automation pyramid of a typical industrial plant.

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Industry 4.0

- 4th industrial revolution
- **the *movement*, the "trend", the place in time**
- it's about **transforming data** into **useful information** to **make/take proper decisions**

Technologies for transforming data into useful information

- **Industrial Internet of Things (IIoT)**
- **Digital Transformation** (artificial intelligence, cloud computing, systems integration, cybersecurity, big data & analytics, augmented reality, simulation, going paperless, unified data, etc.)

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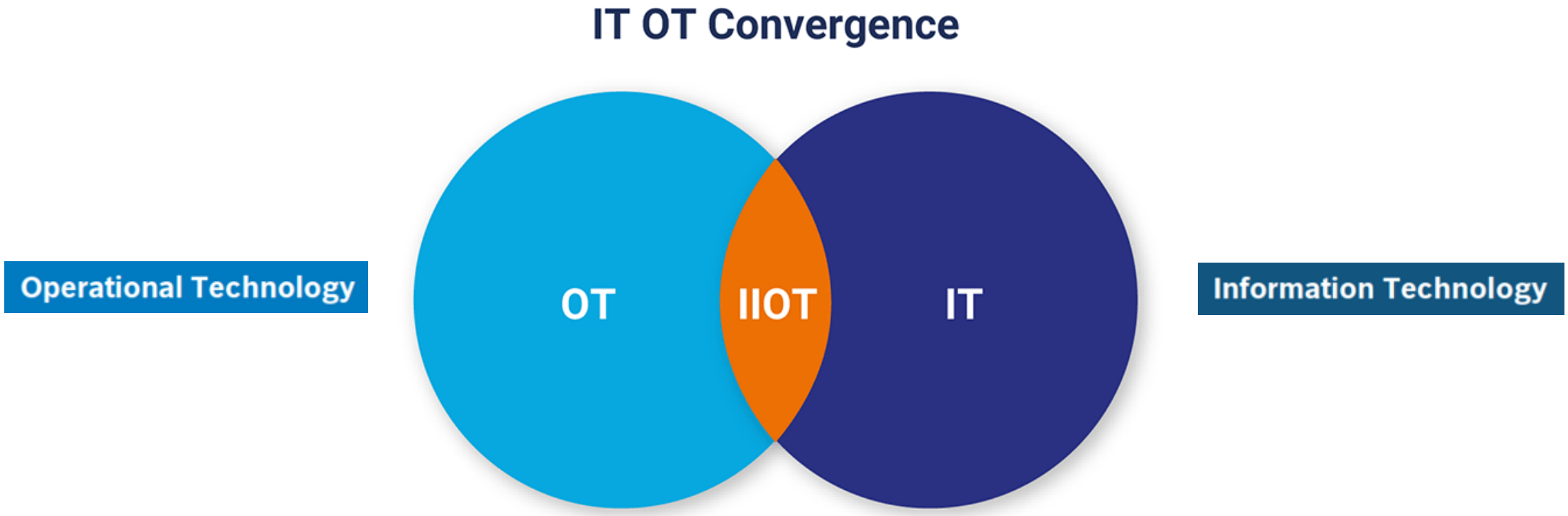
IIoT



Source: https://www.3pillarglobal.com/insights/how-does-iiot-bring-it-and-ot-together/

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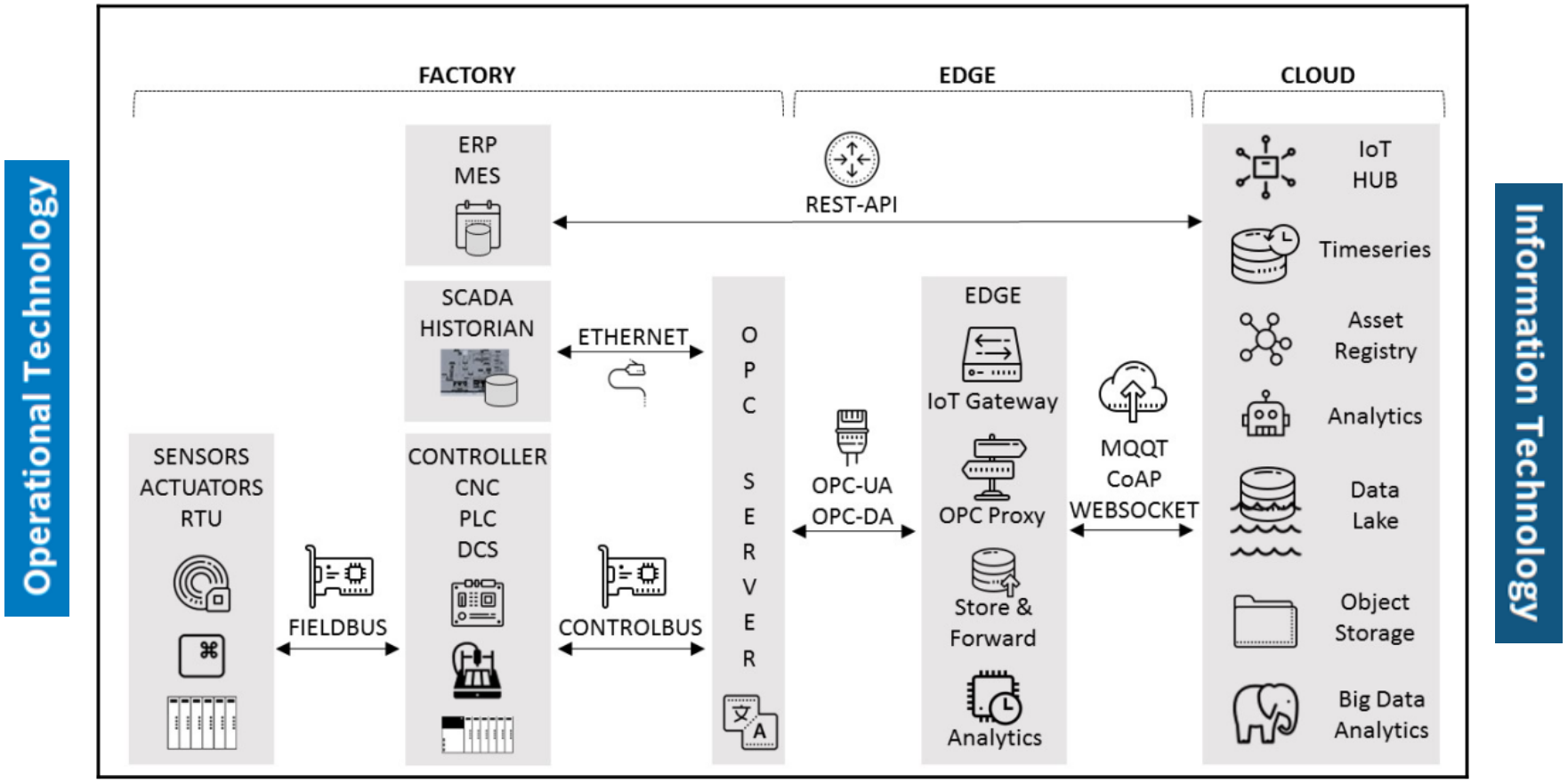
IIoT data flow



Source: https://www.packtpub.com/product/hands-on-industrial-internet-of-things/9781789537222

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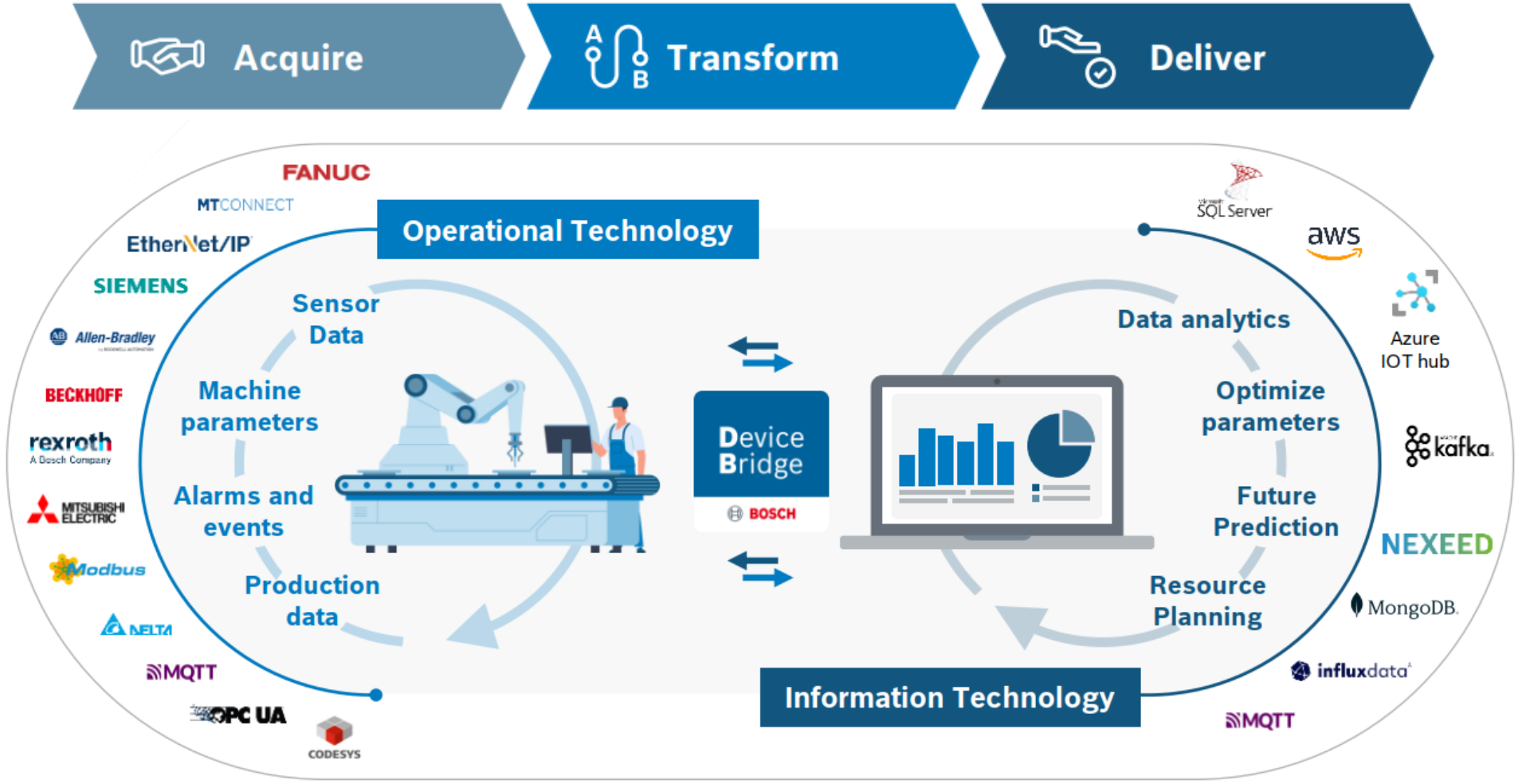
IIoT



Source: https://developer.community.boschrexroth.com/t5/Store-and-How-to/Bosch-DeviceBridge/ba-p/50243

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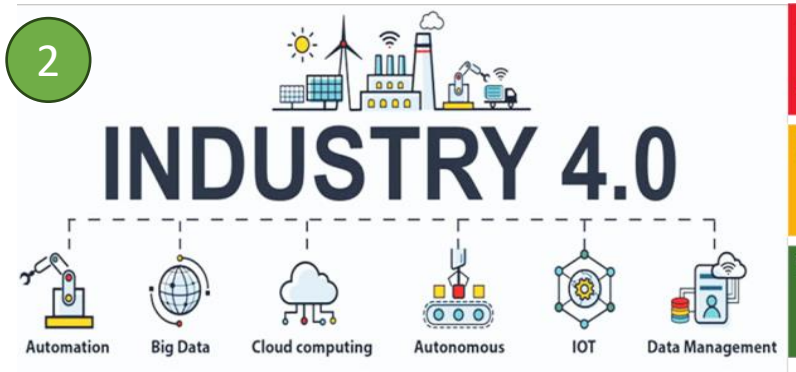
2



Sustainable development through Industry 4.0

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Sustainable development through Industry 4.0

SDG and eco-friendly concepts addressed by the Industry 4.0

- In September 2015, as part of the 70th session of the UN General Assembly adopted the **Sustainable Development Goals (SDGs)**
- The SDGs have been developed as a **corrective response to the gradual negative impact of our chosen way of life on the planet and all forms of life inhabiting it**
- However, they only define **"what to do?"** but we need to figure out **"how to do it?"**
- The **"how"** can be the **choices we make** when embracing the **technologies of Industry 4.0**

Source: https://www.linkedin.com/pulse/wield-industry-40-achieve-sustainable-development-goals-pankaj-jadhav

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Sustainable development through Industry 4.0

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Source: https://www.linkedin.com/pulse/wield-industry-40-achieve-sustainable-development-goals-pankaj-jadhav

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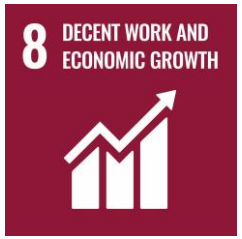
NextGEng

Sustainable development through Industry 4.0

SDG and eco-friendly concepts addressed by the Industry 4.0

- Optimization in energy use
- Promotion of renewable energy
- Reduction of fossil fuel use
- Development of new and more efficient practices and technologies



- Opportunity of economic growth
- New circular business models
- Reinsertion of waste as a valuable resource in the economy
- Higher and optimized productivity

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Sustainable development through Industry 4.0

SDG and eco-friendly concepts addressed by the Industry 4.0

- Development of cutting-edge technologies capable of promoting inclusive, reliable and sustainable production
- Higher and optimized productivity
- Efficient material and energy use

- Innovative technologies to promote inclusive, safer, and smart waste management
- Optimization of energy and resource use by the public sector

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Sustainable development through Industry 4.0

SDG and eco-friendly concepts addressed by the Industry 4.0

- Optimization of energy and resource use throughout supply chains
- Minimization of waste generation
- Reinsertion of waste as a valuable resource in the economy
- News consumption and behavioral patterns

- Climate mitigation
- Promotion of renewable energy

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Sustainable development through Industry 4.0

Towards sustainable development

- To achieve these targets **engineering know-how** and **green skills** are needed for **Next GEneration Engineers**
- **Engineering know-how** means that engineers should be aware that an **efficient material and energy use, minimization of waste generation, reduction of fossil fuel use**, etc. in the development process of **engineering product/system/service** influence/impact the environment in a good way on long term
- **Green skills** are the knowledge, abilities, values and attitudes needed to live in, **develop and support a sustainable and resource-efficient society**

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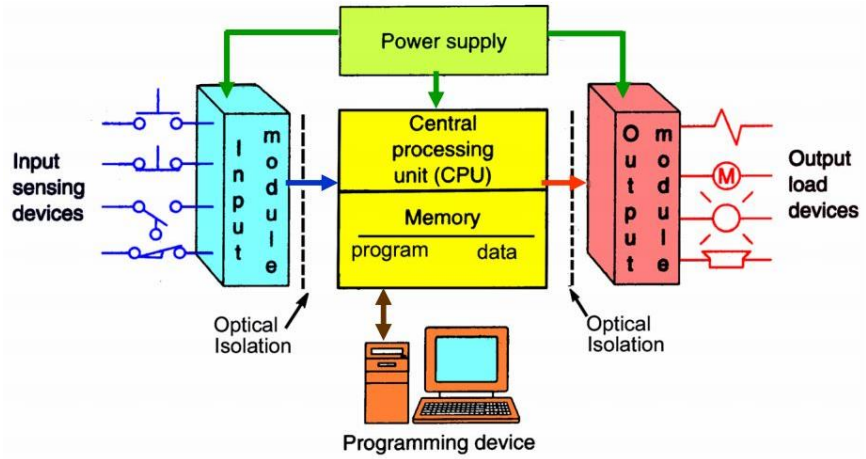
3 **PLC System**



Programmable Logic Controllers

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A brief history of PLC

In the late 1960s, in the context of the **problematic reliability of relay-based control circuits**, the General Motors Company (through the Hydramatic Division, 1968) developed the design specification for a programmable electronic system (Standard Machine Controller, 1968), intended as a **replacement of relay-based control systems**.

Richard “Dick” Morley, commonly referred to as the **Father** of the PLC

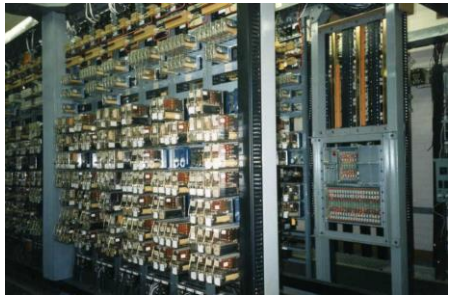
Source: https://www.youtube.com/watch?v=4BxOizho1UE

- Allen-Bradley
- Digital Equipment Corporation
- Century Detroit
- **Bedford Associates (Model 084)**
  - *later became Modicon which is owned nowadays by Schneider Electric*

Programmable Controller (PC)

**Allen Bradley (1971)*

Programmable Logic Controller (PLC)



Source: https://trimantec.com/blogs/t/plcs-explained

Source: https://plc4me.com/what-is-plc/

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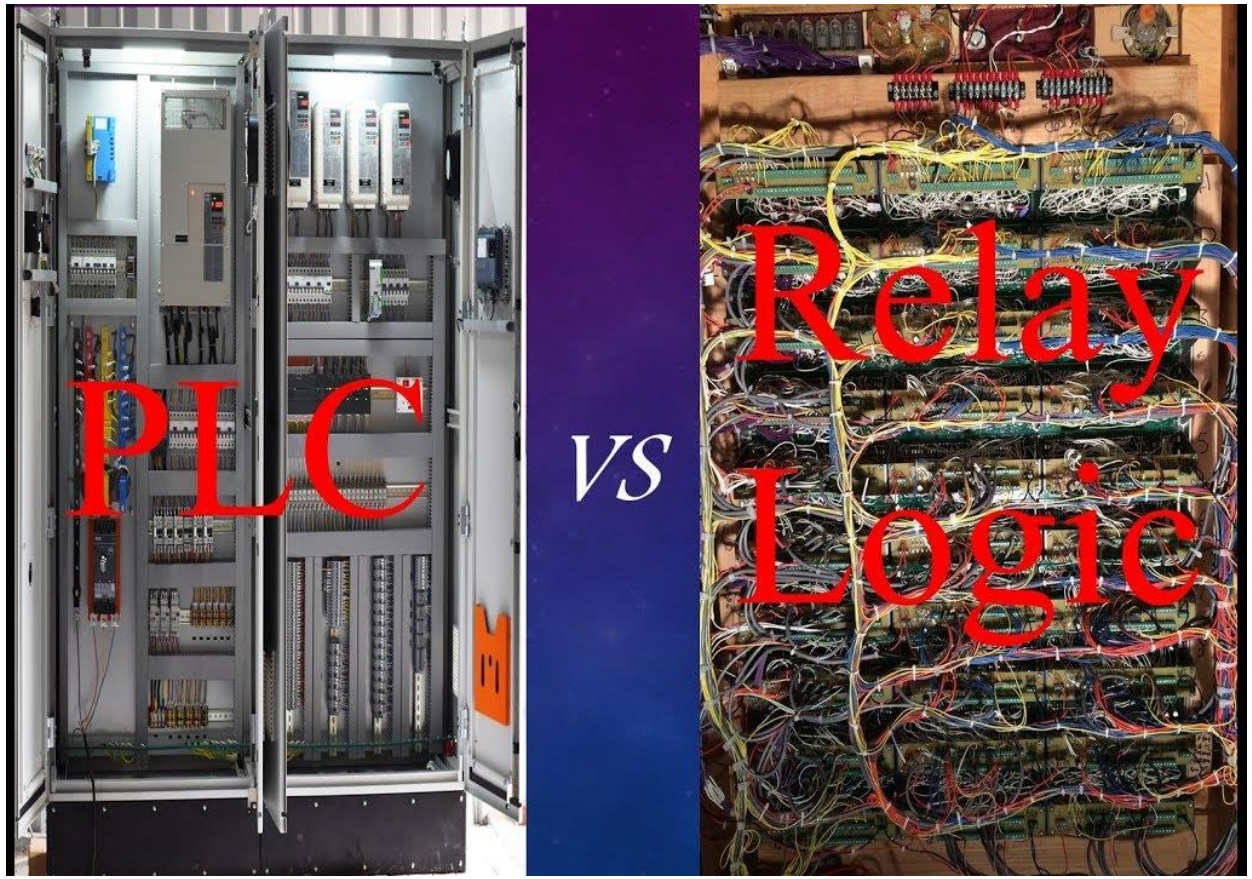
PLC vs Relay Logic



PLC	Relay Logic ("Click-Clack Logic")
Software logic using CPU and memory	Hardwired logic using relay switches
Modular, easier to program	Difficult to upgrade and maintain
Superior in these terms	Limited in terms of speed, size, complexity, and reliability
Special training is required	No special training is required
Additional features like PIDs, Timers, etc.	No additional features are possible
No limitation to the number of I/O	Limitation due to the complexity
"Current" technology	Dead technology

Source: https://www.youtube.com/watch?app=desktop&v=9PGPK5RMHEY

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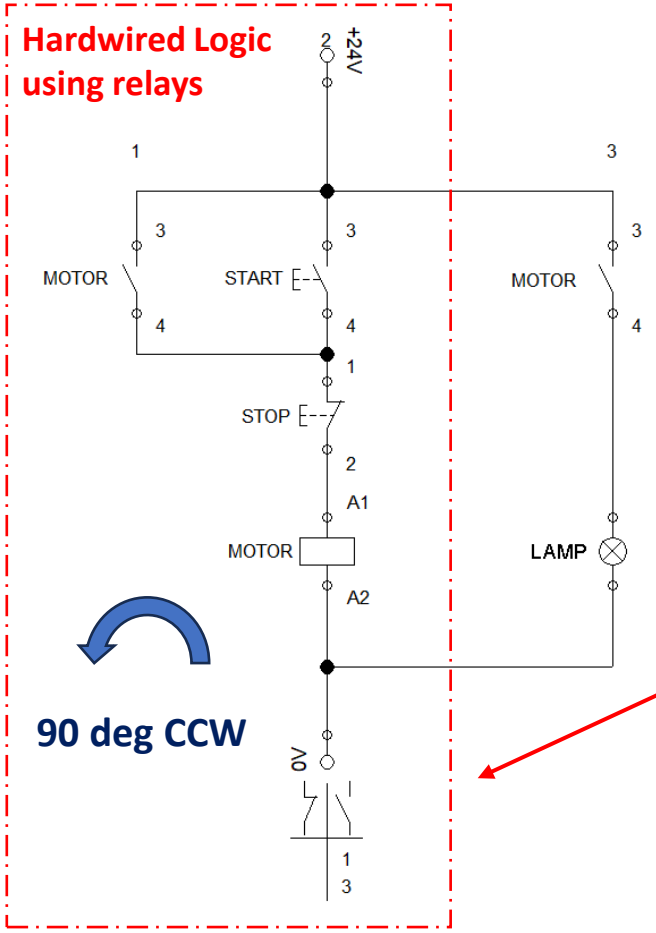
PLC vs Relay Logic

Hardwired Logic using relays

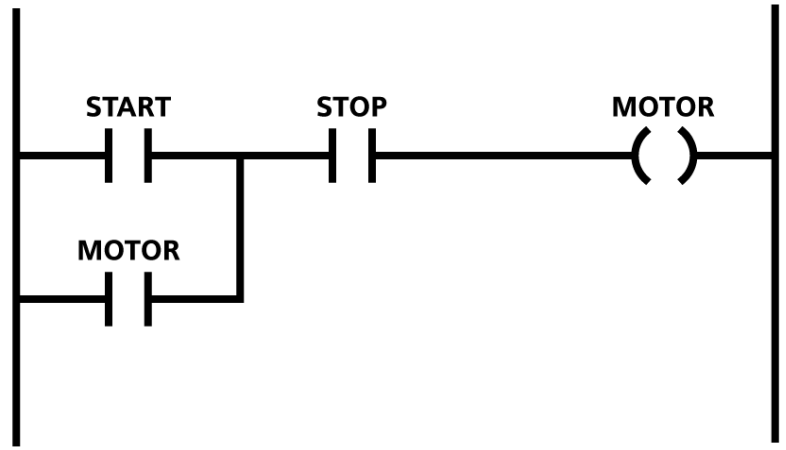


90 deg CCW

Hardwired logic → Software logic

Rotate 90 deg counterclockwise (CCW) the relay circuit to obtain the Ladder Diagram implemented in PLC

Software Logic - PLC implementation using Ladder Diagram (LD) programming language



Start / Stop Motor Control with Latching

Source: https://www.plcacademy.com/ladder-logic-tutorial-part-2/

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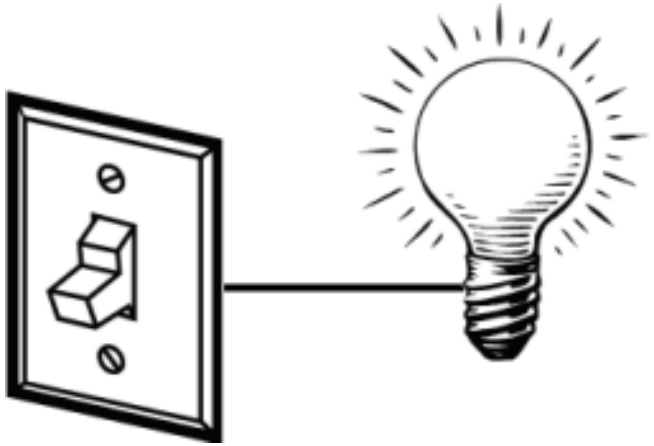
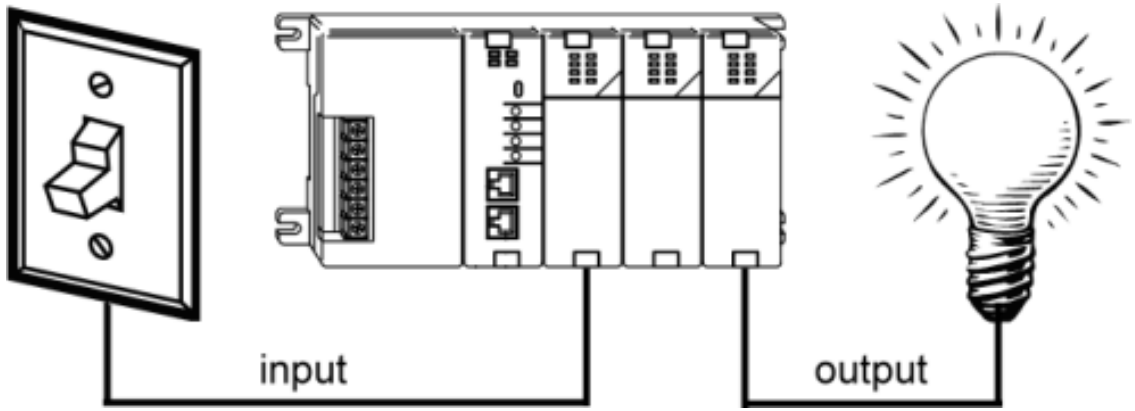
Definition of the PLC

*A **digital electronic system**, designed for use in an **industrial environment**, that uses a **programmable memory** for the internal storage of instructions necessary to implement specific functions (**logic, sequence, timing, counting, mathematical calculation**), to control through **digital and analog inputs and outputs** different types of **machines or processes*** (according to **IEC61131-1**).



A simple switch and a bulb example.

Source: https://www.plcdev.com/definition_of_a_plc



A simple switch and a bulb example with a PLC in the middle.

Source: https://www.plcdev.com/definition_of_a_plc

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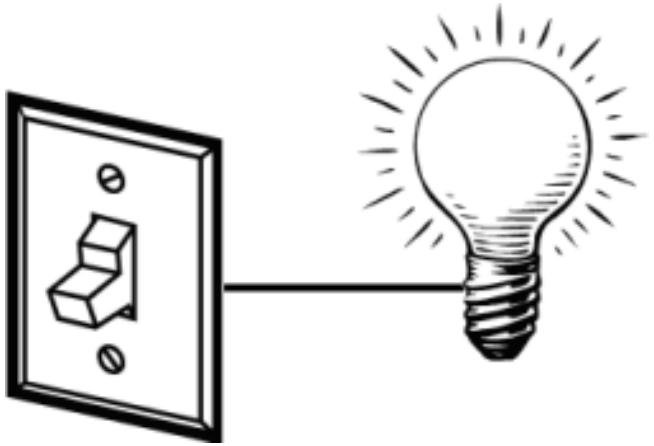
NextGEng

Definition of the PLC

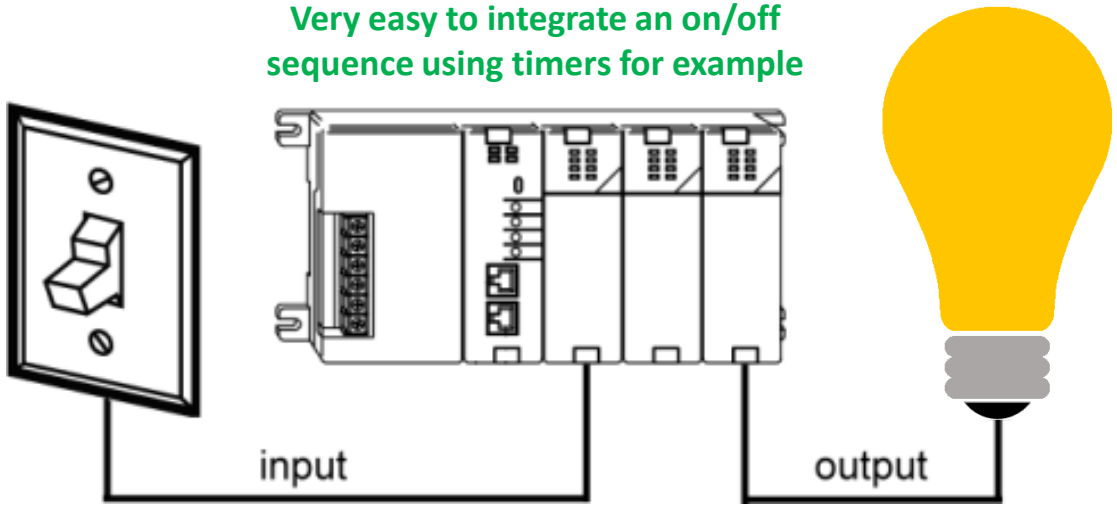
*A **digital electronic system**, designed for use in an **industrial environment**, that uses a **programmable memory** for the internal storage of instructions necessary to implement specific functions (**logic, sequence, timing, counting, mathematical calculation**), to control through **digital and analog inputs and outputs** different types of **machines or processes*** (according to **IEC61131-1**).



A simple switch and a bulb example.

Source: https://www.plcdev.com/definition_of_a_plc

Very easy to integrate an on/off sequence using timers for example



A simple switch and a bulb example with a PLC in the middle.

Source: https://www.plcdev.com/definition_of_a_plc

"Software" changes only!

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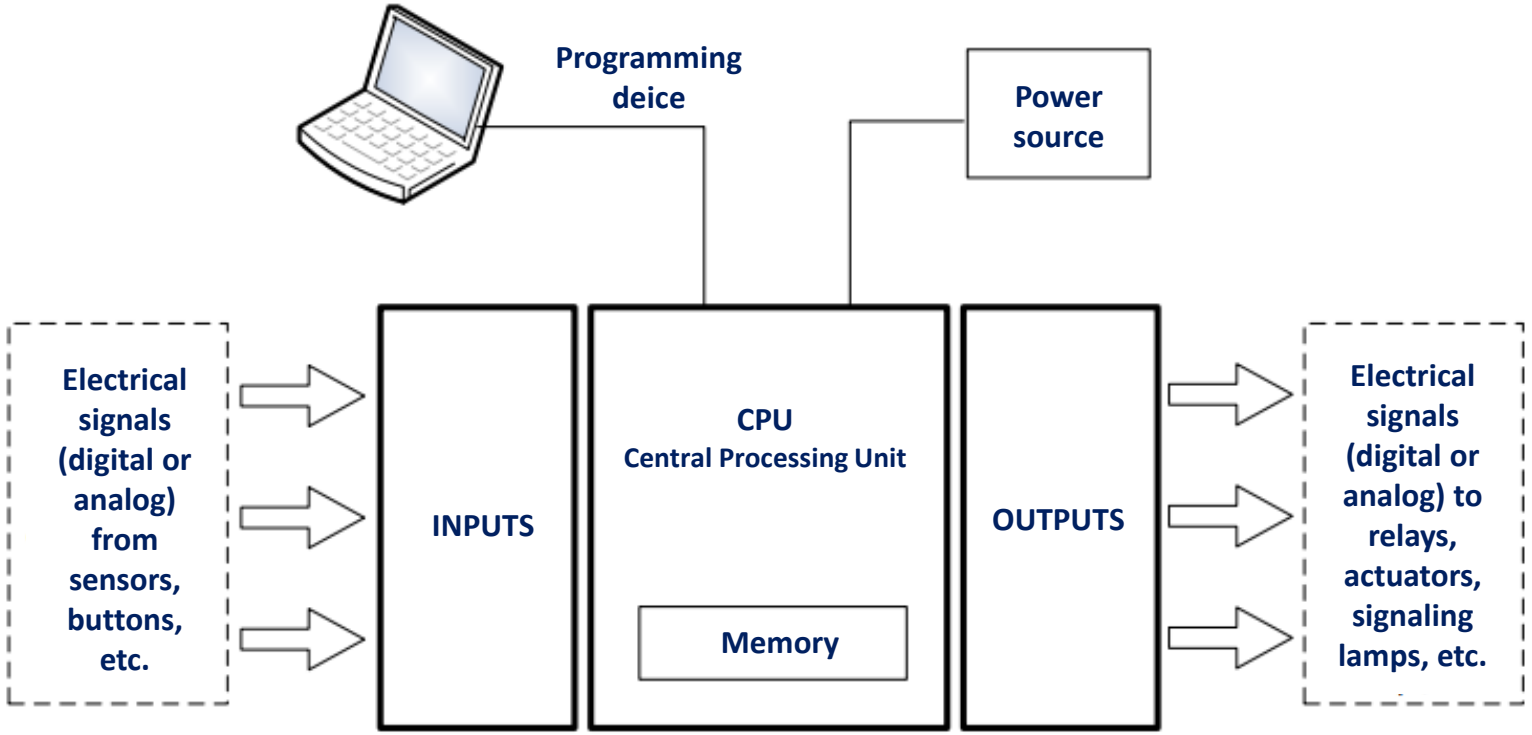
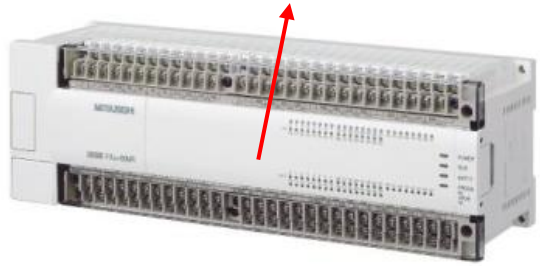
Architecture of the PLC



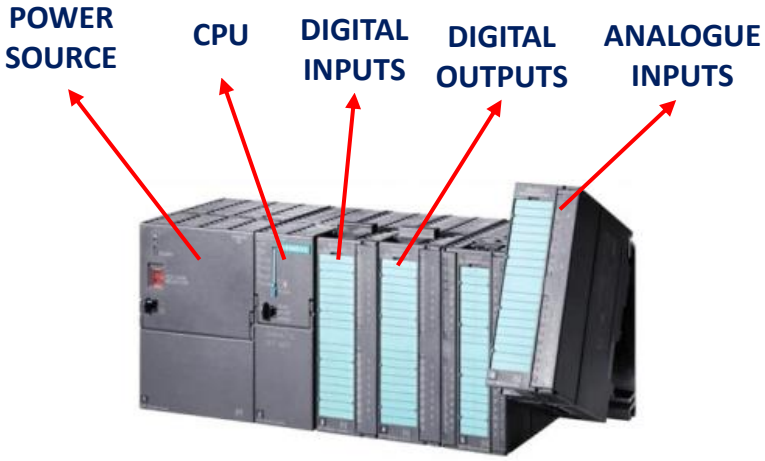
Architecture of the PLC – block diagram.

Everything in one compact/fixed form



a

Mitsubishi PLC. Compact/fixed I/O version.



b

Siemens PLC. Modular I/O version.

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PLC vs DCS

Distributed Control System (DCS) for process automation

Valmet DNA Distributed Control System

A distributed control system (DCS) is a type of control system architecture used in industrial settings to monitor and control various processes and equipment. It is designed to provide centralized control while distributing the control functions across multiple devices and locations.

Differences to a programmable logic controller (PLC)

In comparison, a programmable logic controller (PLC) is another common control system used in industrial automation. Unlike a DCS, a PLC is a standalone controller that is typically used for controlling specific machines or small-scale processes within a larger system. PLCs are often programmed using ladder logic or other programming languages specifically tailored for industrial automation.

Source: https://www.valmet.com/automation/distributed-control-system/

Characteristic	PLC	DCS
Replacement of…	Electromechanical Relays	Pneumatic & Single Loop Controllers
Products Manufactured…	"Things"	"Stuff"
Classic Application	Automotive	Refining
Type of Control	Discrete	Regulatory
Typical Configuration Languages	Ladder Logic	Function Block
Logic Execution Scan Time	20 ms and less	100 ms – 1 sec
Size / Footprint	Compact	Large

Source: https://www.linkedin.com/pulse/7-questions-consider-when-selecting-plc-scada-dcs-steve

Many similarities but different destinations

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4 **IEC 61131-3**

IEC 61131-3

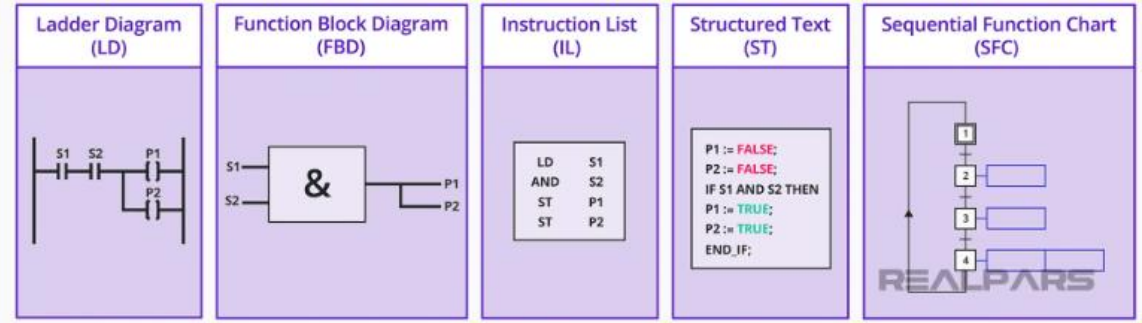
Ladder Logic Diagram (LD)

Function Block Diagram (FBD)

Instruction List (IL)

Structured Text (ST)

Sequential Function Chart (SFC)



IEC 61131-3

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Introduction to IEC 61131-3

- **1979** - an international working group was formed that consisted of PLC experts who were tasked to come up with a first draft for a **comprehensive PLC standard (IEC 61131)**
- **1982** - **first draft appeared** but it was decided that the standard was too comprehensive to be collected into a single document and the original working group was therefore split up into **five different working groups**, each of which dealt with its portion of the standard.
- The five parts of IEC 61131 consisted of:
  1. Part 1 - General information
  2. Part 2 - Hardware and requirements for testing
  3. **Part 3 - Programming languages**
  4. Part 4 - User interface
  5. Part 5 - Communications

Latest version of standard includes 10 parts !!!

Source: https://pas-sa.co.za/2023/03/24/what-are-the-standards-for-plc-programming/

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Introduction to IEC 61131-3

- **March 1993** - the first standard on programming languages (Part 3) was published and was designated **IEC 61131-3**.
- **2002** – the **2nd edition** of IEC 61131-3 was published
- **2013** – the **3rd edition** of IEC 61131-3 was published (**current one**)
- **June 2024** – forecast publication date for the **4th edition** of the standard
- The standard **IEC 61131-3** describes various PLC programming languages:
  1. Structured Text—ST **(very popular nowadays)**
  2. Function Block Diagram—FBD **(popular in DCS systems)**
  3. Ladder Diagram—LD **(the first PLC programming language)**
  4. **Instruction List—IL (becomes obsolete)**
  5. Sequential Function Chart—SFC **(good for sequential control)**

Source: https://pas-sa.co.za/2023/03/24/what-are-the-standards-for-plc-programming/

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Introduction to IEC 61131-3

- **IEC 61131-3** is currently followed to a greater or lesser degree by most of the **major PLC manufacturers**
- The standard defines a comprehensive set of ***guidelines***
- IEC 61131-3 standard is **not an absolute standard** and manufacturers who want to adopt the standard do not need to follow the standard ***ad litteram***
- This means that there **can still be relatively large differences** with respect to programming, user interface, graphics, etc. between the various manufacturers' systems
- LD, SFC, and FBD are **graphical programming languages**, while IL and ST are **text-based languages**

Source: https://pas-sa.co.za/2023/03/24/what-are-the-standards-for-plc-programming/

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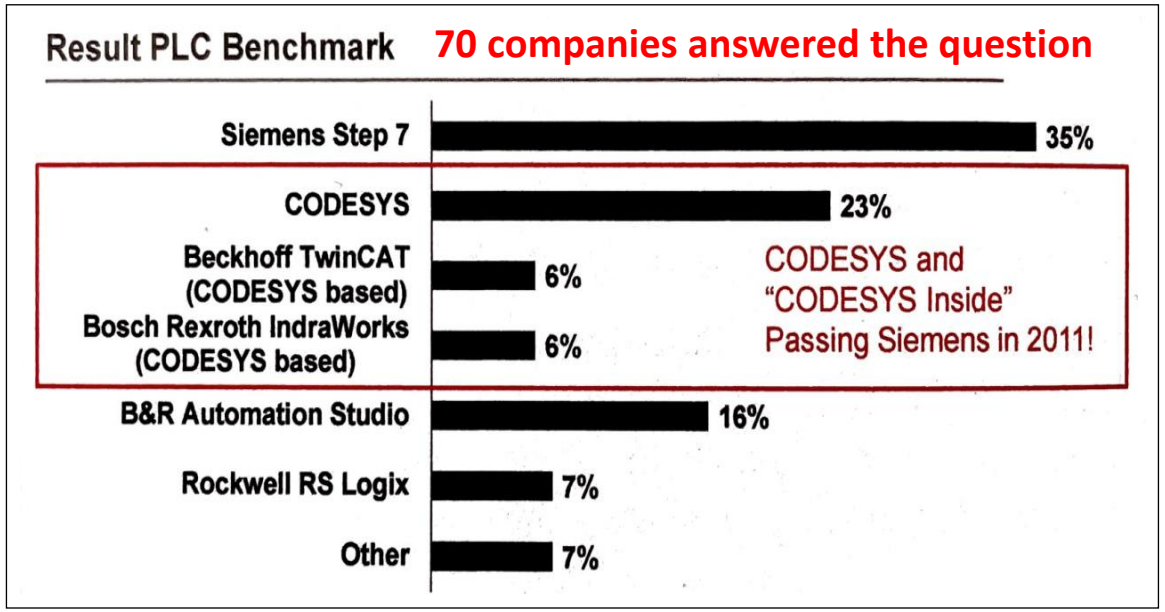
IEC 61131-3 and PLCs manufacturers

“Which development system do you use for programming your control system?”

Survey of “Computer & AUTOMATION” and two German Universities, 2011



Source: The Book of CODESYS: The ultimate guide to PLC and Industrial Controls programming with the CODESYS IDE and IEC 61131-3.

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SIEMENS and IEC 61131-3

How do you program the PLC with STEP 7 (TIA Portal) in compliance with the IEC 61131-3 standard?

Entry | Associated product(s)

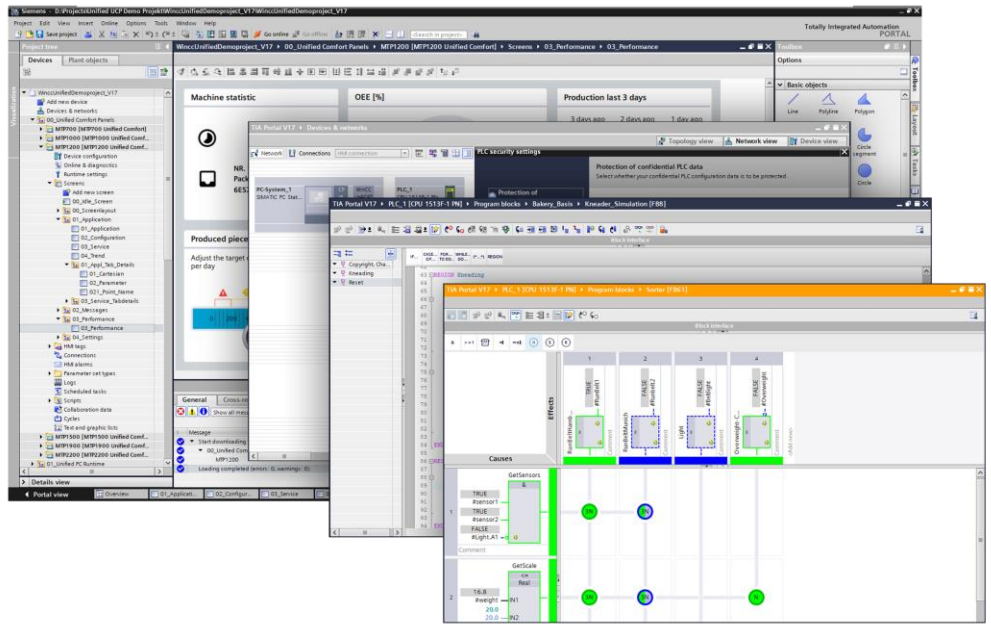
The attached PDF document gives you detailed information.

Description
The programming languages of SIMATIC STEP 7 (TIA Portal) meet the requirements of IEC 61131-3. The IEC 61131-3 standard is the only standard valid worldwide for the programming languages of programmable logic controllers.
The following table gives you an overview:

STEP 7 (TIA Portal)	IEC 61131-3 languages
Instruction List (AWL/STL)	Corresponds to IEC 61131-3 language "AWL/IL"
Ladder Logic KOP/LAD	Corresponds to IEC 61131-3 language "KOP/LD"
Function Block Diagram FUP/FBD	Corresponds to IEC 61131-3 language "FUP/FBD"
Structured Control Language SCL	Corresponds to IEC 61131-3 language "ST"*
S7-GRAPH	Corresponds to IEC 61131-3 language "AS/SFC"*

Detailed information is available in the "IEC_61131_Compliance" file.

PDF IEC_61131_compliance_e.pdf (122 KB)



Source: https://support.industry.siemens.com/cs/document/8790932/iec-61131-3-and-simatic-s7?dti=0&lc=en-RO

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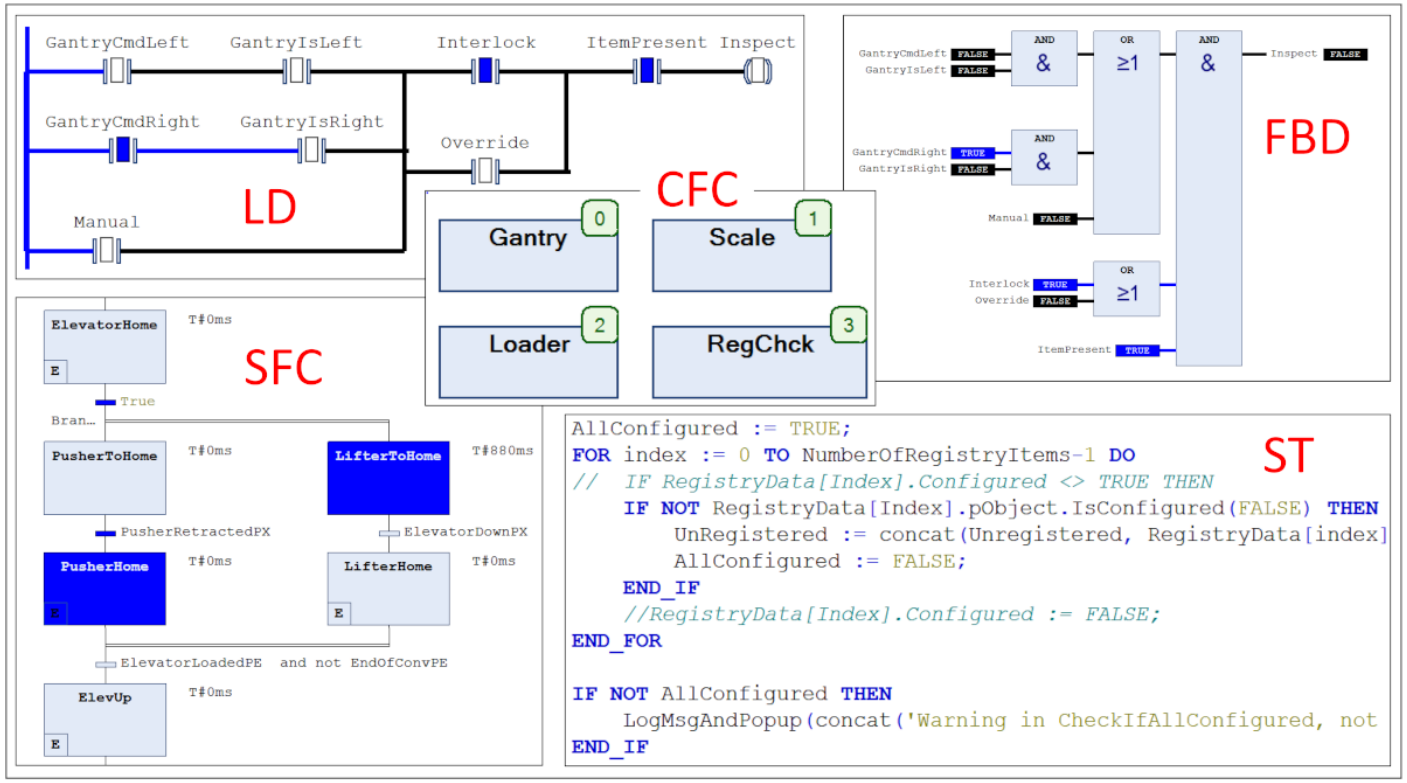
CODESYS and IEC 61131-3



Source: https://www.codesys.com/news-events/publications/article/which-iec-61131-3-programming-language-is-best-part-1.html

PLC – based on CODESYS

- ABB (Switzerland)
- Schneider Electric (France)
- Beckhoff (Germany)
- Bosch (Germany)
- Festo (Germany)
- Lenze (Germany)
- IFM (Germany)
- Mitsubishi (Japan)
- HoneyWell (USA)
- Delta (Taiwan)

PLC – pure CODESYS

- Wago (Germany)
- Kendrion-Kunke (Netherland)
- Phoenix Contact (Germany)
- Hitachi (Japan)
- Eaton (USA)

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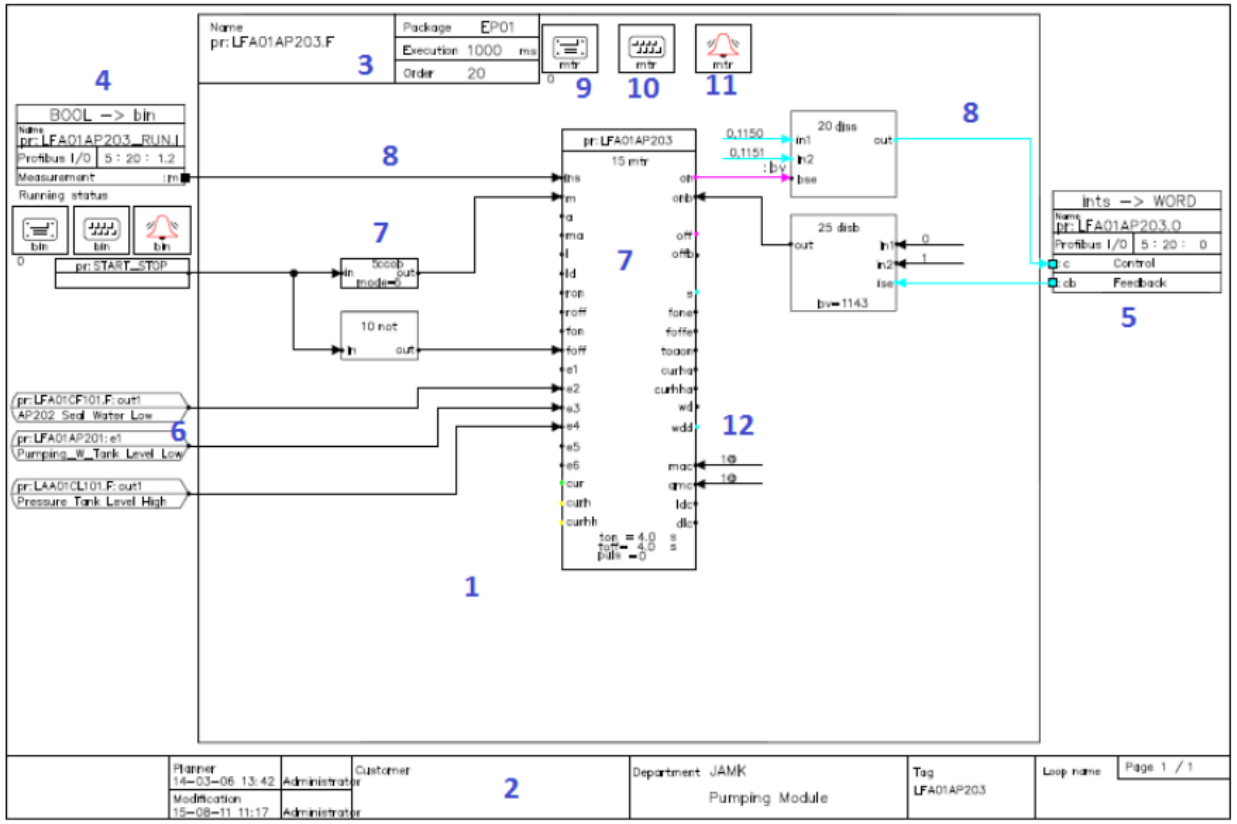
Valmet DNA and IEC 61131-3

- **Valmet DNA Engineering Function Block CAD**

  - ✓ tool is used for designing function block diagrams (FBDs) for process control loops, sequences, links, etc.

  - ✓ Function block CAD (FbCAD) is standardized by Valmet itself, **which must be distinguished from the language defined in IEC 61131-3.**

Function Block Diagram—FBD implementation



Source: https://www.theseus.fi/bitstream/handle/10024/107712/Thesis.pdf?sequence=1

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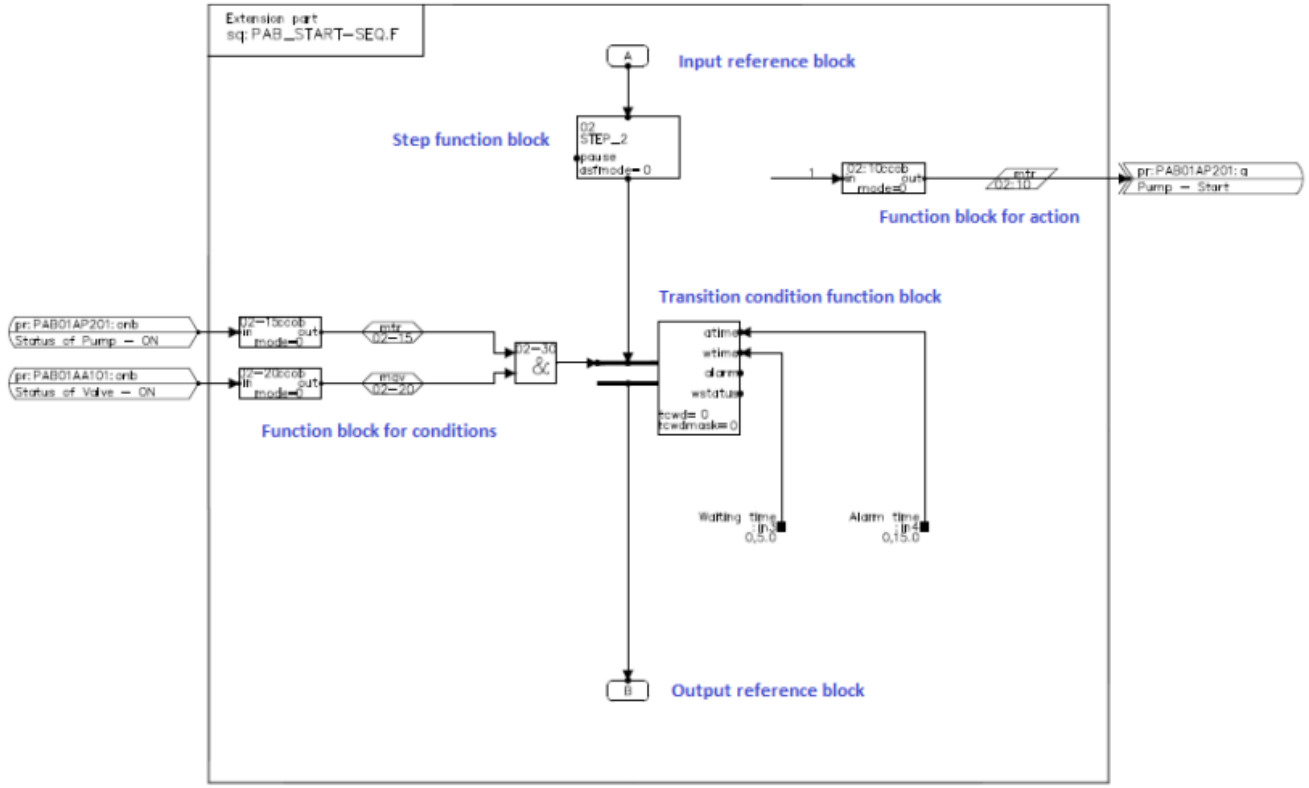
Valmet DNA and IEC 61131-3

- **Valmet DNA Engineering Sequence CAD**

  - ✓ engineering tool that is used in designing sequence diagrams
  - ✓ Sequence CAD supports maximum of 52 steps per one SFC
  - ✓ It's not possible to create conditional or parallel branches with sequence CAD so **is not fully IEC 61131-3 compliant**

Sequential Function Chart—SFC implementation



Source: https://www.theseus.fi/bitstream/handle/10024/107712/Thesis.pdf?sequence=1

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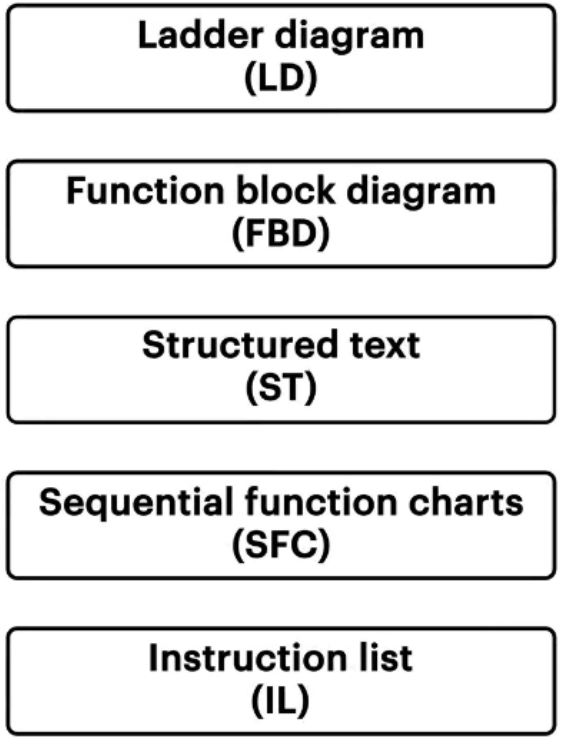
Which Language is Best for PLC Programming?



Source: https://www.youtube.com/watch?v=NxMdpr9SsdA

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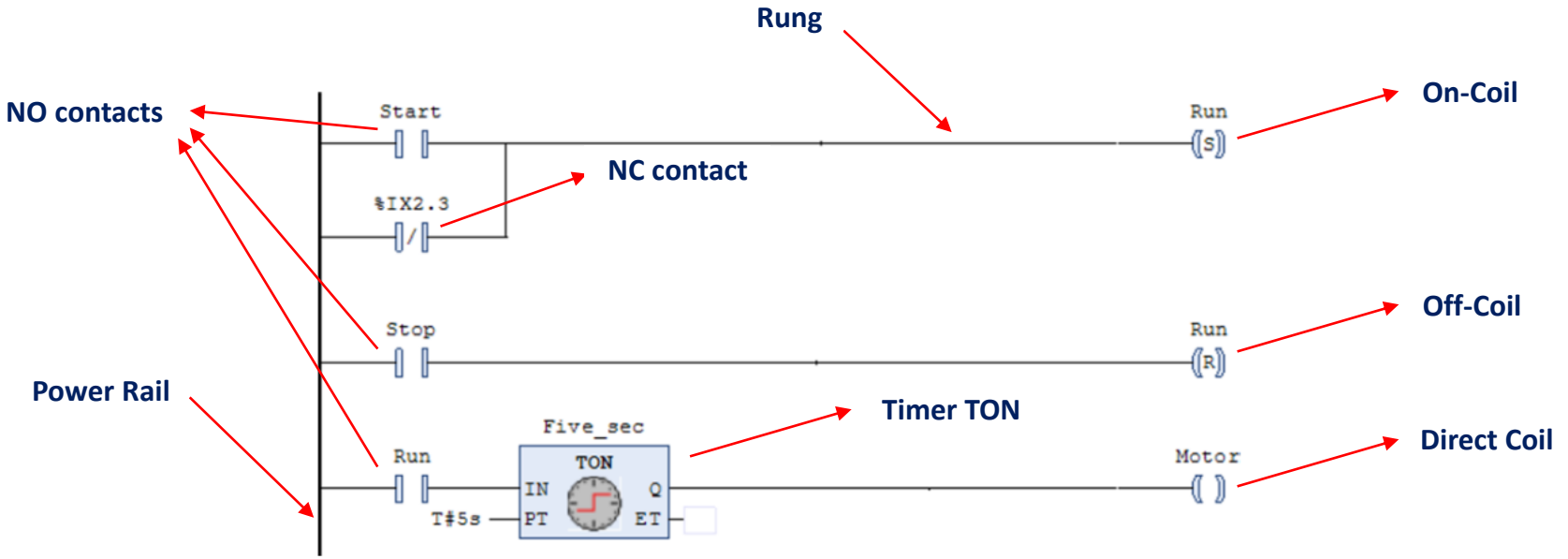
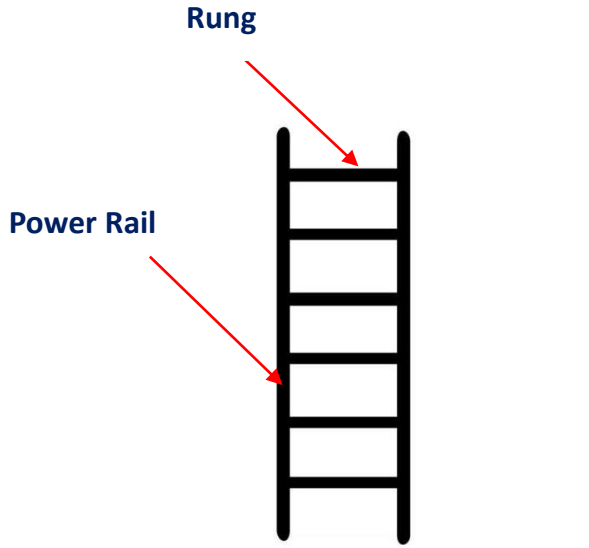
Ladder Diagram (LD)

- ✓ LD **is still used to a large degree** by many PLC programmers and manufacturers
- ✓ It is **simple to understand** because it's base upon traditional **electrical wiring diagrams (relay diagrams)**
- ✓ The most basic elements of LD are **contacts (Normally open - NO and Normally closed - NC)** and **coils** but can include also advanced function blocks such as edge detection, timers, counters, etc.



Example of program code in LD (CODESYS implementation).



Graphical similarities with a "real" ladder.

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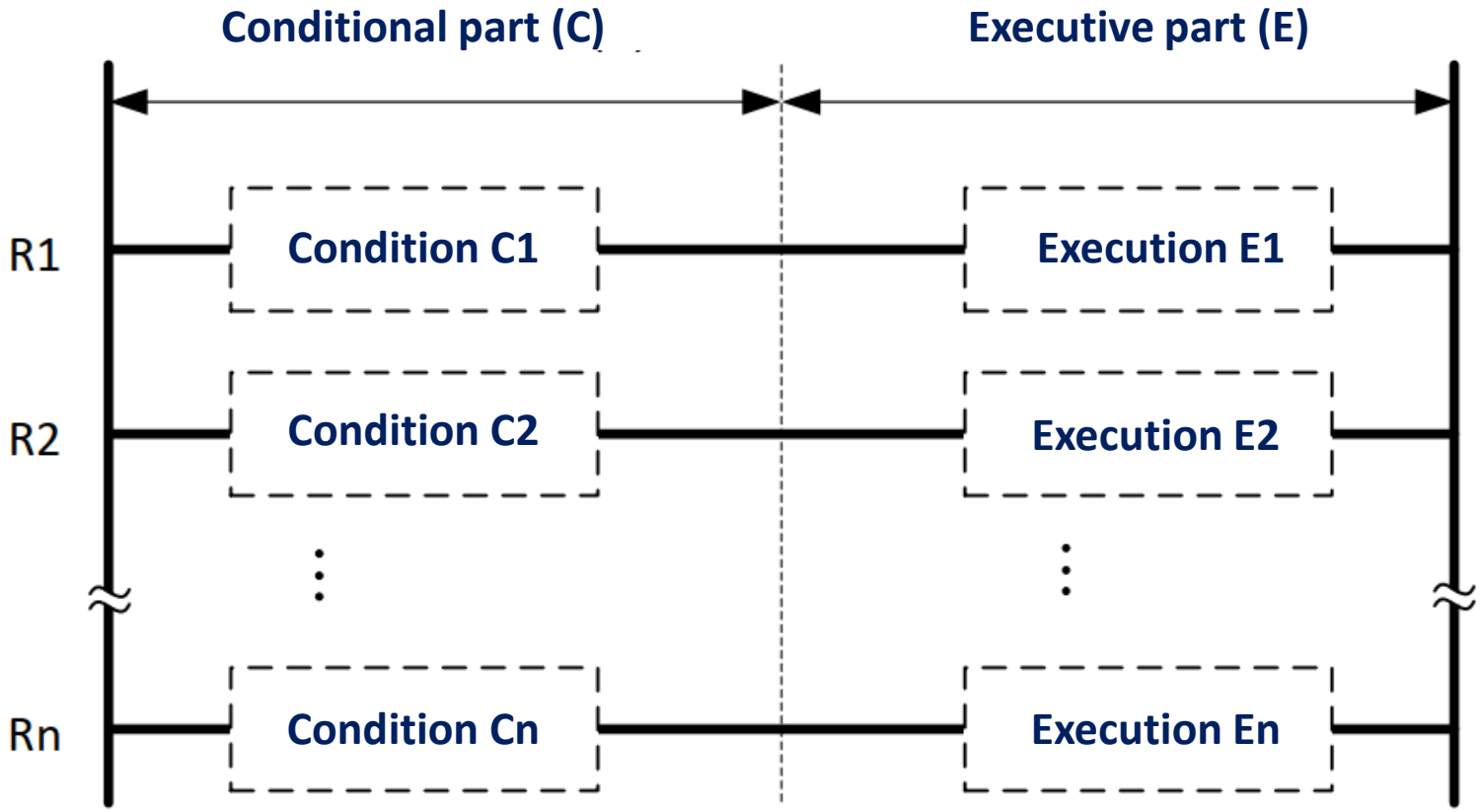
Structure of LD programs



General structure of a LD program.

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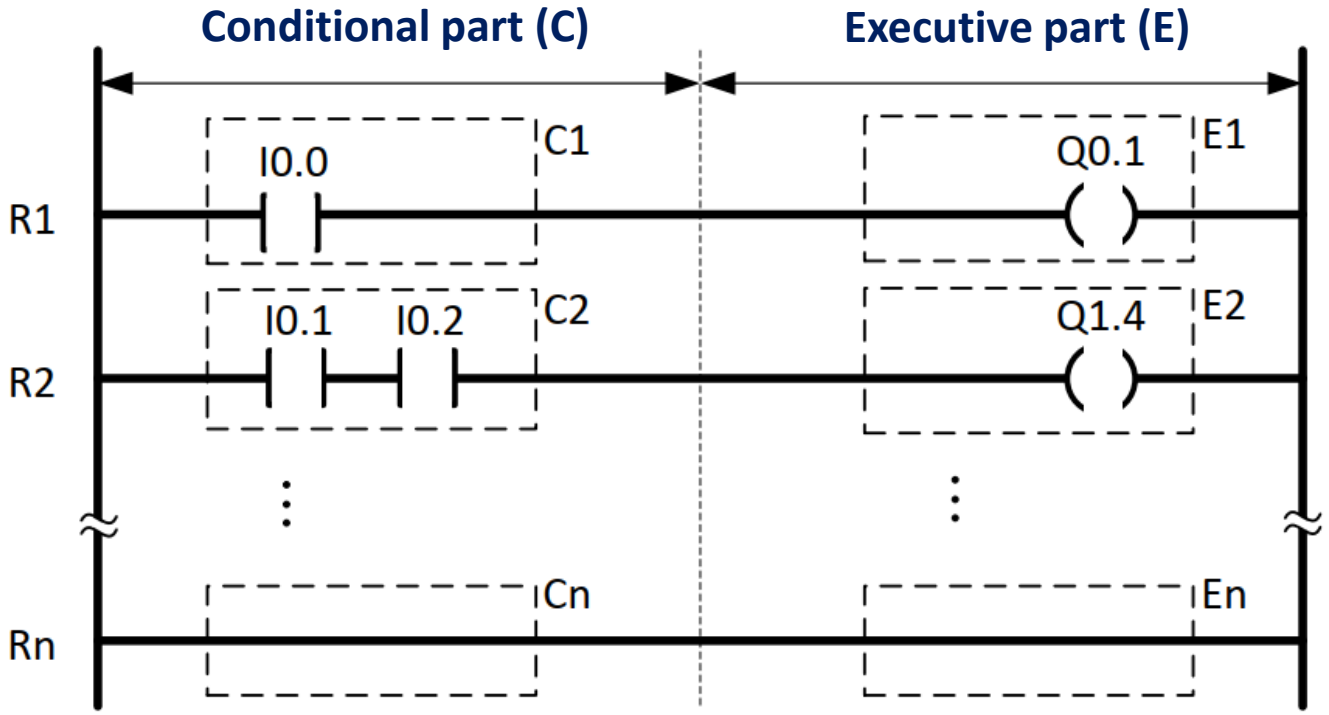
Structure of LD programs



a

Equivalent textual language

IF *I0.0* ***THEN*** *Q0.1*

IF *(I0.1* ***AND*** *I0.2)* ***THEN*** *Q1.4*

⋮

IF *Cn* ***THEN*** *En*

b

General structure of a LD program.

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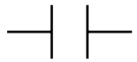
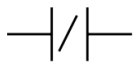
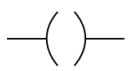
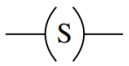
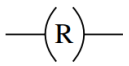
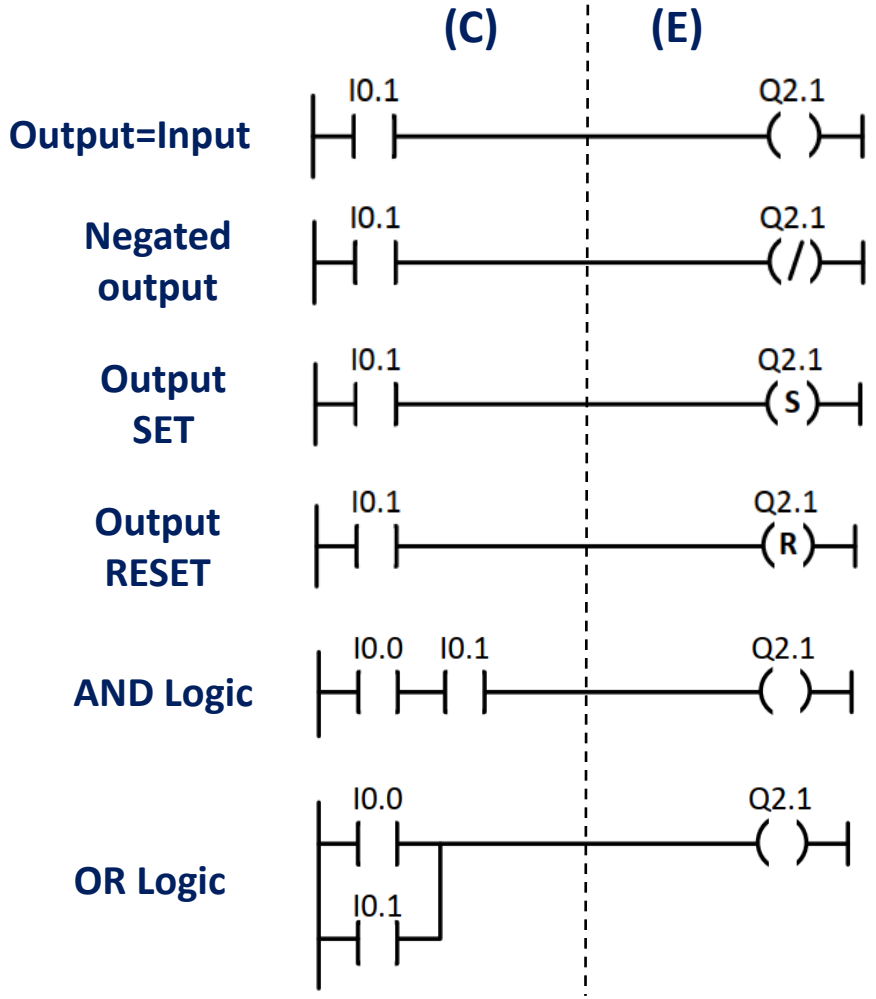
Main symbols that are used in LD

Designation		Symbol	Function
Test element	Normally open contact		The contact closes when the associated Boolean object becomes TRUE
	Normally closed contact		The contact closes when the associated Boolean object becomes FALSE
Connections	Horizontal		To connect elements in series
	Vertical		To connect elements in parallel
Action element	Direct coil		The associated Boolean object is set to the same state as the state of the left side of the coil
	On-coil		The associated Boolean object is set to TRUE when the state of the left side of the coil is TRUE
	Off-coil		The associated Boolean object is set to FALSE when the state of the left side of the coil is TRUE

Source: Programmable Logic Controllers: A Practical Approach to IEC 61131-3 using CoDeSys.

Examples



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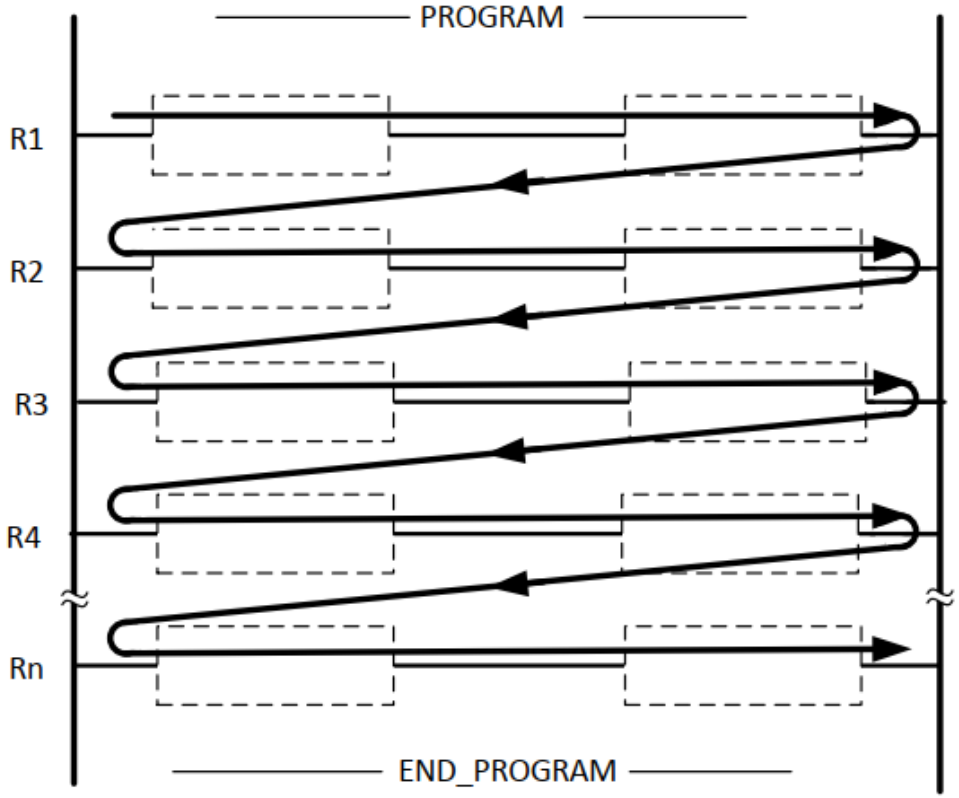
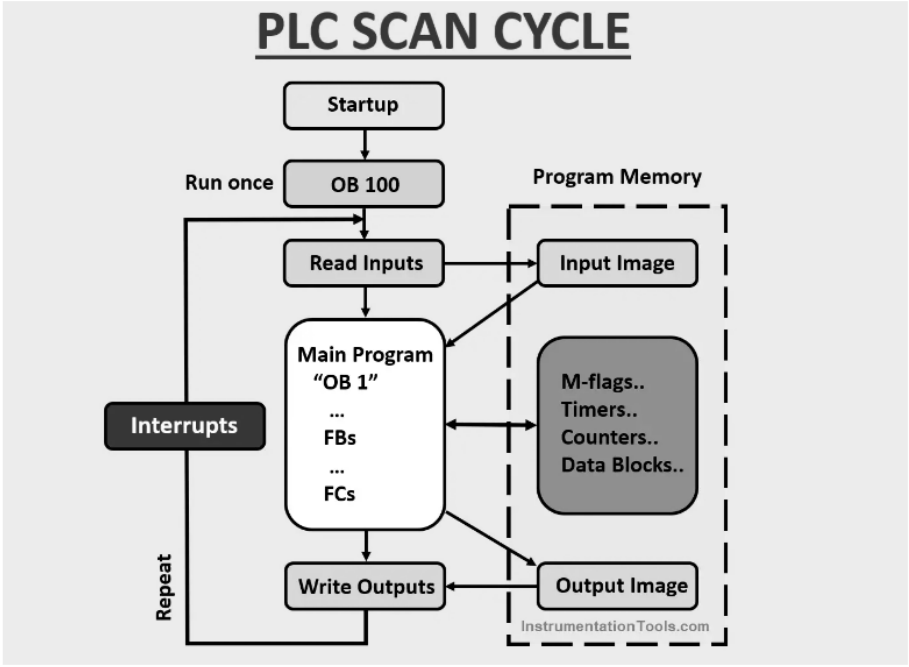
PLC scan cycle – order of execution





PLC scan cycle.

Source: https://instrumentationtools.com/understanding-the-scan-cycle-of-siemens-plc/

How a LD diagram is scanned by a PLC.

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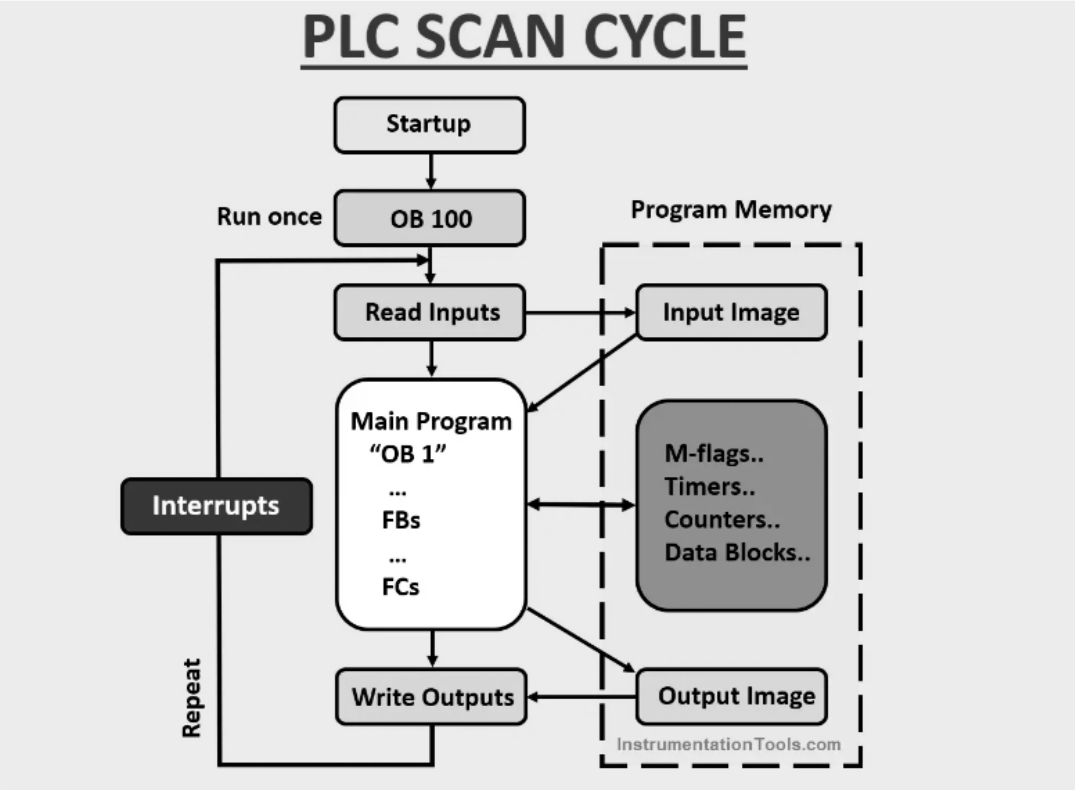
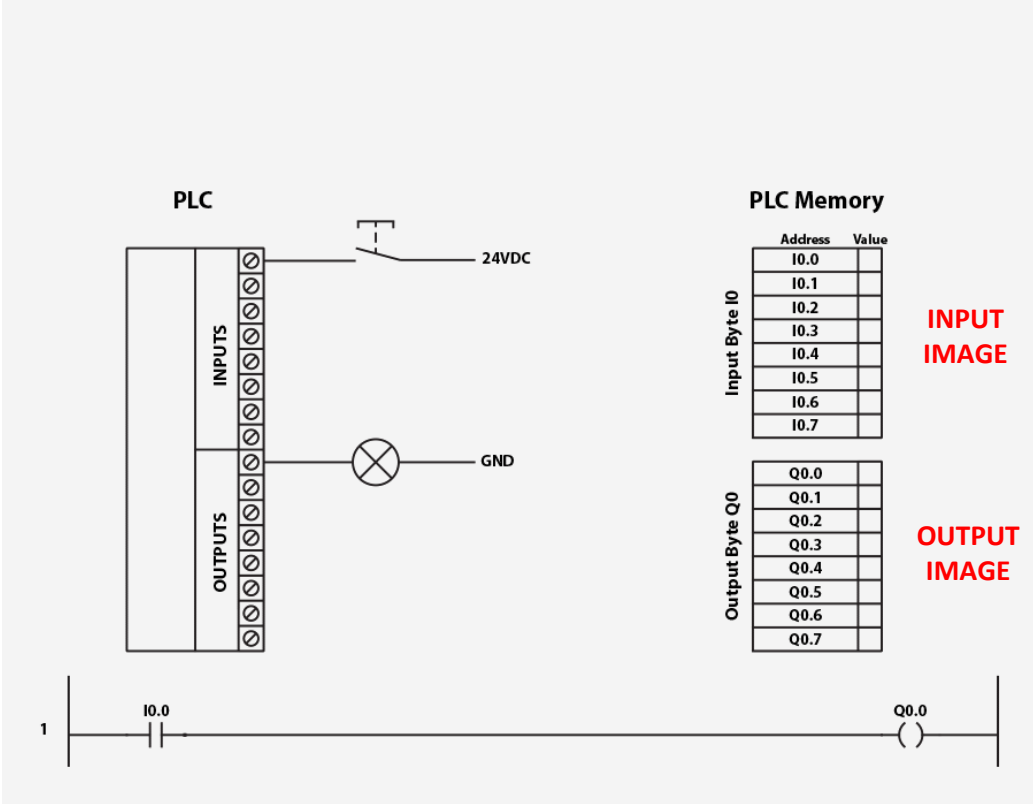
PLC scan cycle – order of execution



PLC scan cycle.

Source: https://instrumentationtools.com/understanding-the-scan-cycle-of-siemens-plc/



Order of execution.

Source: https://www.plcacademy.com/ladder-logic-tutorial/

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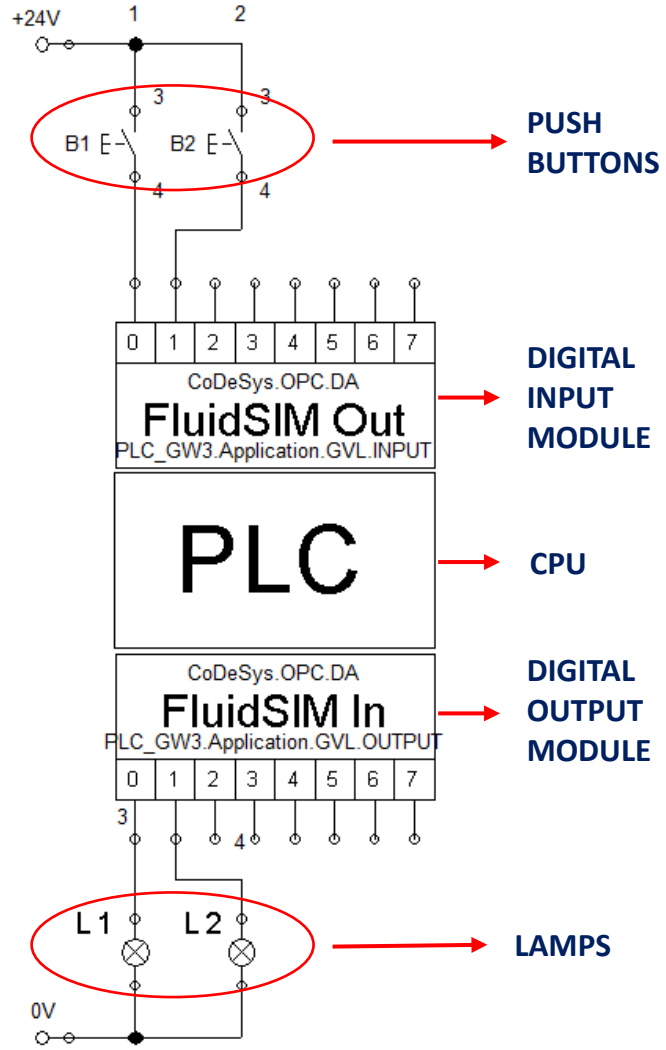
PLC scan cycle – example

Problem definition

- The following PLC circuit will be used for this case study. The circuit consists of two momentary push buttons **(B1)** and **(B2)** connected to input bits 0 and 1 of the **digital input module** and two lamps **(L1)** and **(L2)** connected to output bits 0 and 1 of the **digital output module**.

Find the correct answer for the following tasks:

- Task 1
- Task 2



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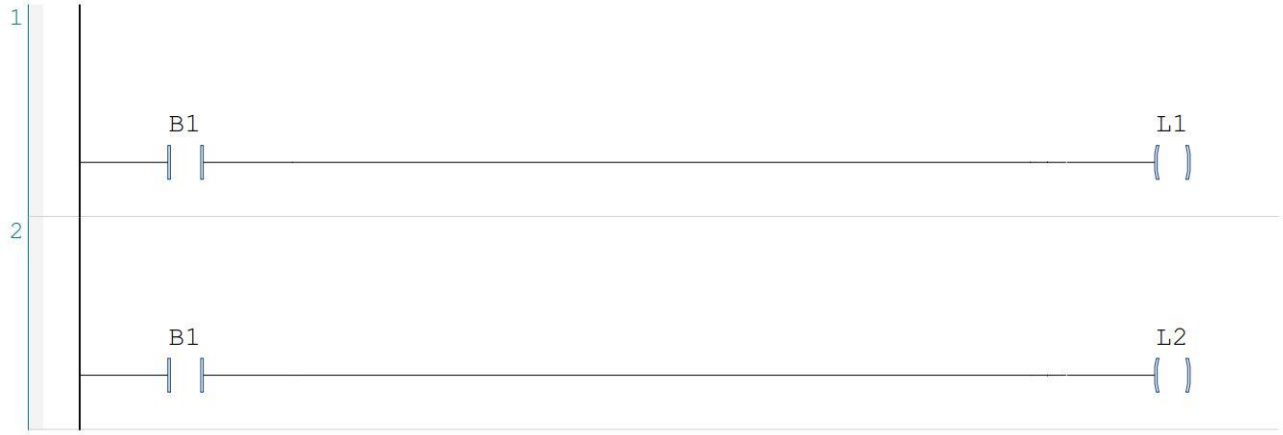
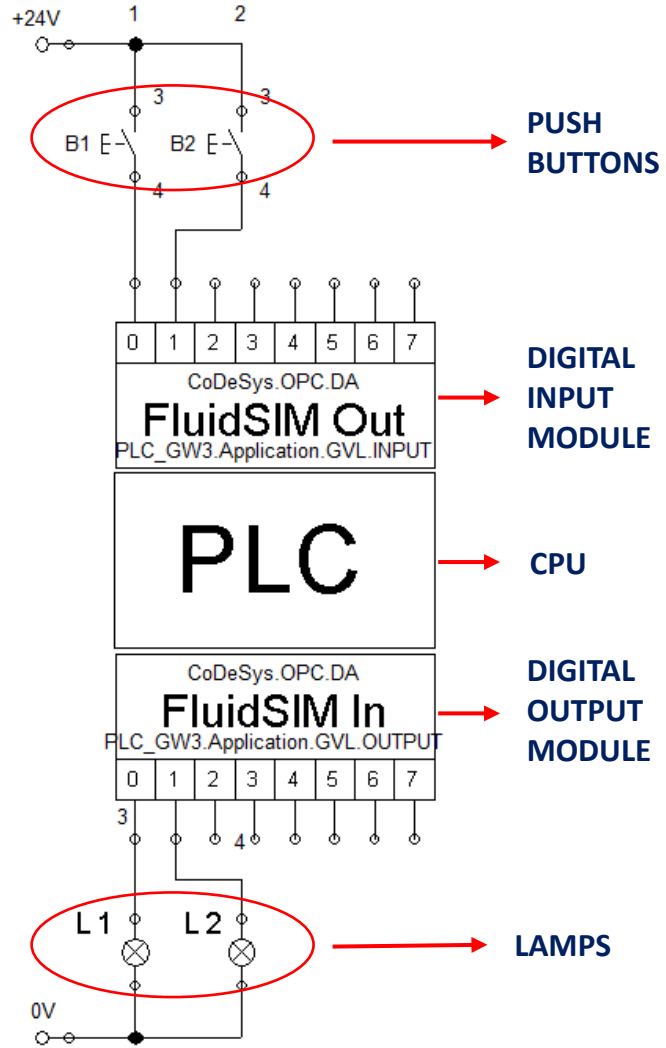
PLC scan cycle – Task 1

Task 1 definition

➢ Let's suppose we have the following **ladder diagram** programmed inside the PLC.



Which lamps **(L1, L2)** will light up when the operator presses the switch **(B1)**?



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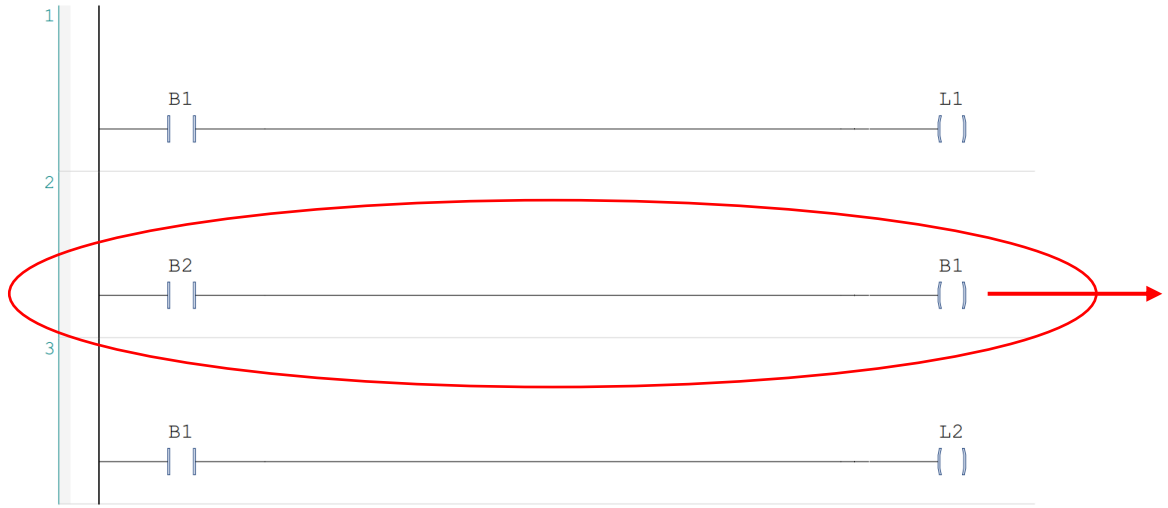
PLC scan cycle – Task 2

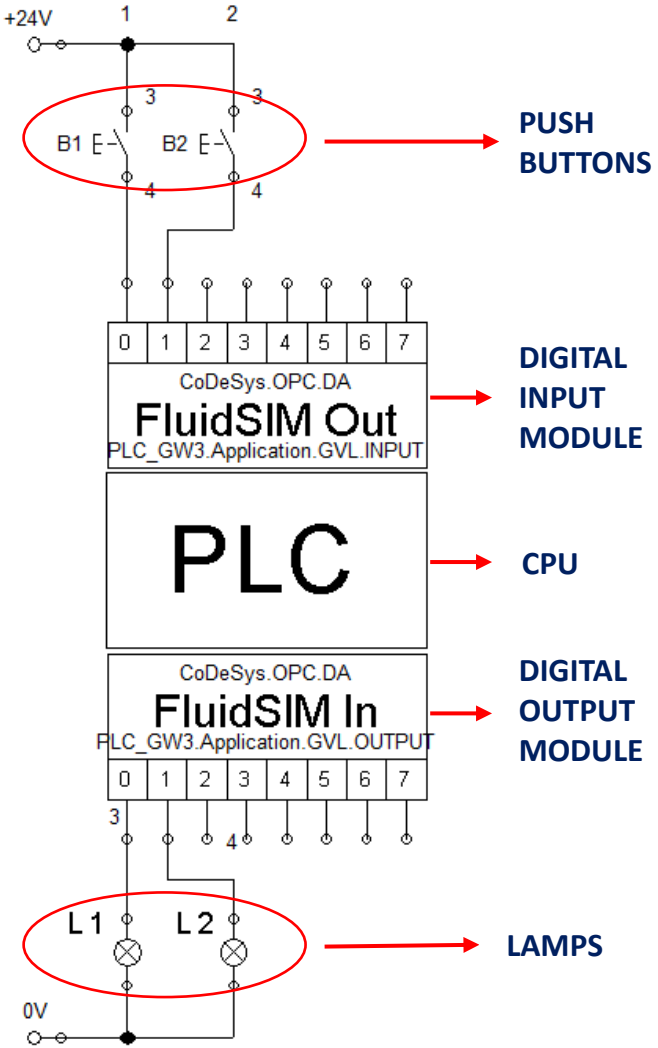
Task 2 definition

➢ Let's suppose we update the previous **ladder diagram** by adding another extra rung.



Placing an input variable in the output area is not a good practice !!!

Here it is used just to demonstrate the way PLC scan cycle works !!!



Which lamps **(L1, L2)** will light up when the operator presses the switch **(B1)**?

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What was covered? What's next?

An overview of IEC 61131-3

A brief introduction in LD !!!

} COVERED

Advanced topics in LD (consult the references slide if your interested):

- ✓ Function blocks such as edge detection, timers, counters, mathematical operations, bit operations, etc.
- ✓ Advanced Boolean operation
- ✓ Combinational Logic Circuits Design (truth tables, Karnaugh map, simplify the Boolean expression, etc.)
- ✓ Structured programming in LD
- ✓ Etc.

Learn about other programming languages: FBD, ST, SFC

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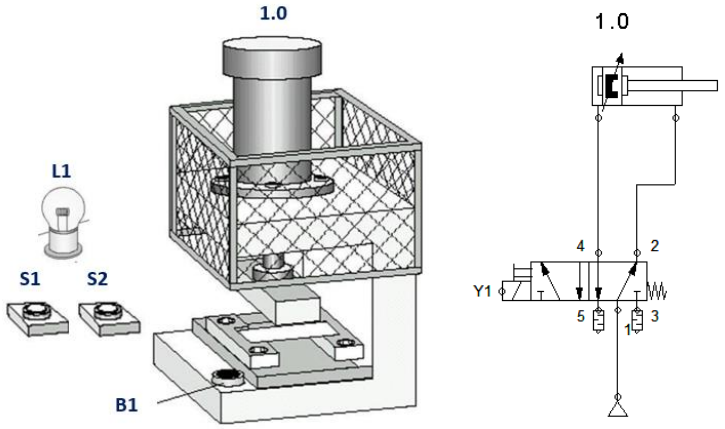
5 **Industry case study – pneumatic press**



Industry case study – pneumatic press

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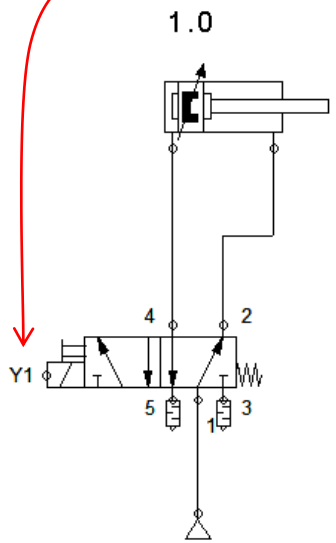
Industry case study – pneumatic press

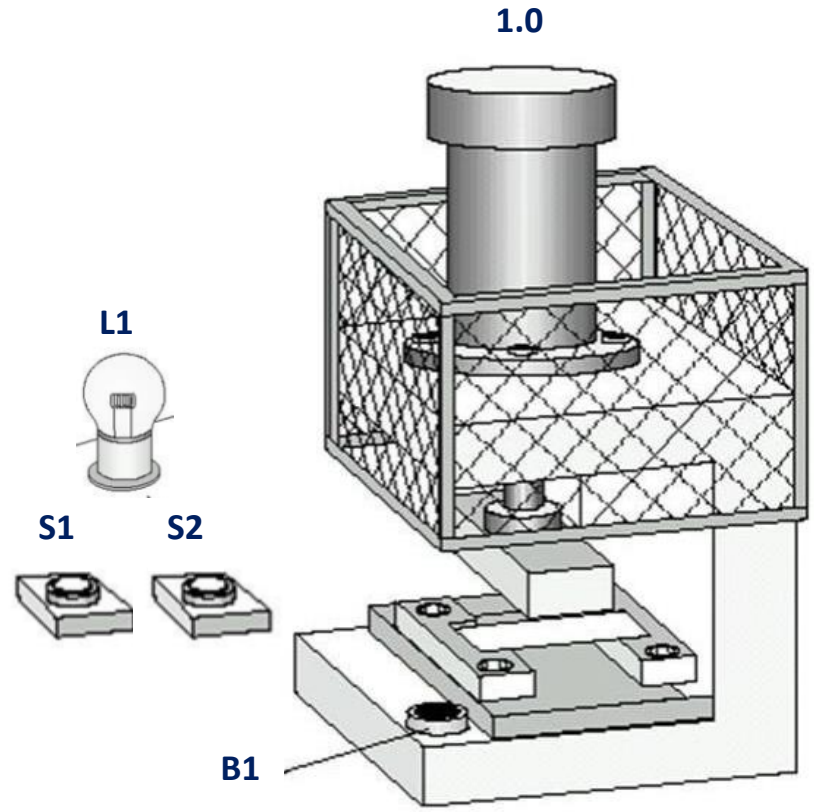
Case study definition

- The system consist of a pneumatic press **(1.0)**, two momentary push buttons **(S1)** and **(S2)**, a lamp **(L1)** and a protective grill. The protective grill is monitored by a proximity sensor **(B1)**. The press advances or retracts via a spring-returned electromagnetic valve **(Y1)**.

Tasks

- Task 1 – Advance/retract the press
- Task 2 – Press safety function
- Task 3 – Start/Stop the press with on-coil and off-coil
- Task 4 – Start/Stop the press with latching





Pneumatic press.

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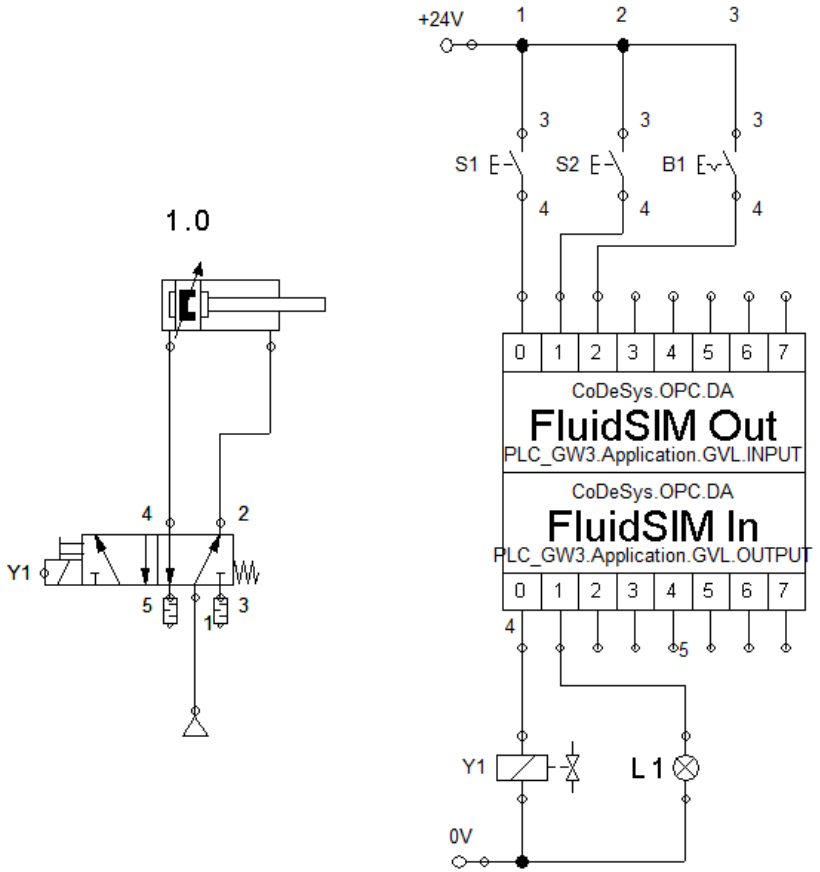
Task 1 – Advance/retract the press

Task 1 definition

- When the button **(S1)** is pressed the pneumatic press **(1.0)** advances and when the button **(S1)** is released, the pneumatic press **(1.0)** retracts.

To Do List

- Create a LD program that performs the task
- Add an extra ON/OFF signaling function for ADVANCE/RETRACT motion using lamp **(L1)**



Pneumatic press – electropneumatic circuit.

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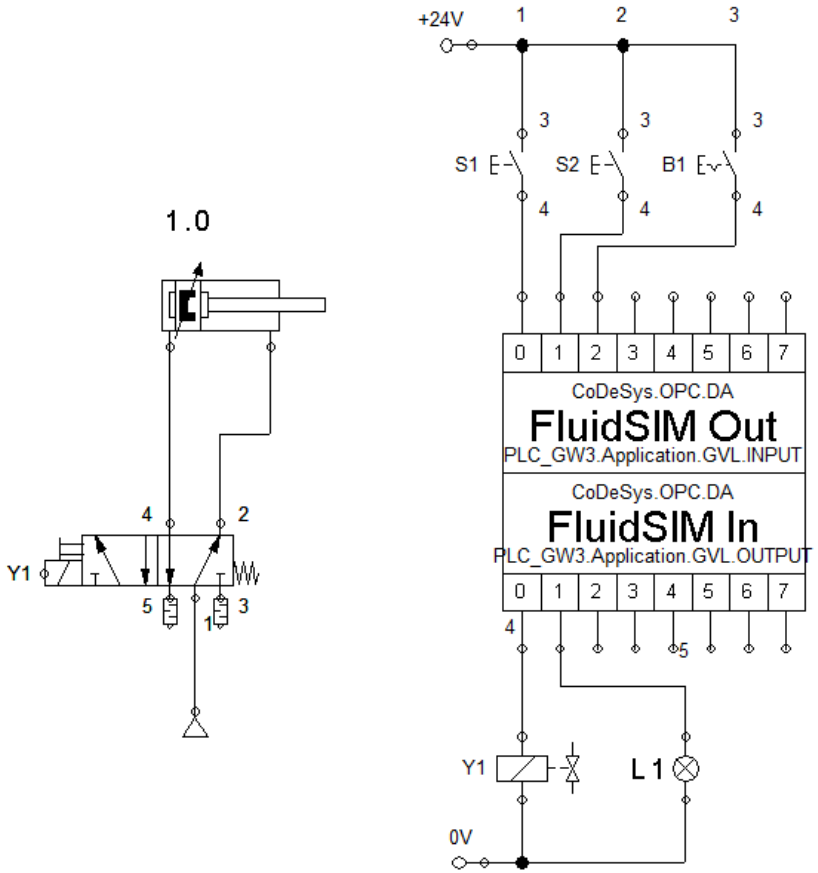
Task 2 – Press safety function

Task 2 definition

- The pneumatic press **(1.0)** is only allowed to advance if button **(S1)** is pressed, and the protective grill covers the processing area **(B1=1)**. If one of these conditions is not met, the press will withdraw immediate.

To Do List

- Create a LD program that performs the task



Pneumatic press – electropneumatic circuit.

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Task 3 – Start/Stop the press with on-coil and off-coil

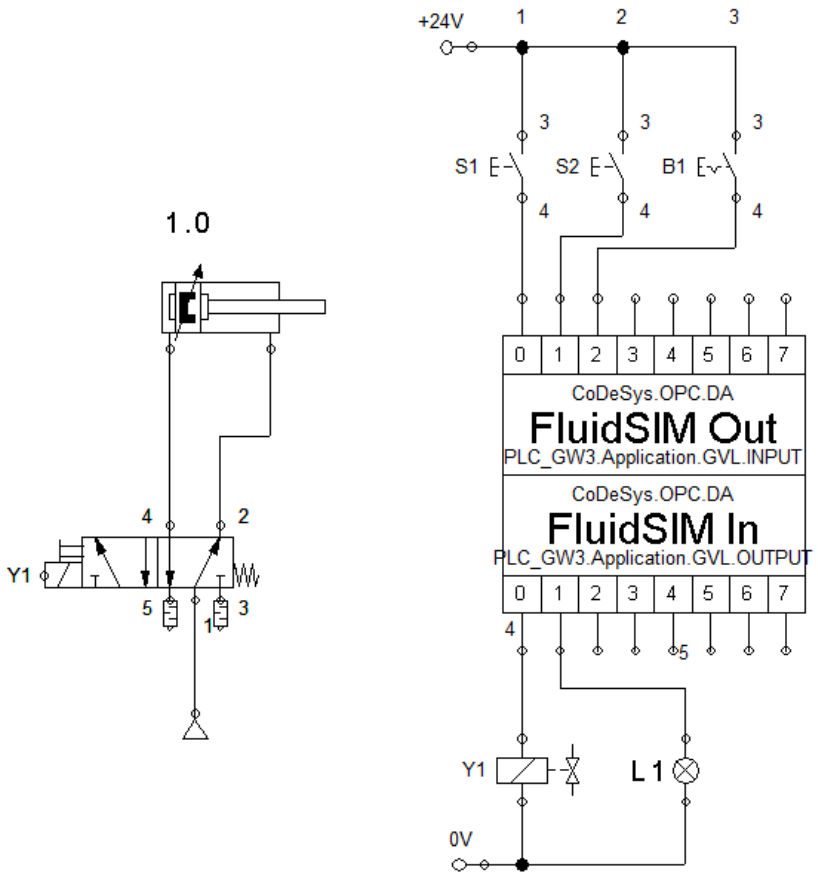
Task 3 definition

- When the button **(S1)** is pressed and then released the press **(1.0)** advances and stays there. When the button **(S2)** is pressed and then released the press **(1.0)** retracts and stays there.

To Do List

- Create a LD program that performs the task
- Use on-coil and off-coil

On-coil	—(S)—	The associated Boolean object is set to TRUE when the state of the left side of the coil is TRUE
Off-coil	—(R)—	The associated Boolean object is set to FALSE when the state of the left side of the coil is TRUE



Pneumatic press – electropneumatic circuit.

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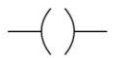
Task 4 – Start/Stop the press with latching

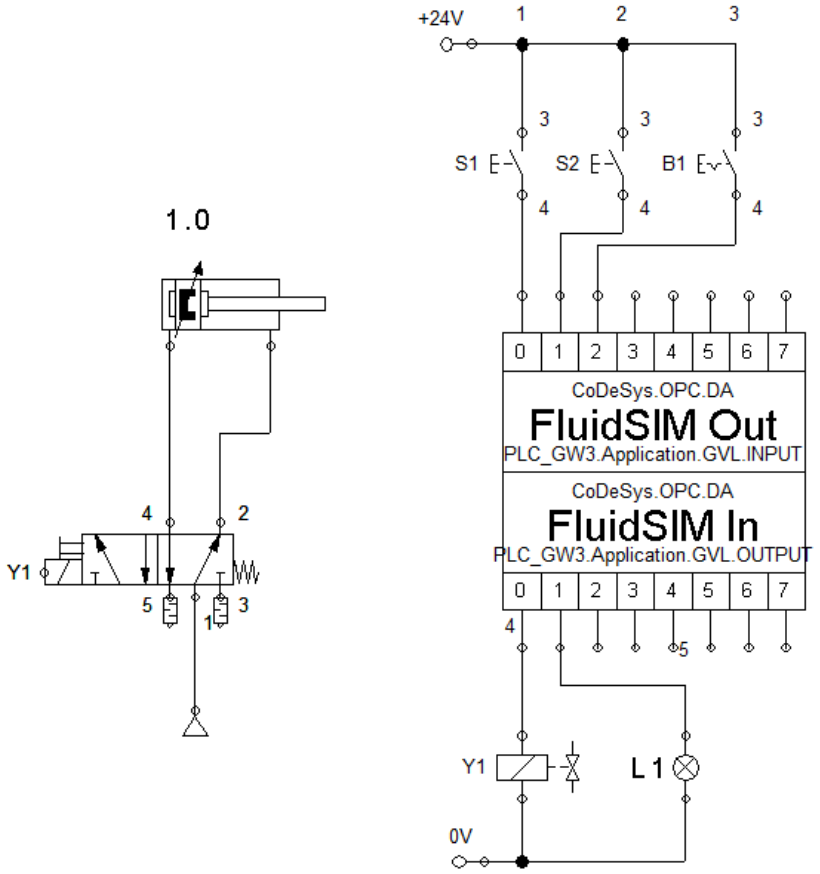
Task 4 definition

- When the button **(S1)** is pressed and then released the press **(1.0)** advances and stays there. When the button **(S2)** is pressed and then released the press **(1.0)** retracts and stays there.

To Do List

- Create a LD program that performs the task
- Use direct coil, normally open and normally closed contacts (one rung)

Direct coil		The associated Boolean object is set to the same state as the state of the left side of the coil
Normally open contact		The contact closes when the associated Boolean object becomes TRUE
Normally closed contact		The contact closes when the associated Boolean object becomes FALSE



Pneumatic press – electropneumatic circuit.

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Summary

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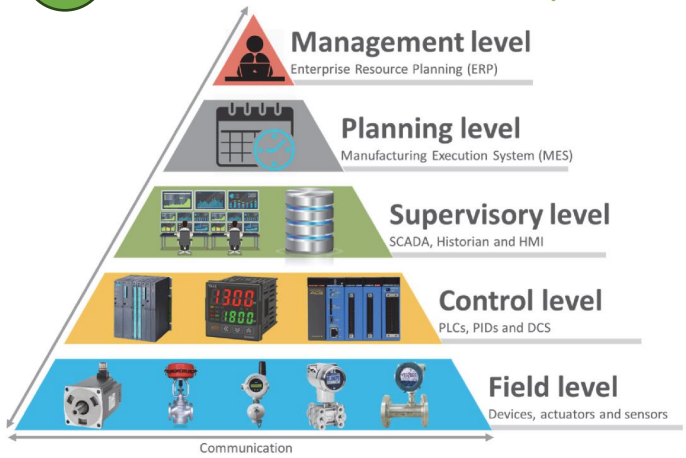
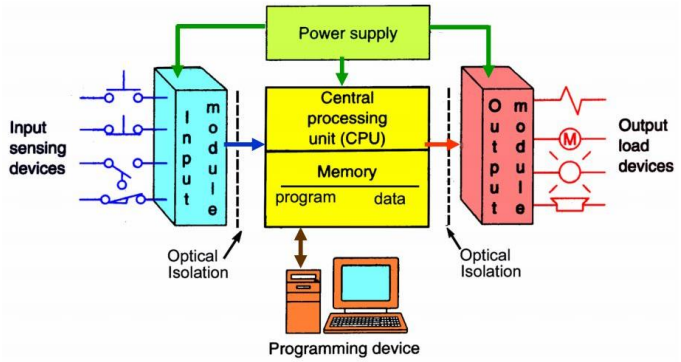
M1 - Industrial Control Systems. Industrial Programming Languages

1 Industrial Control System



3 PLC System



Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.

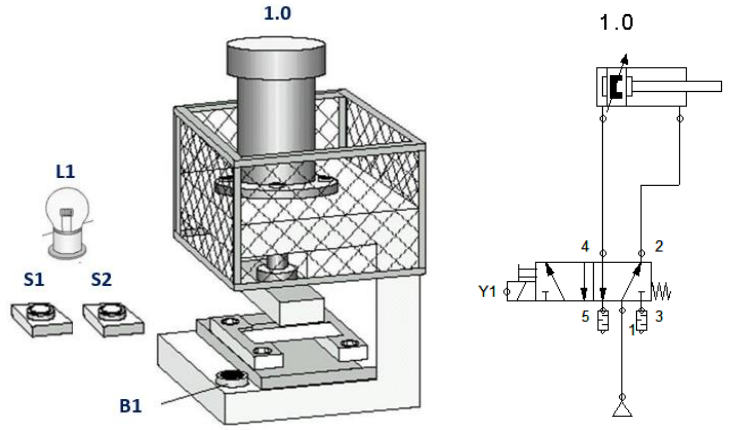
2

4 IEC 61131-3

IEC 61131-3

- **Ladder Logic Diagram (LD)**
- Function Block Diagram (FBD)
- Instruction List (IL)
- Structured Text (ST)
- Sequential Function Chart (SFC)

5 Industry case study – pneumatic press



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[1] Olimpiu Hancu, Ciprian R. Rad, *Controlere Logice Programabile – Programarea și Dezvoltarea Aplicațiilor Industriale*, UT PRESS, 1st edition, Cluj-Napoca, 2017, ISBN: 978-6067372328.

[2] Dag H. Hanssen, *Programmable Logic Controllers: A Practical Approach to IEC 61131-3 using CoDeSys,* Wiley, 1st edition, September 11, 2015, ISBN: 978-1118949245.

[3] Gary L. Pratt PE, *The Book of CODESYS: The ultimate guide to PLC and Industrial Controls programming with the CODESYS IDE and IEC 61131-3,* ControlSphere LLC, First Edition, October 25, 2021, ISBN: 978-1737821403.

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Thank you!

Kiitos!

Gracias!

Mulțumesc!

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- Ciprian RAD
- E-mail: ciprian.rad@mdm.utcluj.ro

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C2 – Industrial Automation

M2 - Structured Programming. Sequential Function Chart (SFC). GRAFCET

CO - Technical University of Cluj-Napoca

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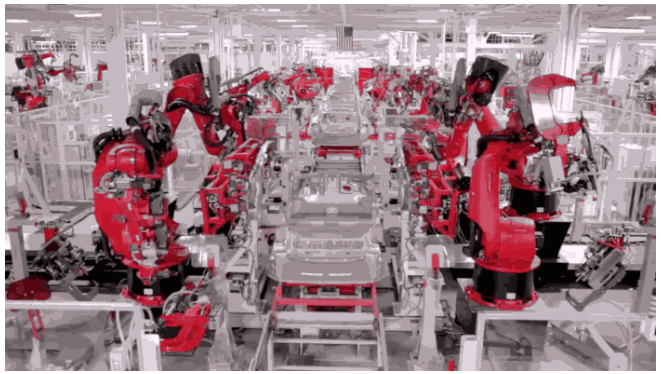
M2 - Structured Programming. Sequential Function Chart (SFC). GRAFCET

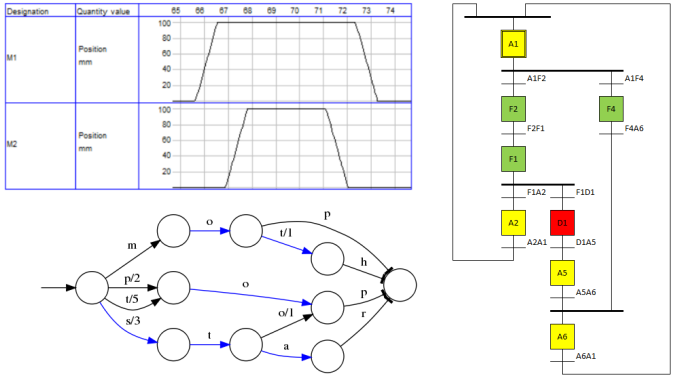
1 Industry 4.0 - Automation Reinvented



*"Tesla says the **Model 3** body line is now **95 percent automated**, including the transfer, loading, and welding of parts."*

Source: https://www.carrushome.com/en/tesla-model-3-body-line-now-95-percent-automated

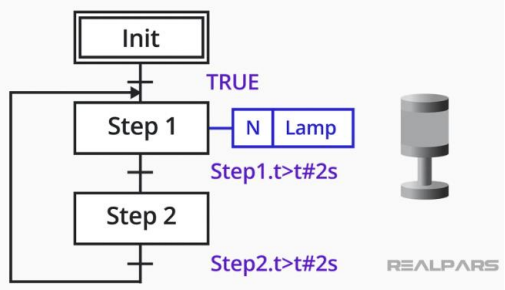
2 Sequential Control Design



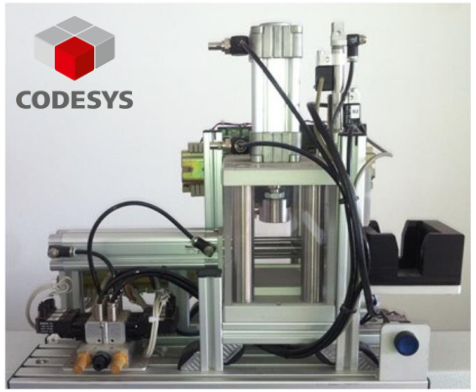
3 Structured programming using SFC

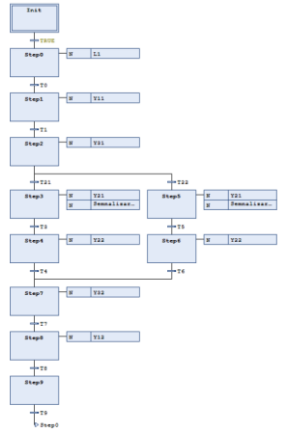
IEC 61131-3:2013

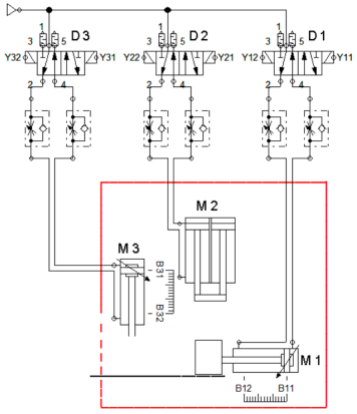
- Ladder Logic Diagram (LD)
- Function Block Diagram (FBD)
- Instruction List (IL)
- Structured Text (ST)
- Sequential Function Chart (SFC)

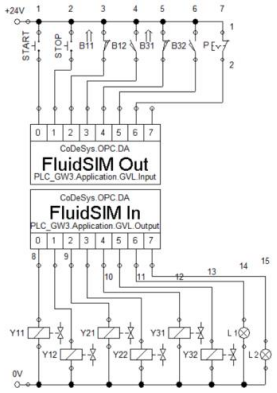


4 Industry case study – pneumatic press









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M2 - Structured Programming. Sequential Function Chart (SFC). GRAFCET

Upon completion of this module, the student will be able to:

1) Understand the key technologies of ***Industry 4.0***
2) Understand the methods to ***planning, structuring, and presenting industrial processes*** that have a ***sequential structure***
3) Understand the basics of ***Sequential function chart (SFC) IEC 61131-3*** industrial programming language
4) Design the sequence control of an ***industrial pneumatic press using SFC and CODESYS IDE***

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NextGEng

Content

- Industry 4.0 - Automation Reinvented
- Sequential Control Design
- Structured programming using SFC
- Industry case study – pneumatic press
- Summary

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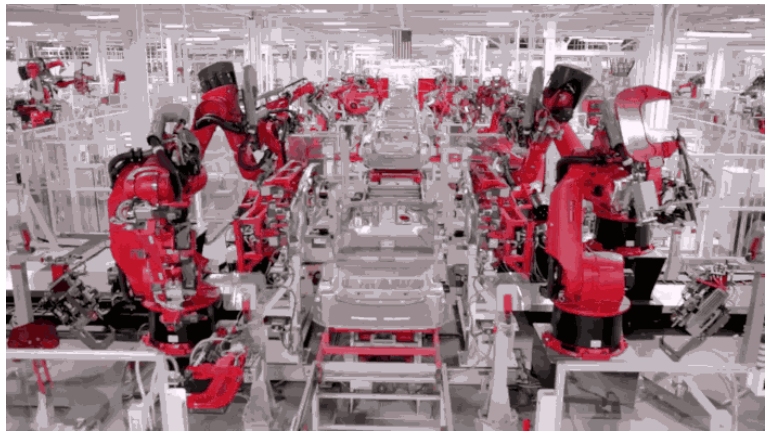
1 **Industry 4.0 - Automation Reinvented**



*"Tesla says the **Model 3** body line is now **95 percent automated**, including the transfer, loading, and welding of parts."*

Industry 4.0 - Automation Reinvented

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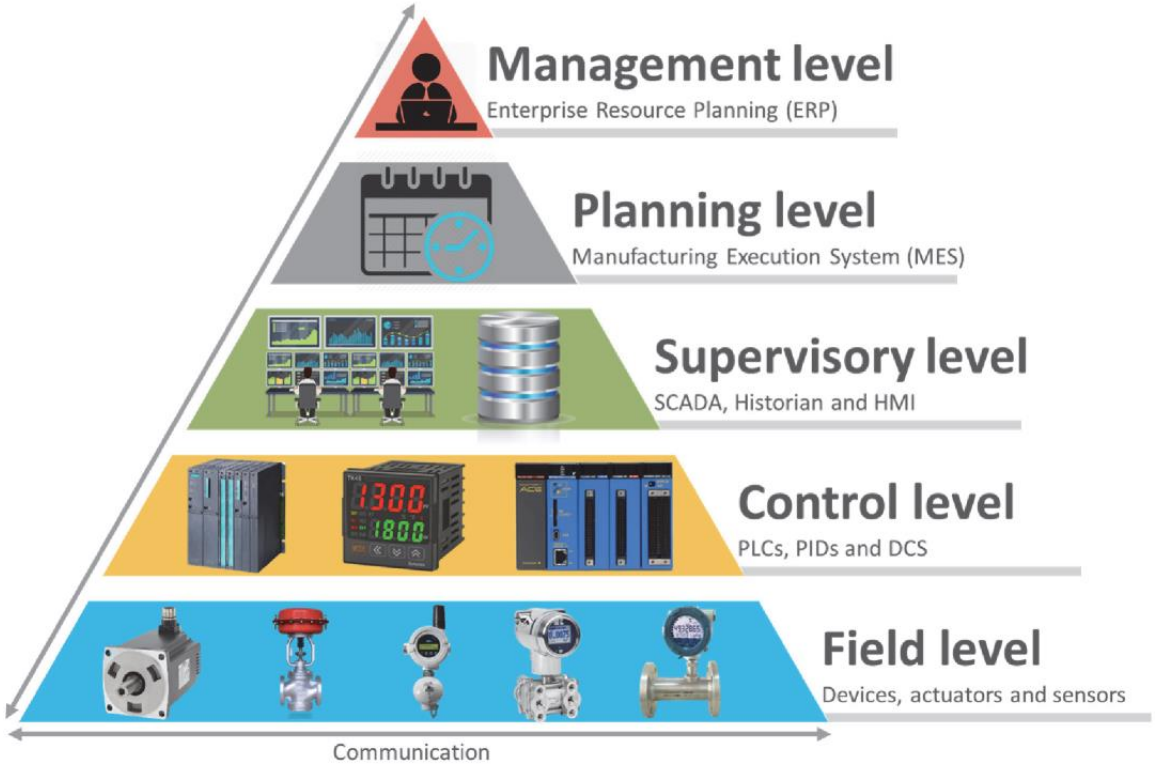
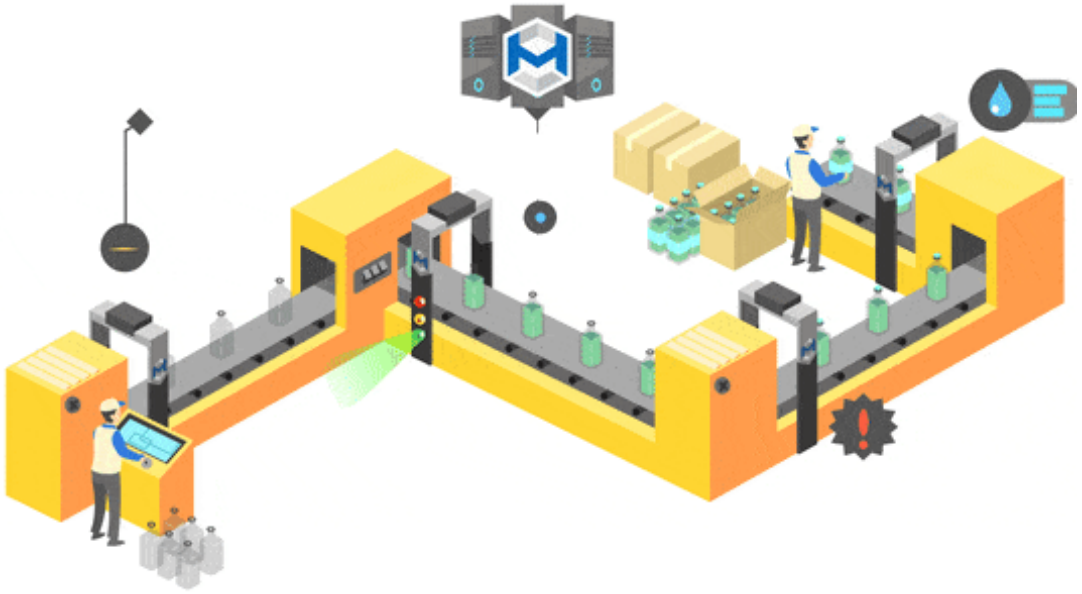
Industrial Automation Pyramid



The automation pyramid of a typical industrial control system.

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.



Example of industrial control system.

Source: https://heliconia.io/blog/industry-2/what-is-industry-4-0-1

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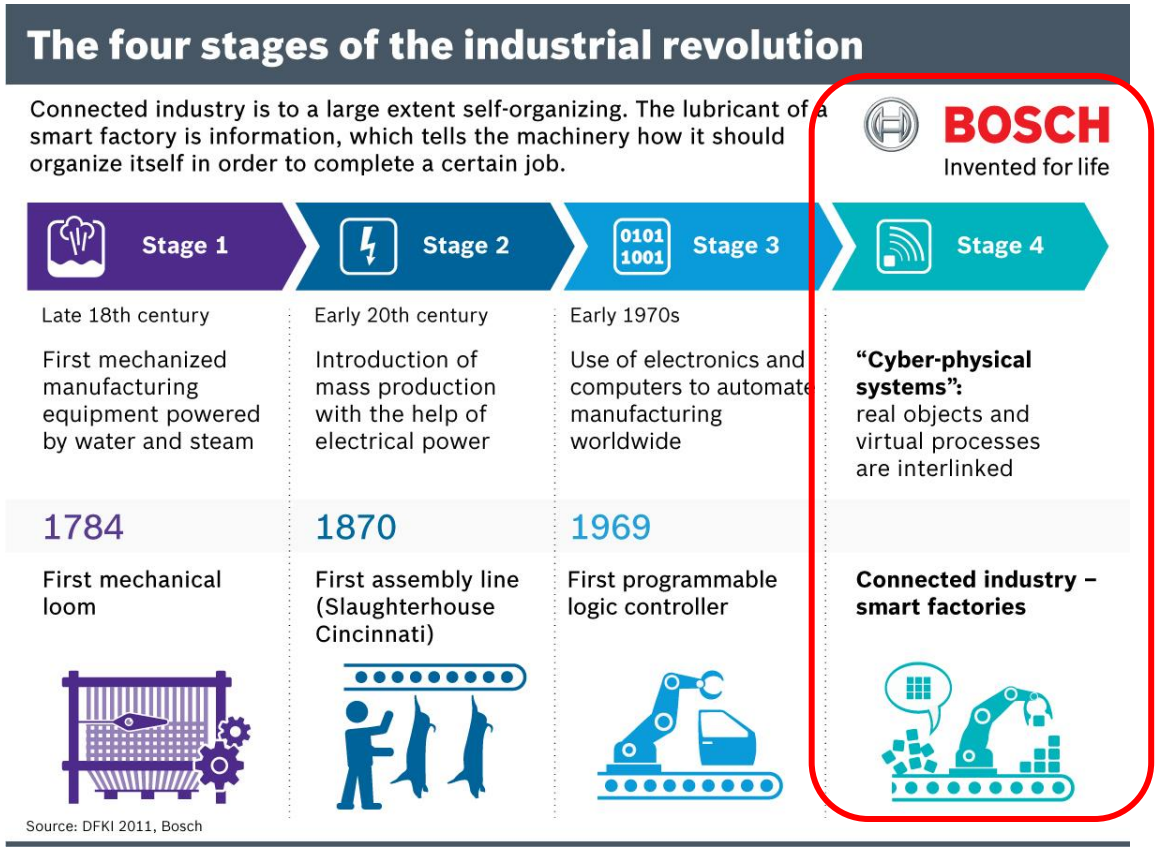
Industry 4.0



Source: https://www.bosch-presse.de/pressportal/de/en/the-four-stages-of-the-industrial-revolution-154113.html

4th Industrial Revolution

- originated in **2011** from a project in the high-tech strategy of the German government, which promotes the **computerization of manufacturing**
- **the *movement*, the "trend", the place in time**
- it's about **transforming data** into **useful information** to **make/take proper decisions**

Key Technologies for transforming data into useful information

- **Industrial Internet of Things (IIoT)**
- **Digital Transformation** (artificial intelligence, cloud computing, systems integration, cybersecurity, big data & analytics, augmented reality, simulation, going paperless, unified data, etc.)

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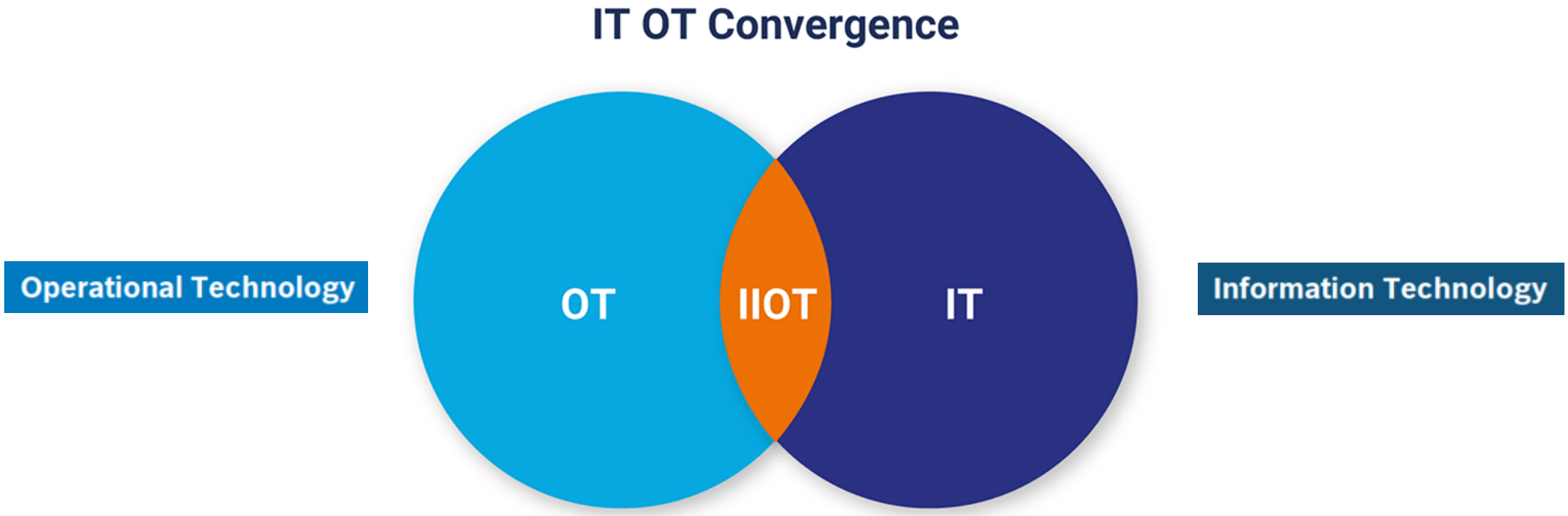
IIoT



Source: https://www.3pillarglobal.com/insights/how-does-iiot-bring-it-and-ot-together/

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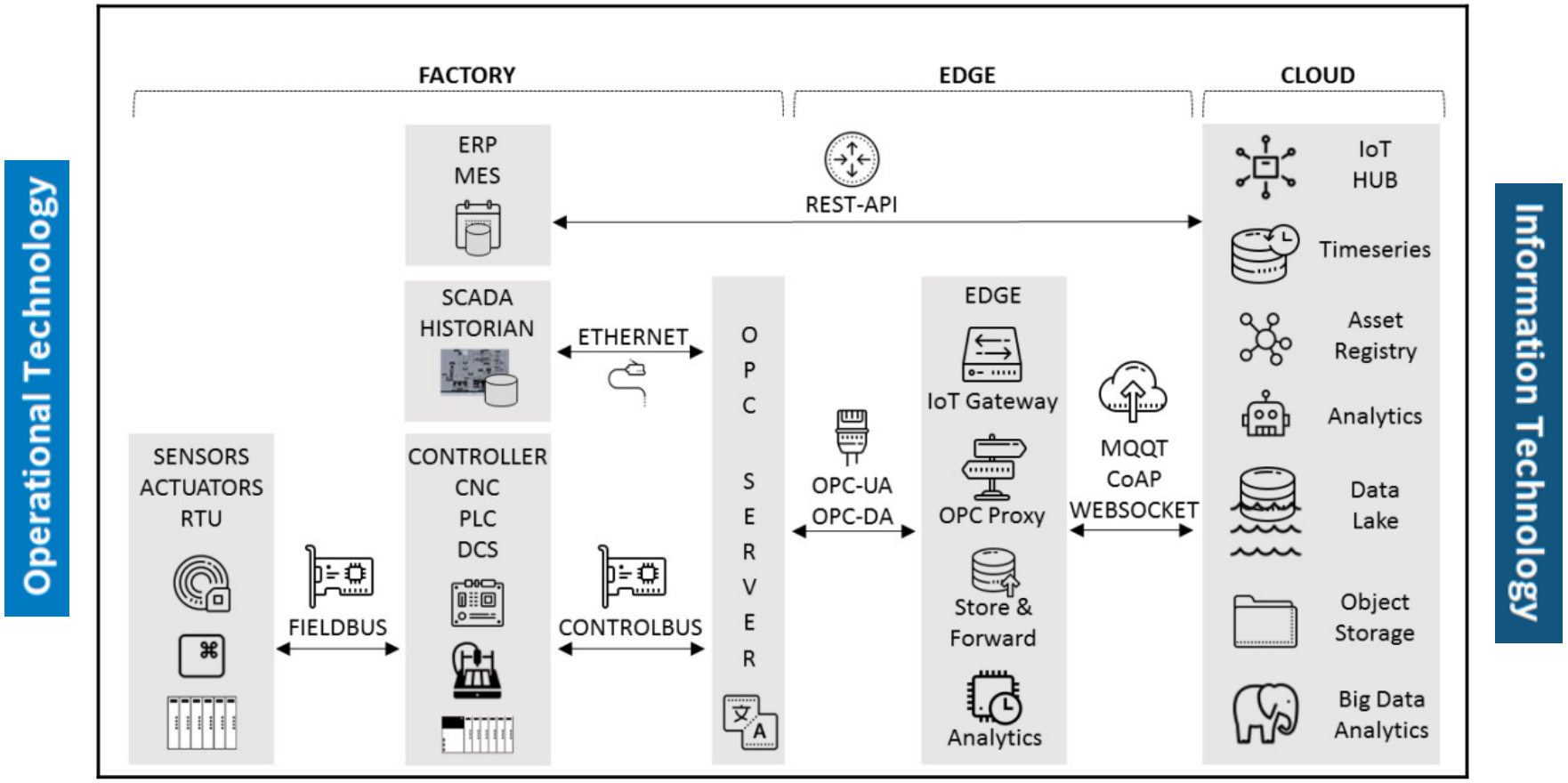
IIoT data flow



Source: https://www.packtpub.com/product/hands-on-industrial-internet-of-things/9781789537222

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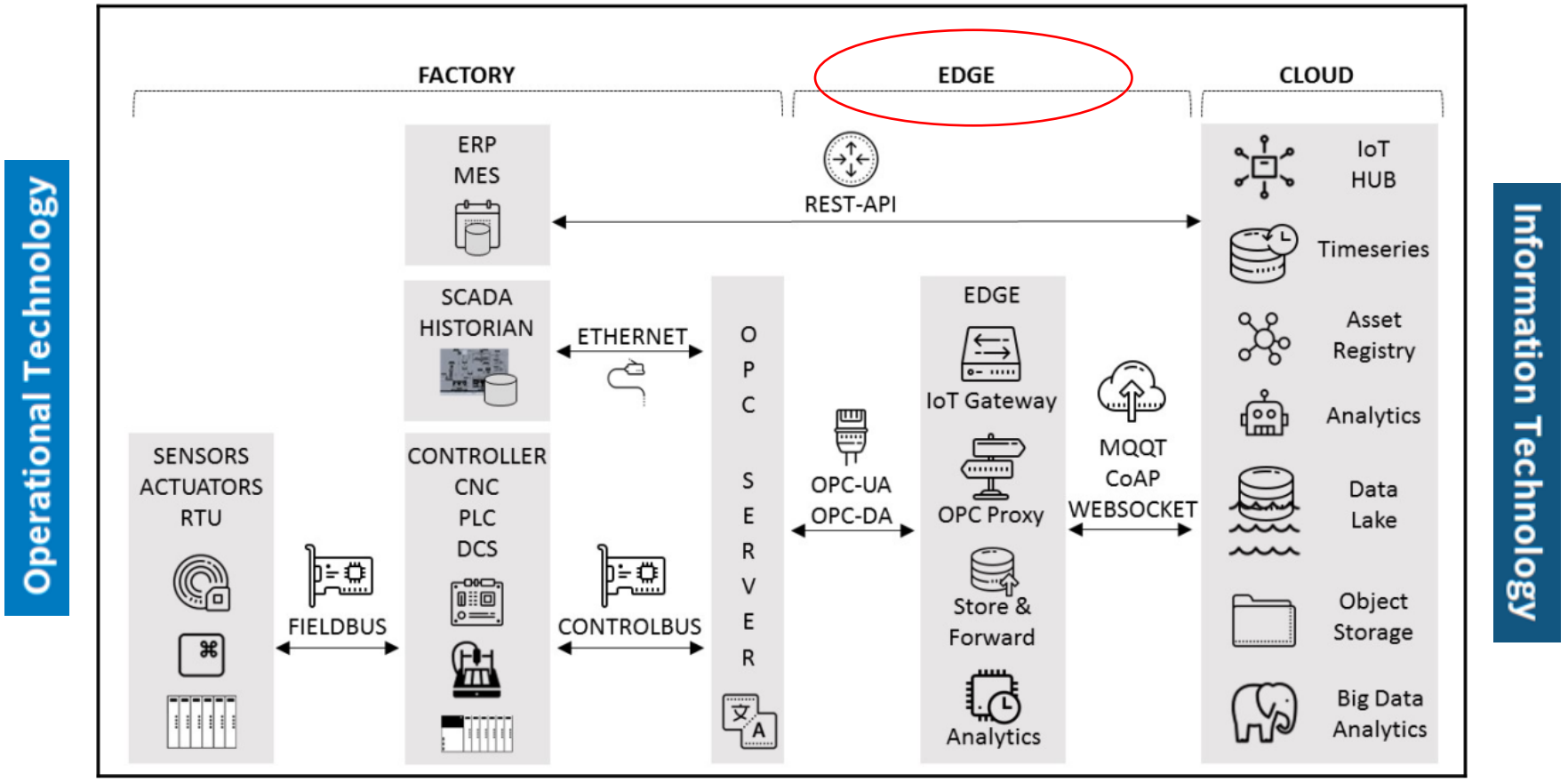
IIoT data flow

Acquire → Transform → Deliver



Source: https://www.packtpub.com/product/hands-on-industrial-internet-of-things/9781789537222

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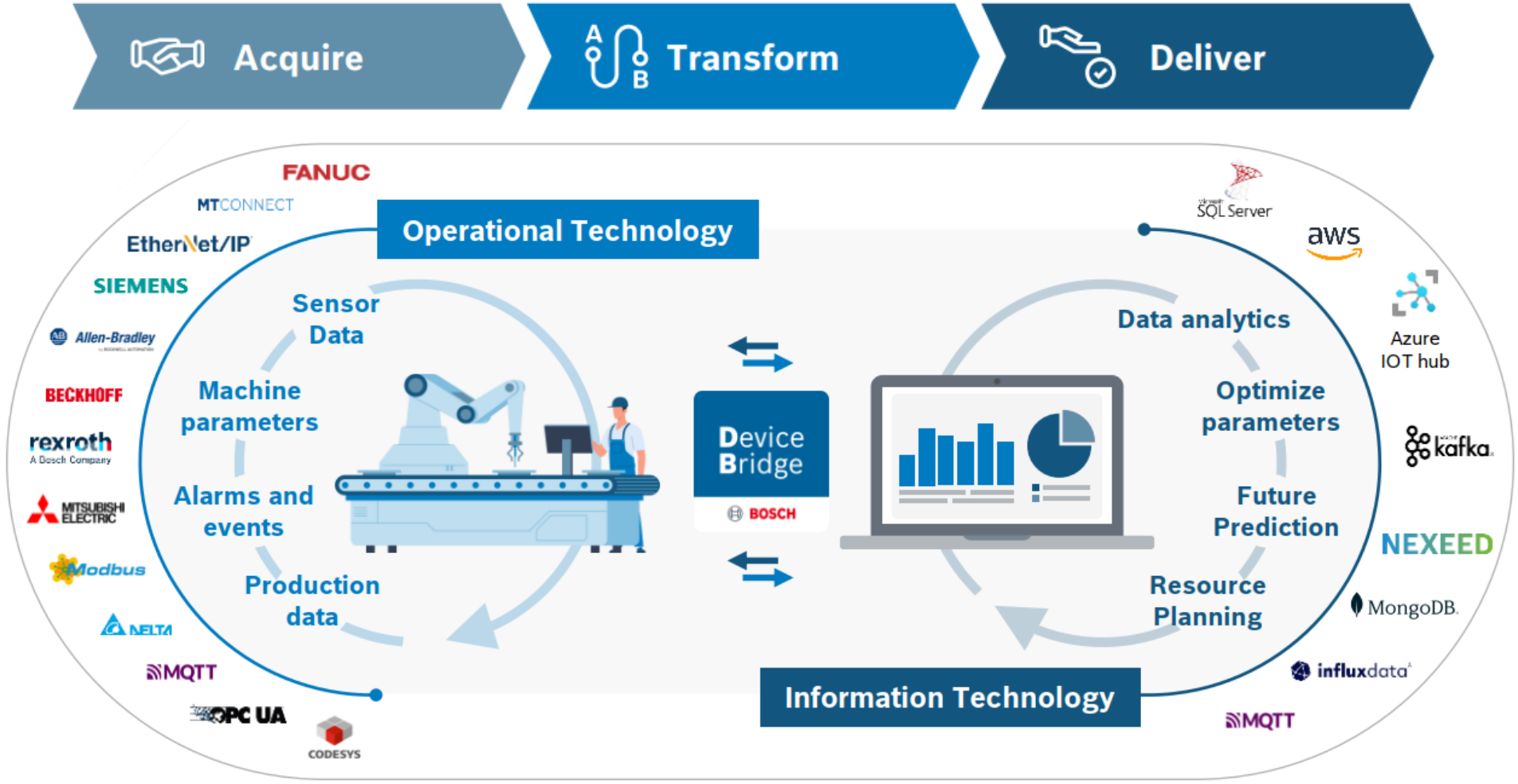
IIoT



Source: https://developer.community.boschrexroth.com/t5/Store-and-How-to/Bosch-DeviceBridge/ba-p/50243

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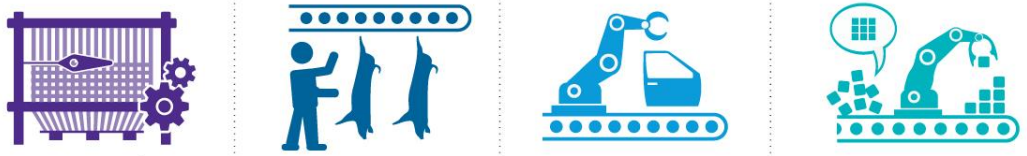
Towards Industry 5.0

The four stages of the industrial revolution

Connected industry is to a large extent self-organizing. The lubricant of a smart factory is information, which tells the machinery how it should organize itself in order to complete a certain job.

BOSCH
Invented for life

Stage 1	Stage 2	Stage 3	Stage 4
Late 18th century	Early 20th century	Early 1970s	
First mechanized manufacturing equipment powered by water and steam	Introduction of mass production with the help of electrical power	Use of electronics and computers to automate manufacturing worldwide	**"Cyber-physical systems":** real objects and virtual processes are interlinked
1784	1870	1969	
First mechanical loom	First assembly line (Slaughterhouse Cincinnati)	First programmable logic controller	**Connected industry – smart factories**



Source: DFKI 2011, Bosch

Source: https://www.bosch-presse.de/pressportal/de/en/the-four-stages-of-the-industrial-revolution-154113.html

Industry 5.0 - A Transformative Vision for Europe

Source: https://www.interregeurope.eu/policy-learning-platform/news/industry-50-a-transformative-vision-for-europe

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Why Industry 5.0?

- It complements the existing **"Industry 4.0"** approach by specifically putting research and innovation at the service of **the transition to a sustainable, human-centric and resilient European industry**
- Industry 5.0 will lead the **digital and green transitions**

How to make it happen?

- adopting a **human-centric approach** for digital technologies including artificial intelligence
- **up-skilling and re-skilling European workers**, particularly digital skills
- modern, **resource-efficient and sustainable industries** and transition to a **circular economy** (**green skills**)

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Sustainable development through Industry 5.0

- To achieve these targets **engineering know-how** and **green skills** are needed for **Next GEneration Engineers**
- **Engineering know-how** means that engineers should be aware that an **efficient material and energy use, minimization of waste generation, reduction of fossil fuel use**, etc. in the development process of **engineering product/system/service** influence/impact the environment in a good way on long term
- **Green skills** are the knowledge, abilities, values and attitudes needed to live in, **develop and support a sustainable and resource-efficient society**

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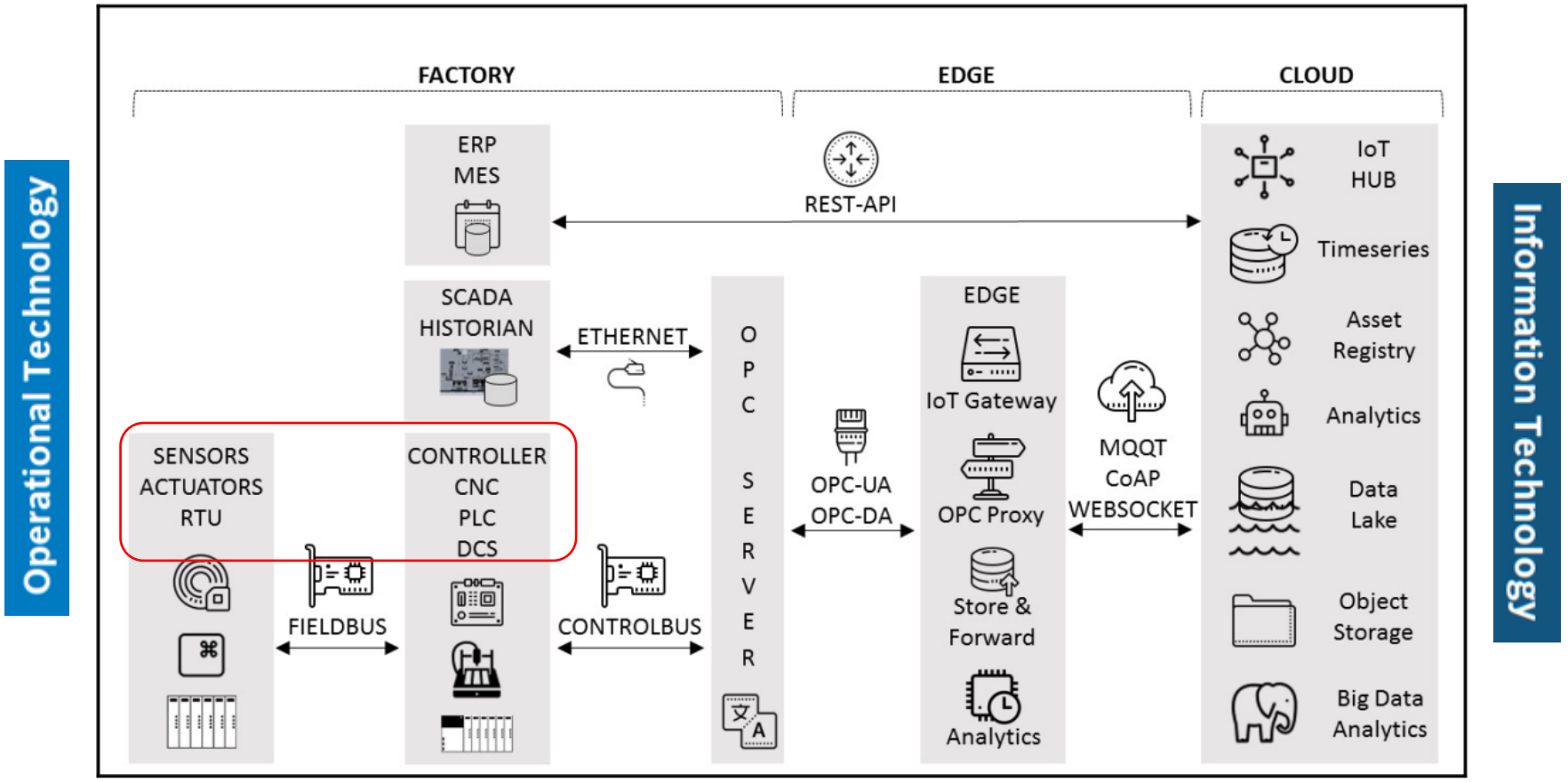
IIoT data flow



Source: https://www.3pillarglobal.com/insights/how-does-iiot-bring-it-and-ot-together/

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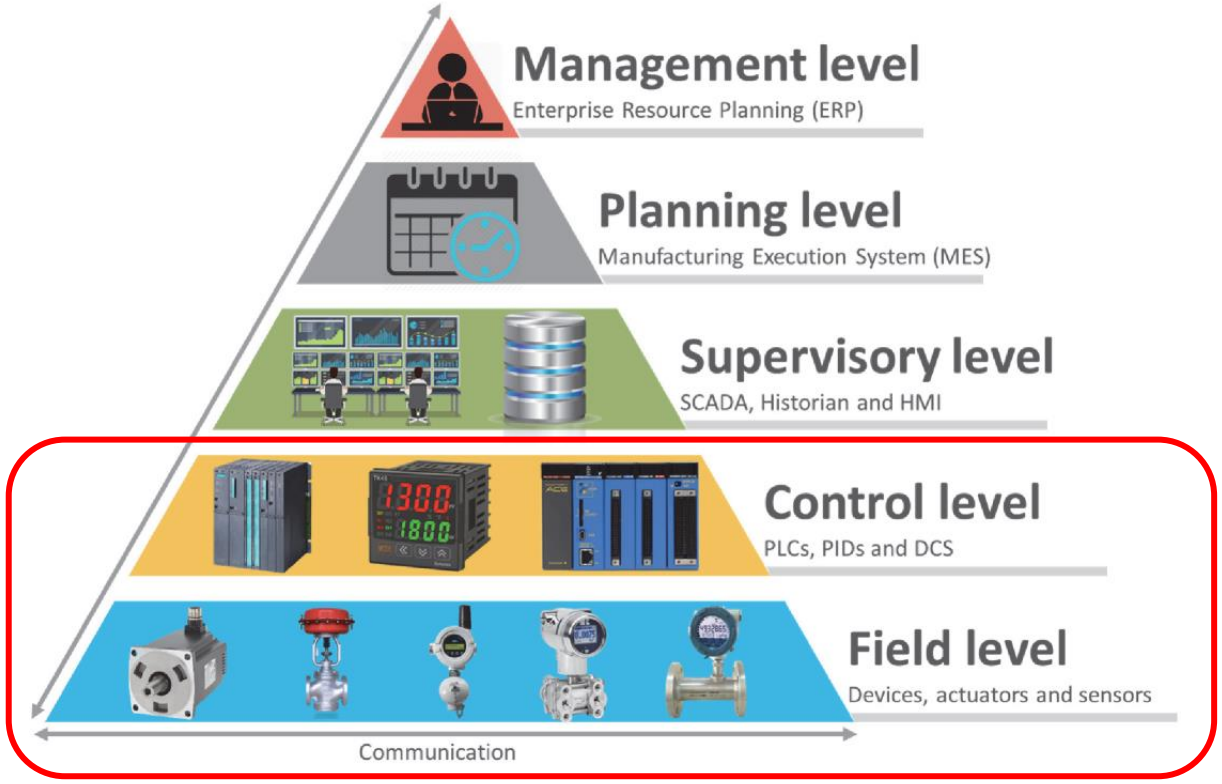
Levels of industrial automation



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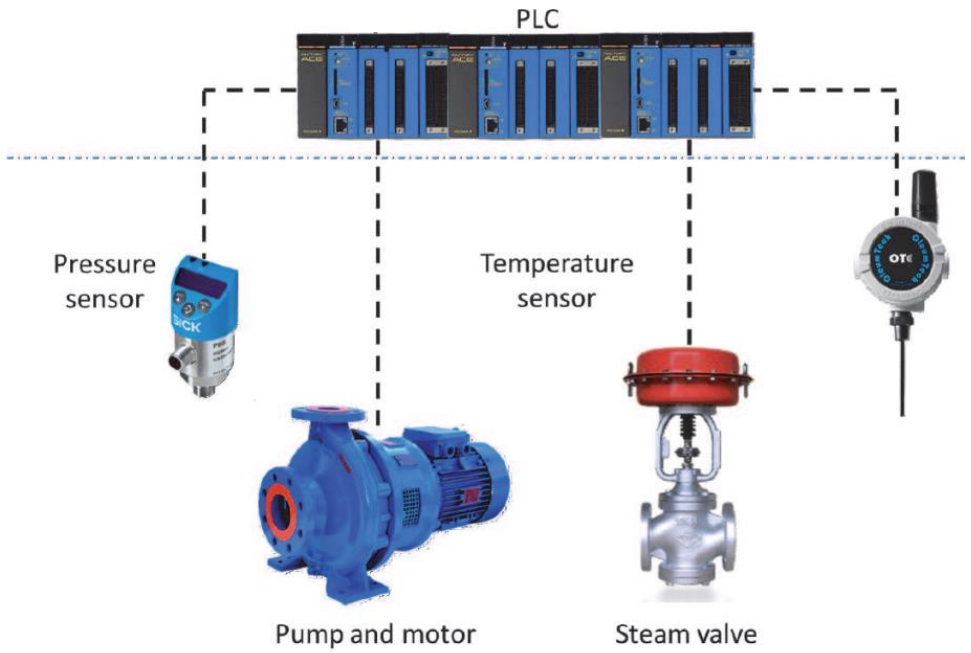

Example of the integration between field and control level.

Source: Rahman, Moksadur, et al. 'A Framework for Learning System for Complex Industrial Processes'. AI and Learning Systems - Industrial Applications and Future Directions, IntechOpen, 17 Feb. 2021. Crossref, doi:10.5772/intechopen.92899.

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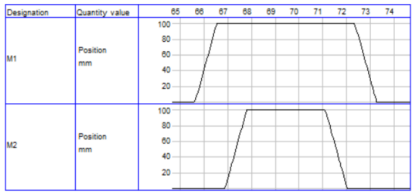
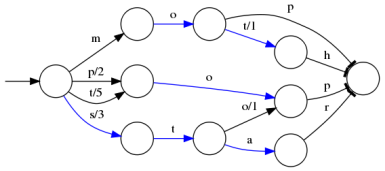
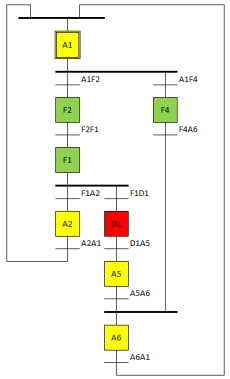
2 **Sequential Control Design**







Sequential Control Design

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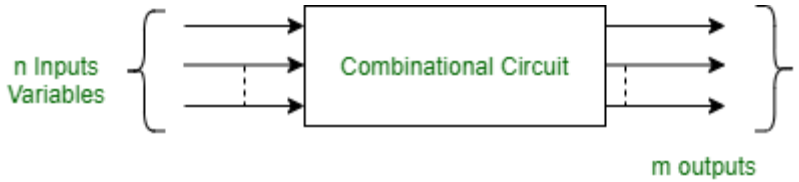
NextGEng

Sequential Control Design

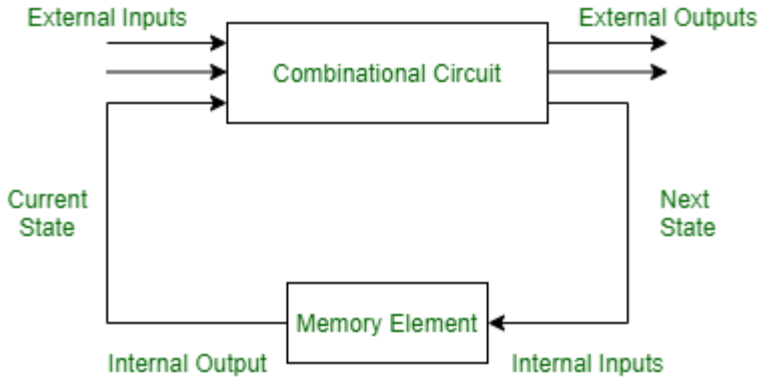
A system that has the property that the output signals from the control depend only upon the instantaneous value of the input signals is called a ***combinational system***.

If the output signals also depend upon what phase or state (in time) the process takes place, we have a ***sequential system***.



- ***Truth tables***
- ***Karnaugh map***
- ***Boolean algebra***
- ***Canonical form***
- ***etc.***

Source: https://www.geeksforgeeks.org/combinational-and-sequential-circuits/



- ***Textually description***
- ***Flowchart diagrams***
- ***Sequence diagrams***
- ***State-Based diagrams***
- ***GRAFCET diagrams***
- ***SFC diagrams***
- ***etc.***

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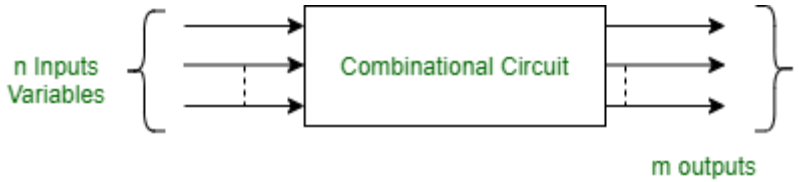

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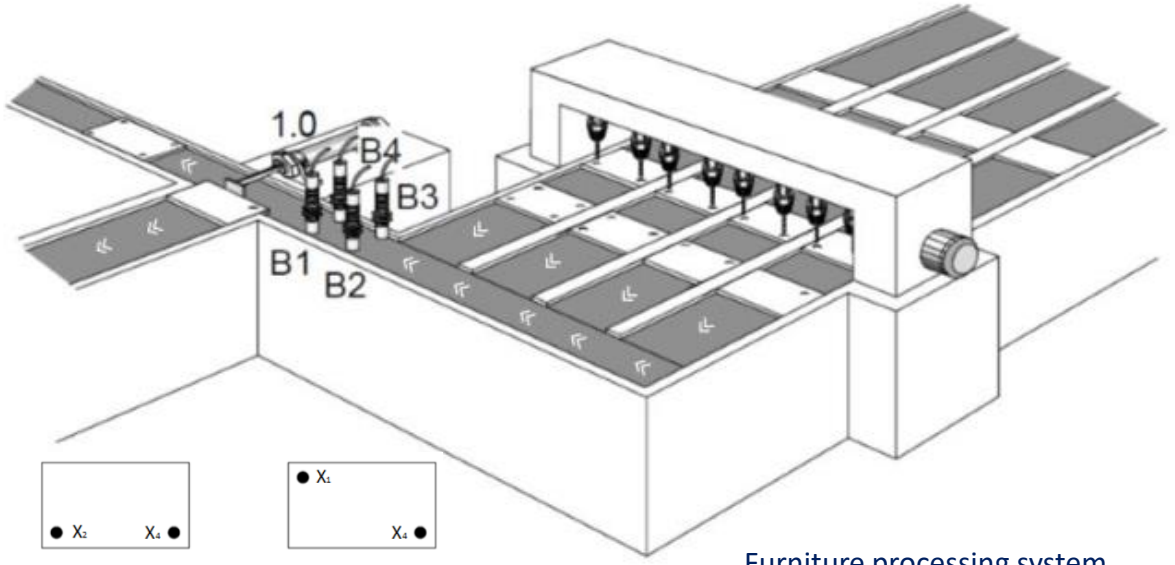
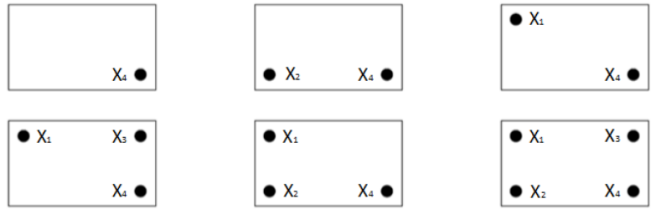


Furniture processing system



Good templates

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NextGEng

Sequential Control Design

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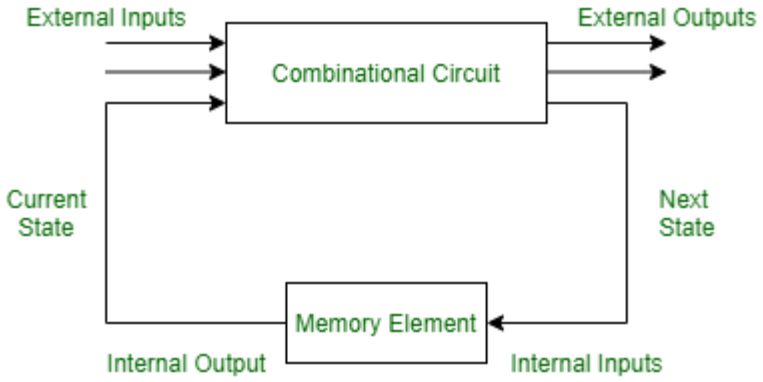

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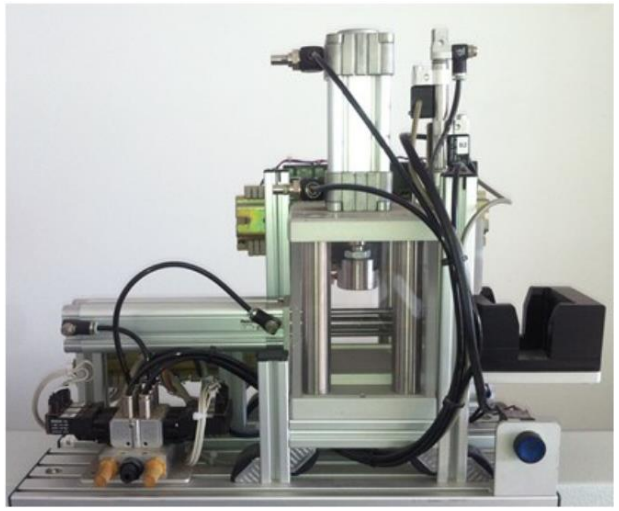

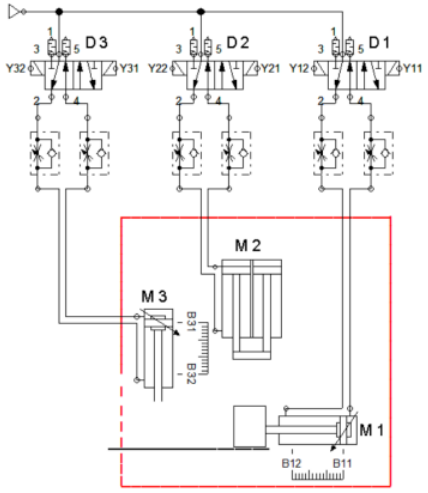

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Pneumatic press

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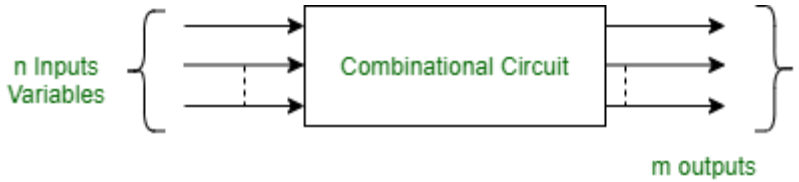

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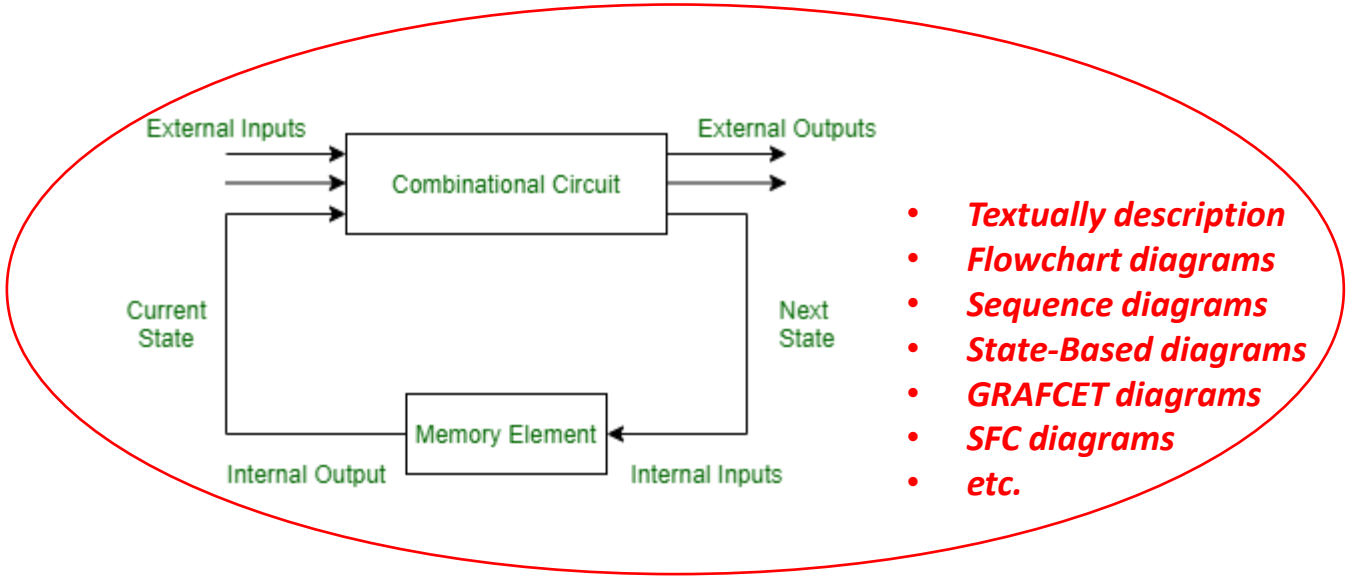

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Source: https://www.geeksforgeeks.org/combinational-and-sequential-circuits/

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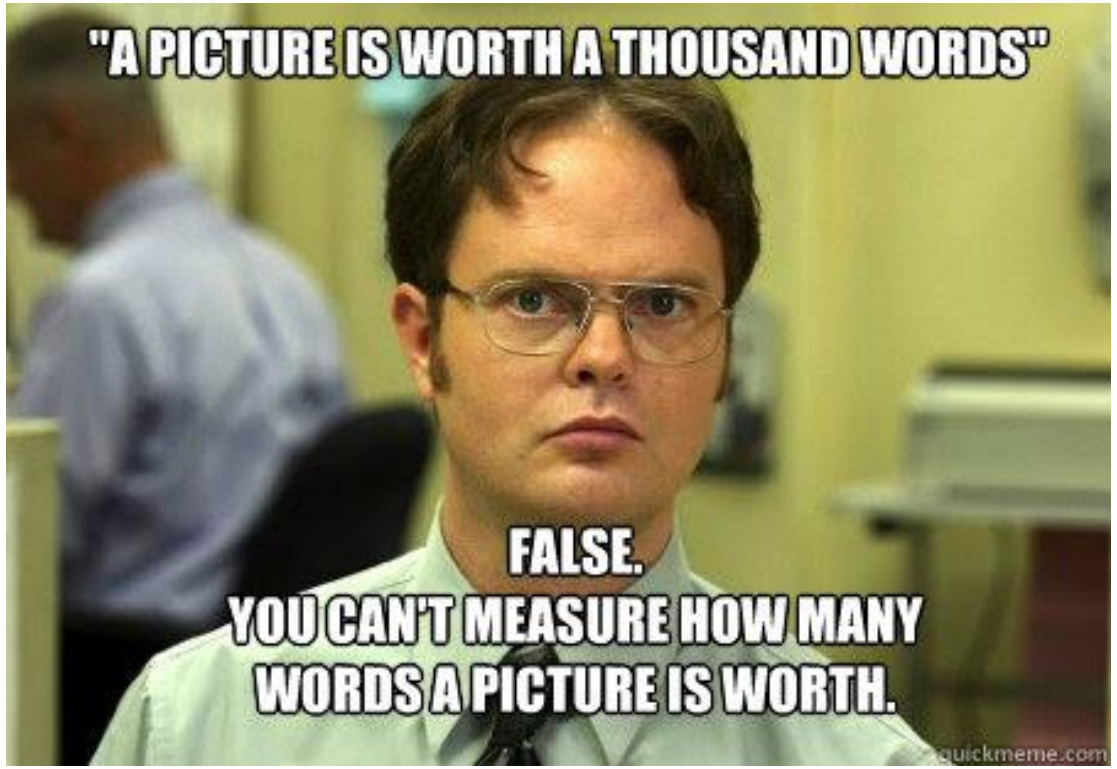
Sequential Control Design

- ✓ The **functional description** of an industrial process can be presented **graphically** or **textually**
- ✓ If the industrial process is very complex, it is recommended to use a **graphical representation (diagrams)**
- ✓ Diagrams are more *powerful* for **planning**, **structuring**, and **presenting processes or production procedures** that have a **sequential structure**
- ✓ **Graphical representations** can be helpful also in working out the **PLC algorithms for the sequential process**



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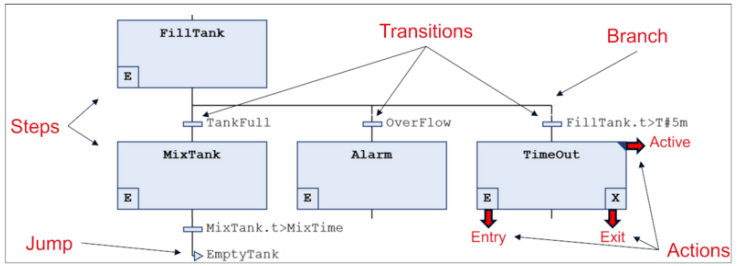
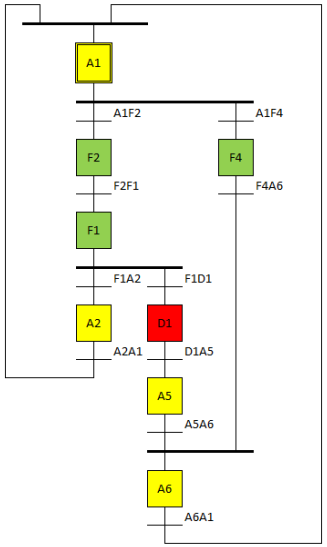
Sequential Control Design

When a starting switch is activated, the tank is filled with water by holding a valve open
until the tank is full (level sensor gives logical high signal).
…

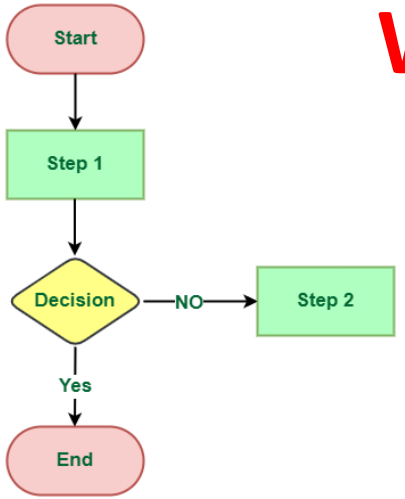
Textual description



SFC diagram

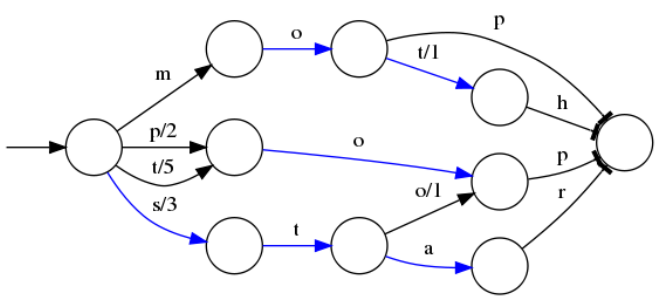


GRACET diagram

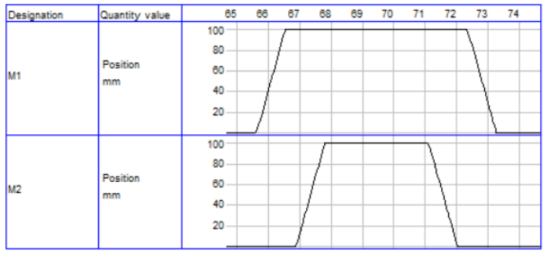


Flowchart diagram

What's the best way of representing sequential processes after all ?



State-Based diagram



Sequence diagram

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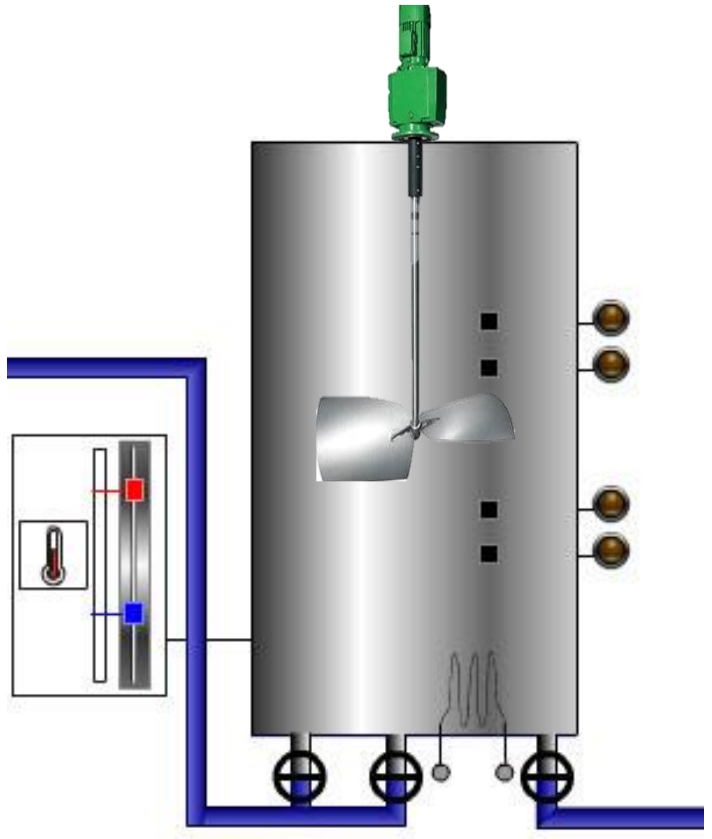
Textual description – wash operation

A bottling plant has a juice tank that is used in soft drink production. This tank is washed after each batch.

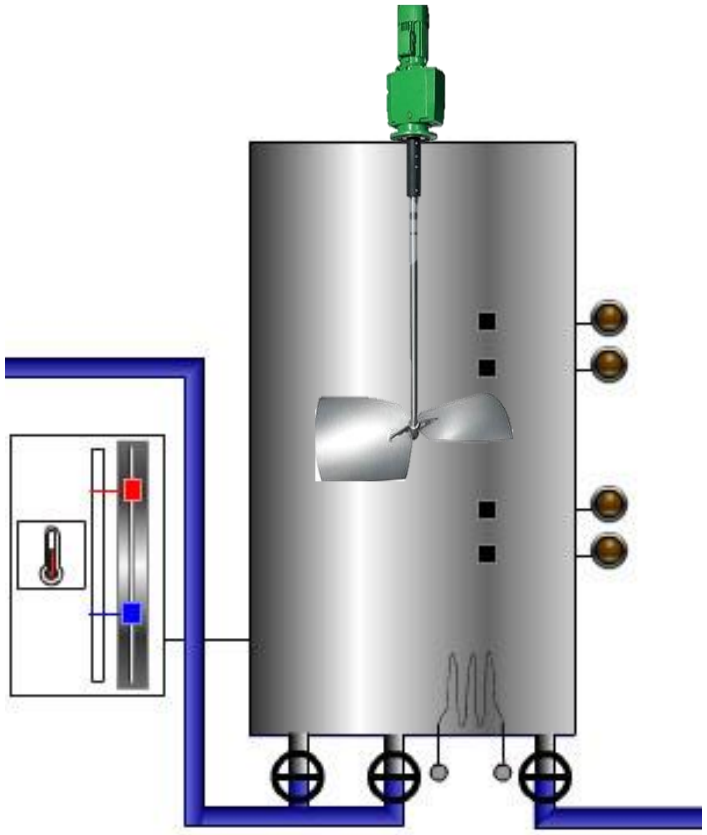
- When a starting switch is activated, the tank is filled with water by holding a valve open until the tank is full (level sensor gives logical high signal).
- Then the water is heated with the help of a heating element.
- When the water has reached a temperature of 95°C, the heating is stopped, and an agitator starts.
- The agitator runs for 5 minutes.
- Then the tank is drained by holding a bottom valve open until the tank is empty (another level sensor switches to logical low signal).
- The entire operation is repeated three times. After that, the program awaits a new signal to start.



Juice tank

Co-funded by the European Union

Flowchart diagram – wash operation



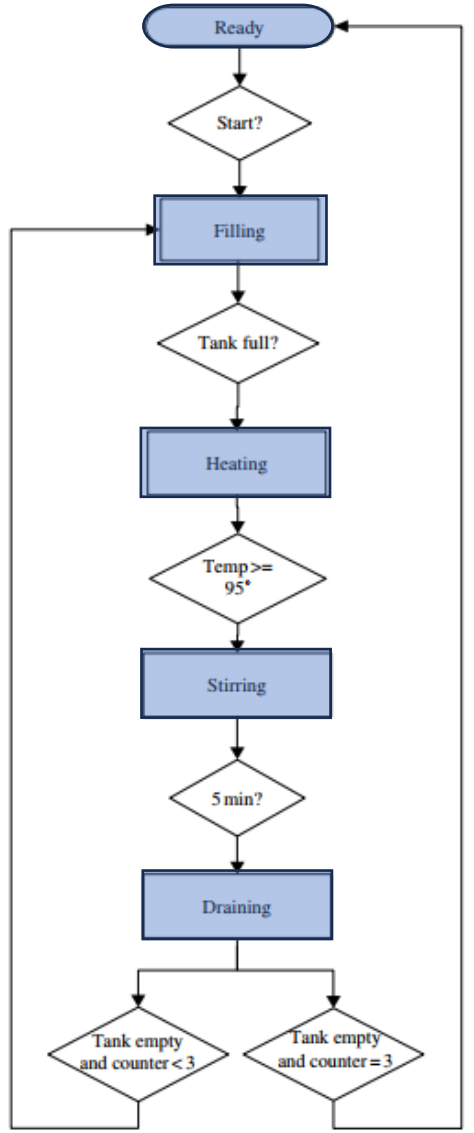
Juice tank

From the flowchart we can identify the following five states:

- Ready
- Filling
- Heating
- Stirring
- Draining

**A counter may be incremented by one every time "Filling" starts and reset to zero when the state in "Ready"*

*** Microsoft Visio can be used to build flowcharts*



Flowchart for wash operation

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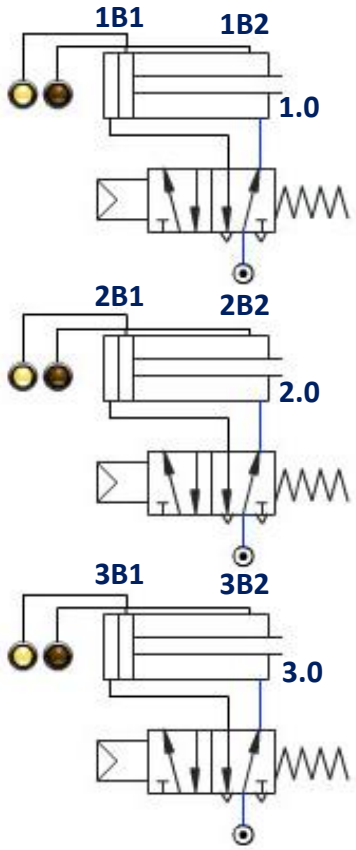
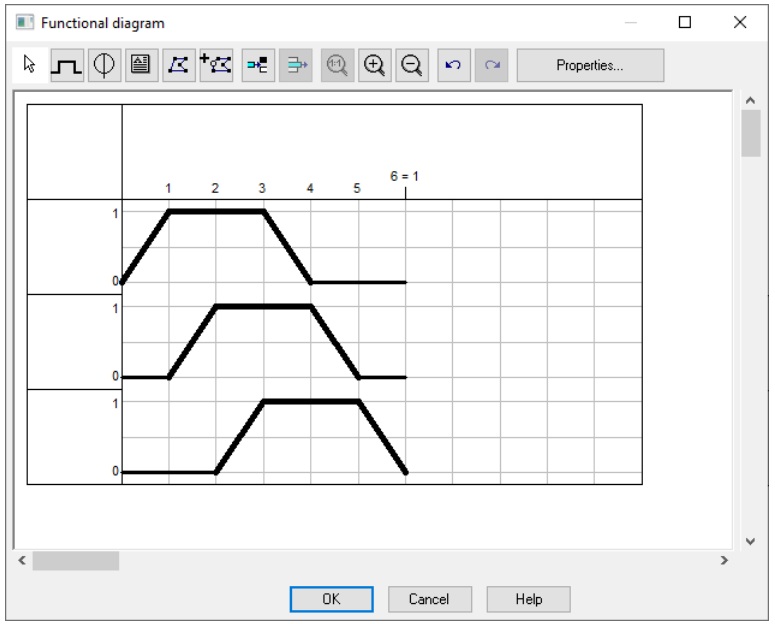
NextGEng

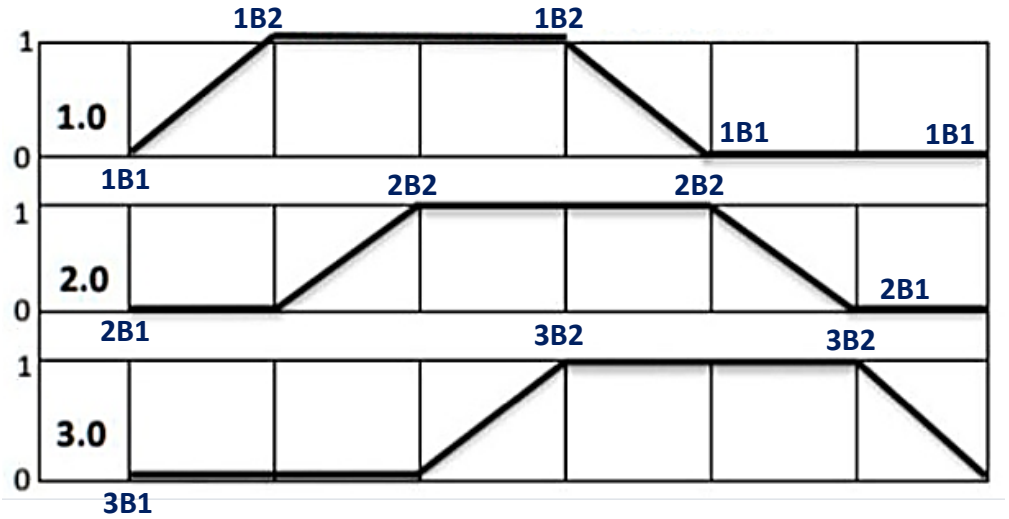
Sequence diagram - piston displacement





FESTO FluidSIM – Functional diagram tool

The purpose of a sequence diagram is to show the state of all Boolean signals in the control unit for a defined sequential operation.



Sequence Diagram for three Double-Acting Cylinder

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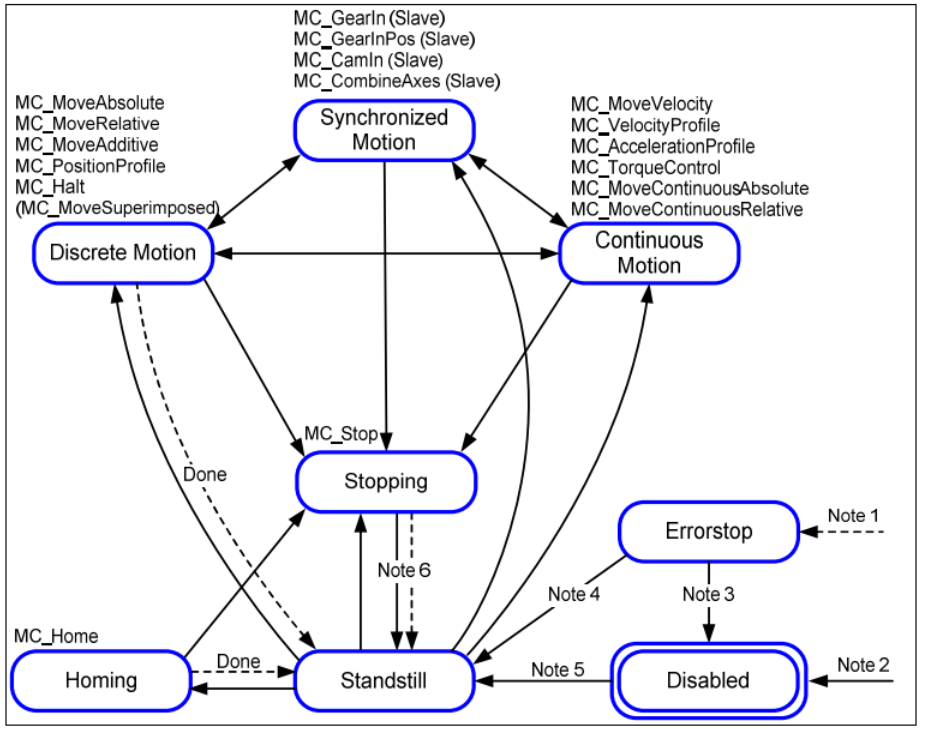
NextGEng

State diagram – motion control of axes

Currently the suite of **PLCopen Motion Control** Specifications consists of the following parts:

Part 1 - Function Blocks for Motion Control
Part 2 - Extensions (in the new release 2.0 merged with Part 1)
Part 3 - User Guidelines
Part 4 - Coordinated Motion
Part 5 - Homing Procedures
Part 6 - Fluid Power Extensions

https://plcopen.org/



Note 1:	From any state. An error in the axis occurred.
Note 2:	From any state. MC_Power.Enable = FALSE and there is no error in the axis.
Note 3:	MC_Reset AND MC_Power.Status = FALSE
Note 4:	MC_Reset AND MC_Power.Status = TRUE AND MC_Power.Enable = TRUE
Note 5:	MC_Power.Enable = TRUE AND MC_Power.Status = TRUE
Note 6:	MC_Stop.Done = TRUE AND MC_Stop.Execute = FALSE

State diagram for motion control of industrial axes

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GRAFCET diagrams

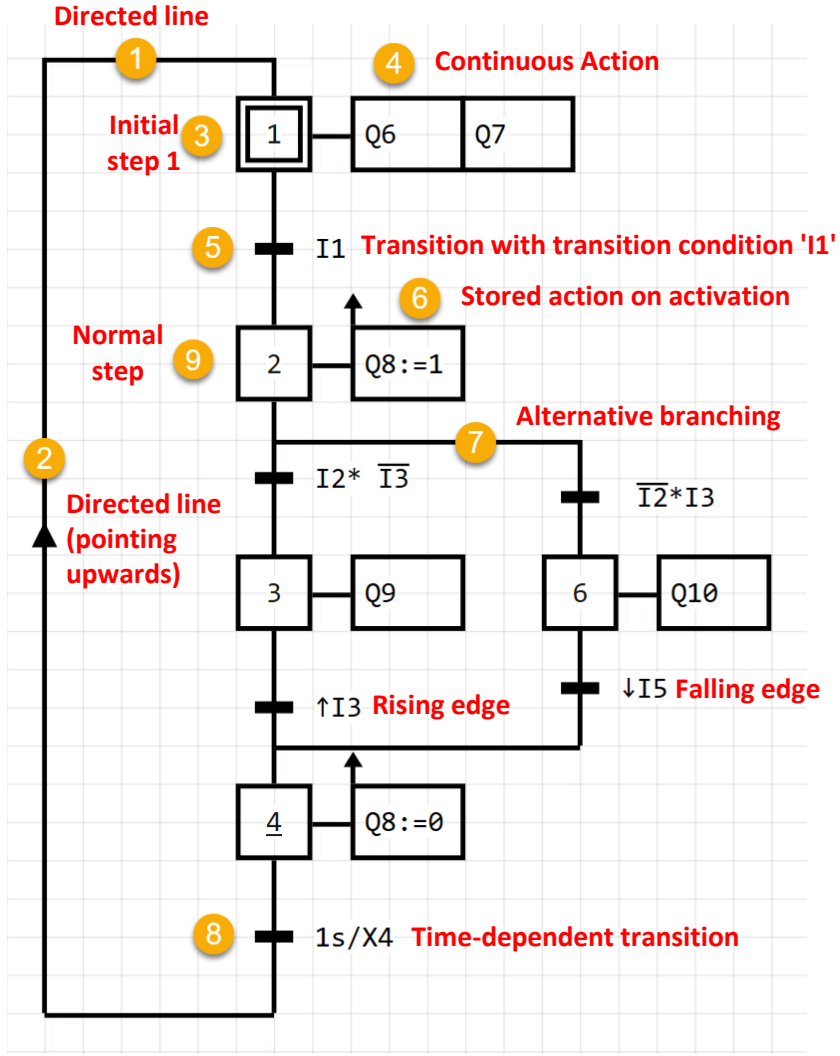
IEC 60848:2013 - GRAFCET specification language for sequential function charts

IEC 60848:2013 defines the GRAFCET ***specification language for the functional description of the behaviour of the sequential part of a control system****.*

It specifies the ***symbols and rules for the graphical representation of this language****, as well as for its interpretation and has been prepared for automated production systems of industrial applications.*

GRAFCET *is an important topic for anyone concerned with* ***engineering*** *in any of its facets.* ***Mechanics, electrical engineers and programmers can now speak one common language when discussing how a machine works: GRAFCET****.*

https://www.mhj-wiki.de/en/grafcet-workbook/introduction/



Example of a GRAFCET diagram

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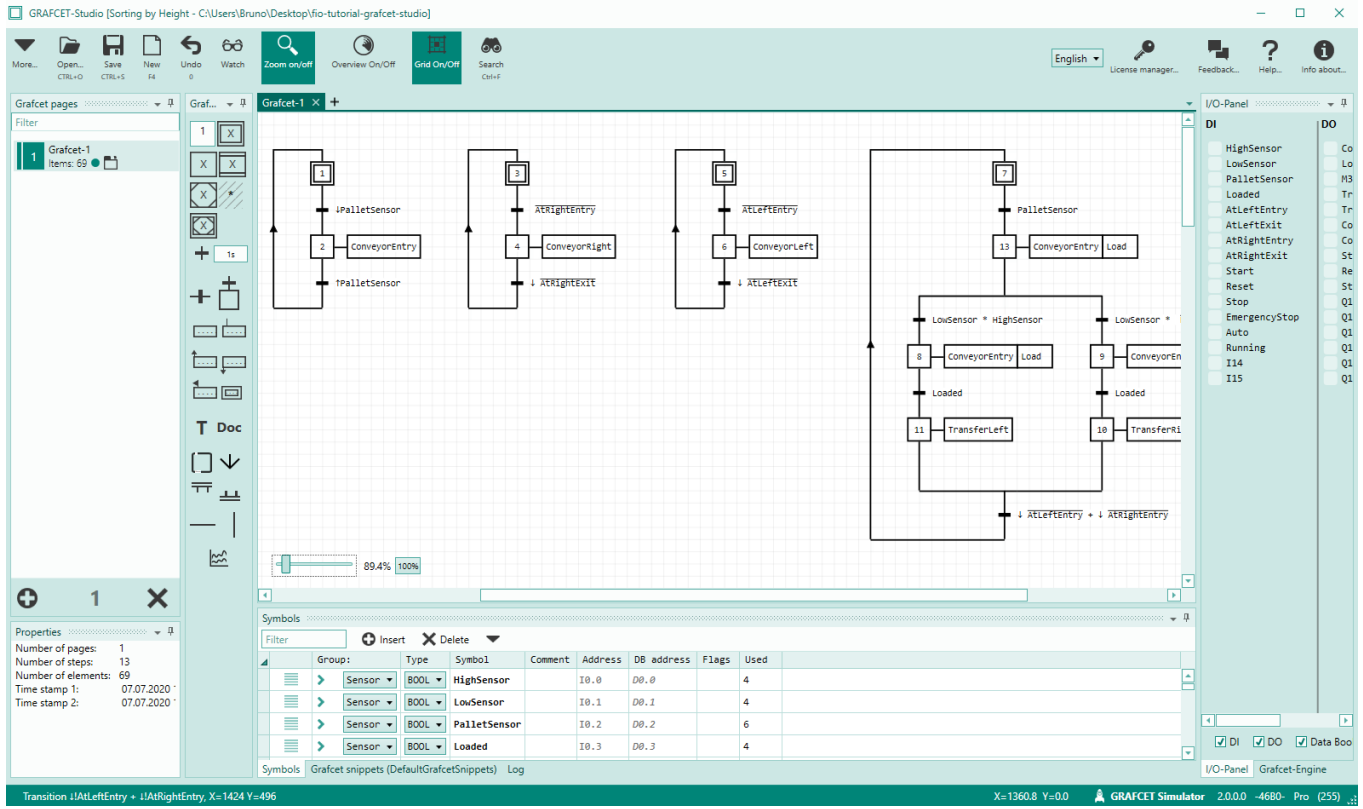
GRAFCET diagrams



GRAFCET-Studio: https://www.mhj-tools.com/?page=grafcet-studio

Draw it - simulate it - 'device it'

Supported devices: Siemens S7-300, S7-400, S7-1200, S7-1500, CODESYS V3 based PLCs, Raspberry-Pi, Arduino-Due.

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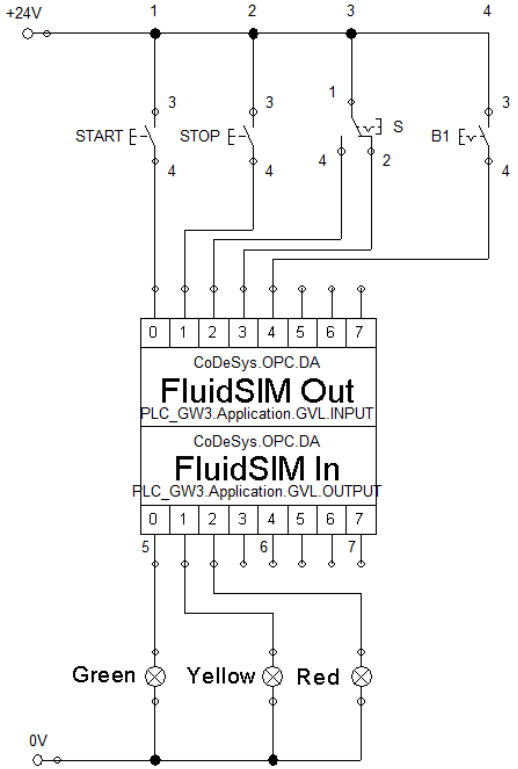
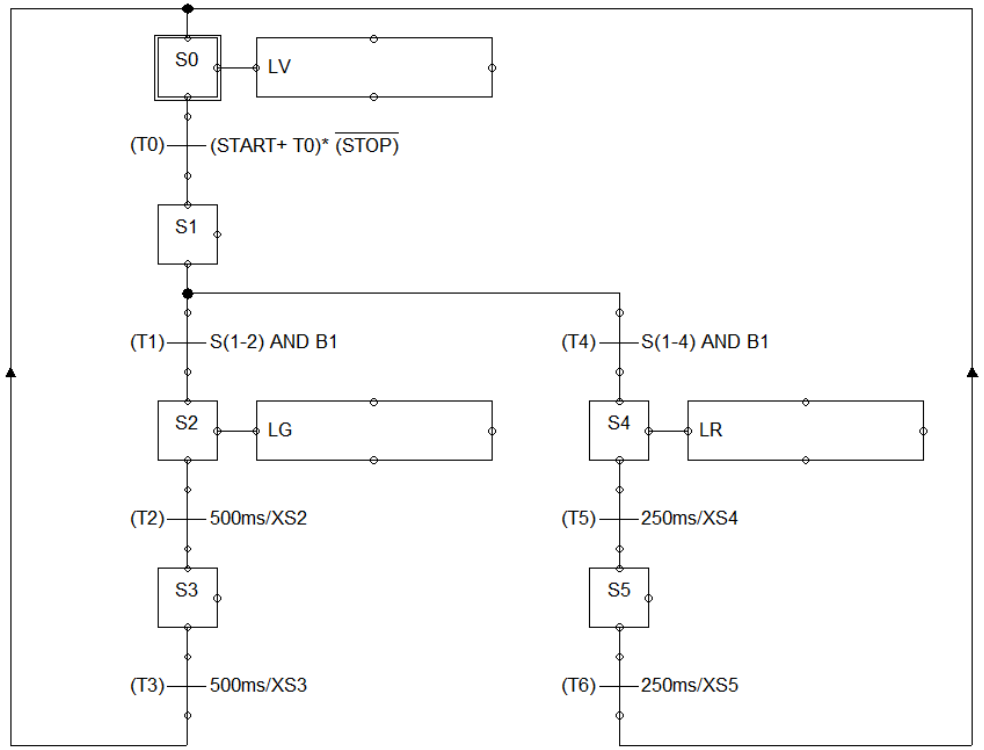
GRAFCET diagram – blinking lamps



Fluid-SIM electric circuit



Fluid-SIM GRAFCET diagram

Textual description

1) When powering up the PLC, the green lamp must be on.
2) When the START button is pressed, the green lamp turns off and the following steps are performed:
 - if the selector S is on position 1-2, then the yellow lamp must work intermittently with a frequency of 1 Hz.
 - if the selector S is on position 1-4, then the red lamp must work intermittently with a frequency of 2 Hz.
3) When the STOP button is pressed, the current cycle is completed, after which the green lamp remains on waiting for the START button to be pressed.

State equations

S0 = S3*T3 + S5*T6 + S0*NOT_S1 + INIT (S0=1)
S1 = S0*T0 + S1*NOT_S2*NOT_S4
S2 = S1*T1 + S2*NOT_S3
S3 = S2*T2 + S3*NOT_S0
S4 = S1*T4 + S4*NOT_S5
S5 = S4*T5 + S5*NOT_S0

Used for translating GRAFCET into LD language for example

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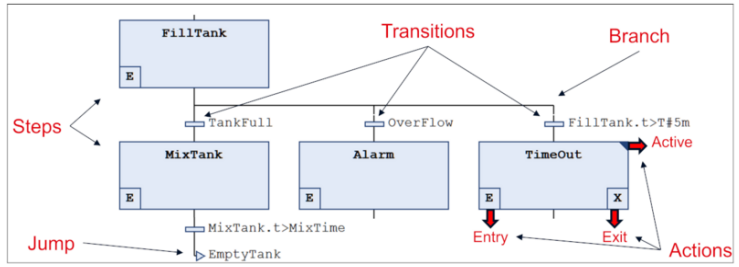
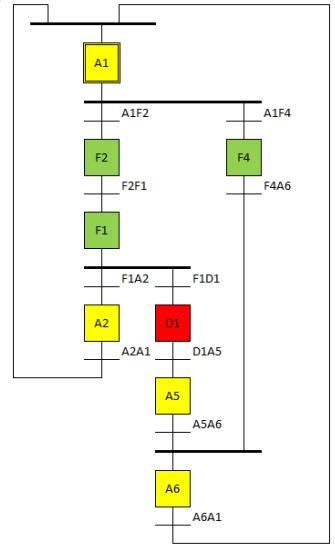
Sequential Control Design

When a starting switch is activated, the tank is filled with water by holding a valve open
until the tank is full (level sensor gives logical high signal).
…

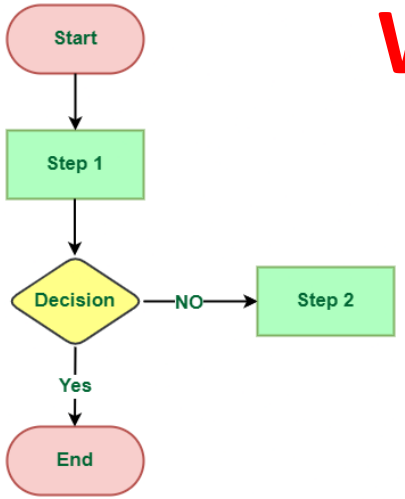
Textual description



SFC diagram

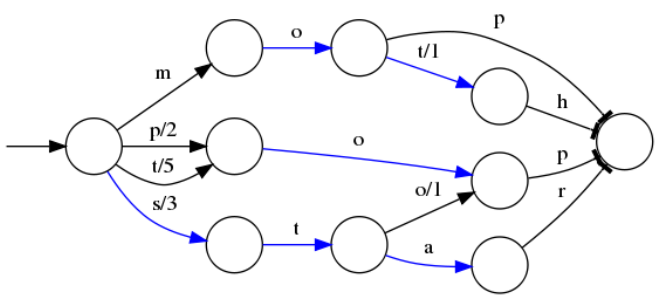


GRACET diagram

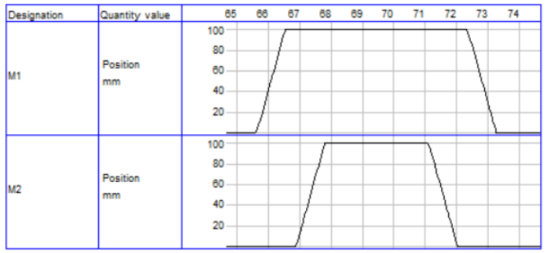


Flowchart diagram

What's the best way of representing sequential processes after all ?



State-Based diagram



Sequence diagram

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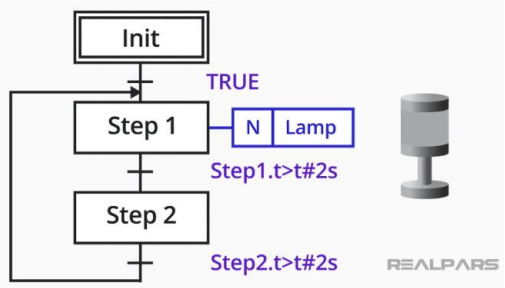
3 **Structured programming using SFC**

IEC 61131-3:2013

- Ladder Logic Diagram (LD)
- Function Block Diagram (FBD)
- Instruction List (IL)
- Structured Text (ST)
- **Sequential Function Chart (SFC)**



Structured programming using SFC

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Structured programming using SFC

- **SFC** is one of the five IEC61131-3 industrial languages and is **"derived"** from GRAFCET
- **GRAFCET** is a **specification language** while **SFC** is a **structuring language** of **sequential applications**, useful in the development and implementation of PLC programs
- The two "languages", even though they are similar, have **different destinations**
- SFC graphs can be implemented in **implicit form** (using the specific instructions of an industrial programming language – LD for example) or in an **explicit form** (using applications or independent software tools that allow graphic structuring of programs)
- **Explicit implementation forms** of SFC are made available to users by most major PLC manufacturers: S7 Graph (Siemens), CX Programmer (Omron), RSLogix5000 (Rockwell Automation/Allen Bradley), Unity Pro (Schneider), etc.

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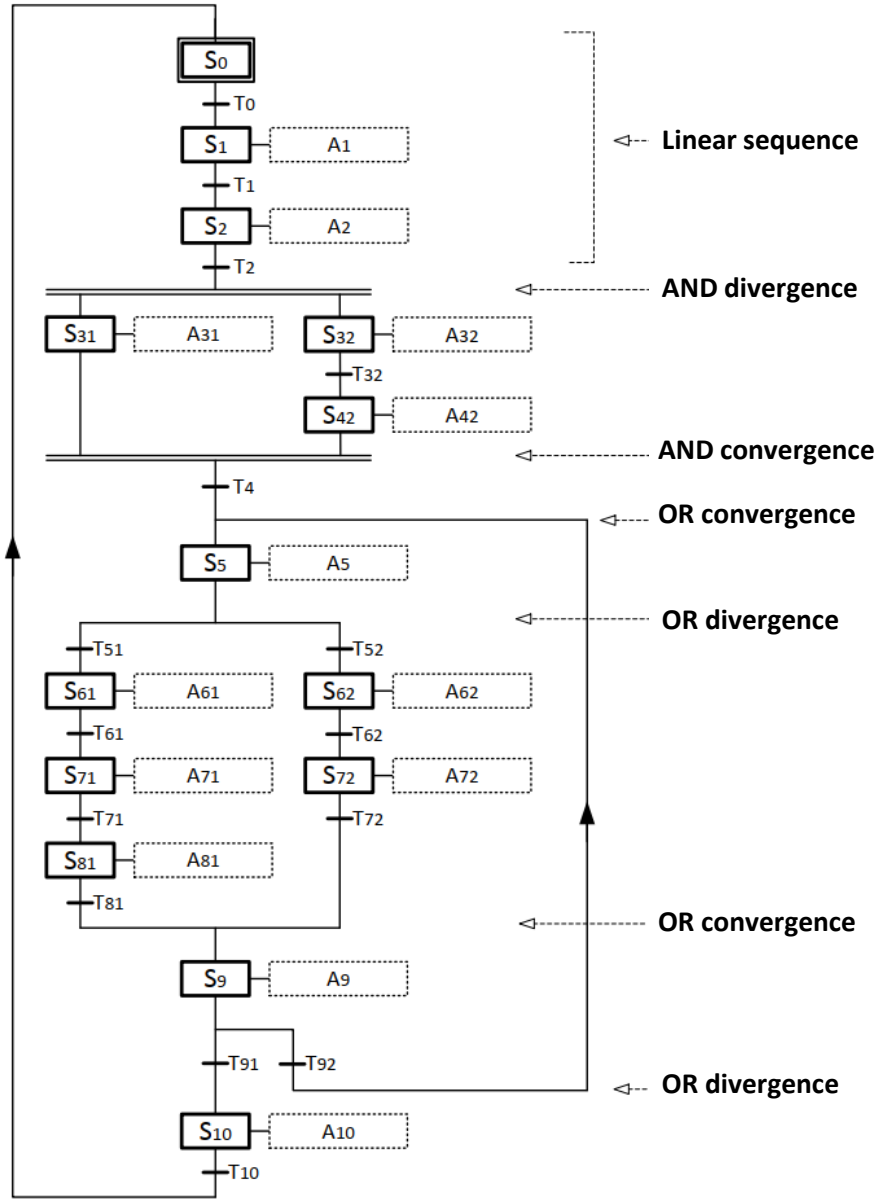
SFC structuring rules

- Linear sequences
- Simultaneous branches
- Alternative branches

→ **Enough to represent any sequential application**

- Steps (initial and normal steps)
- Transitions
- Actions

→ **Structuring elements**



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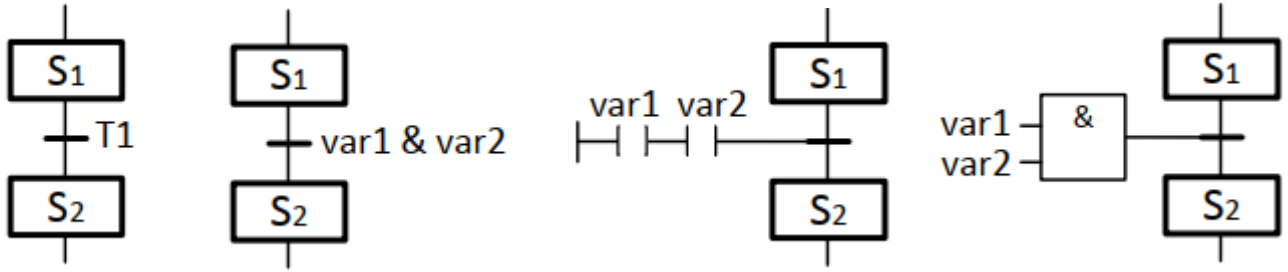
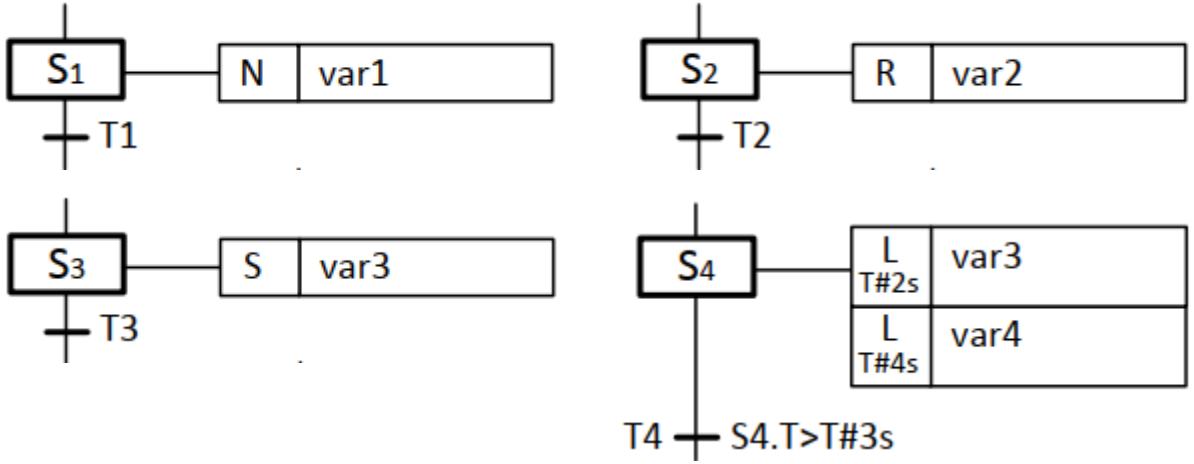
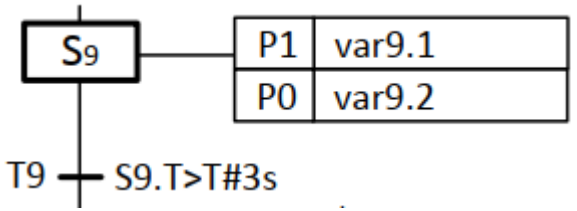
SFC structuring rules

Transitions implementation - examples



Action implementation - examples





Action type	IEC 61131-3 description
N	**N**on-stored
R	overriding **R**eset
S	**S**et (**S**tored)
L	time **L**imited
D	time **D**elayed
P	**P**ulse
SD	**S**tored and time **D**elayed
DS	**D**elayed and **S**tored
SL	**S**tored and time **L**imited
P1	**P**ulse (rising edge)
P0	**P**ulse (falling edge)

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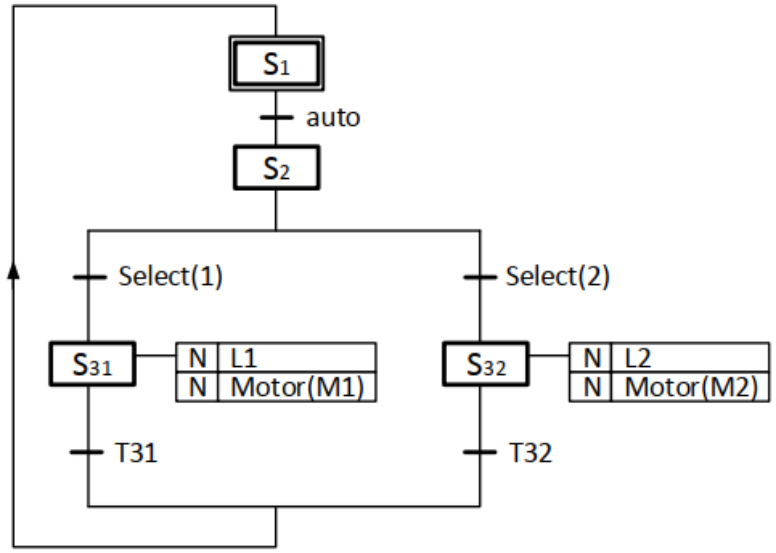
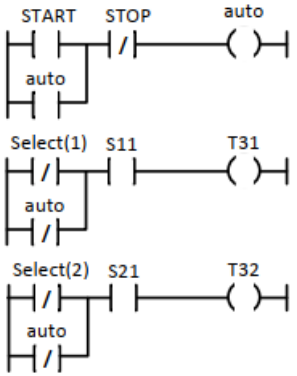
SFC structuring rules

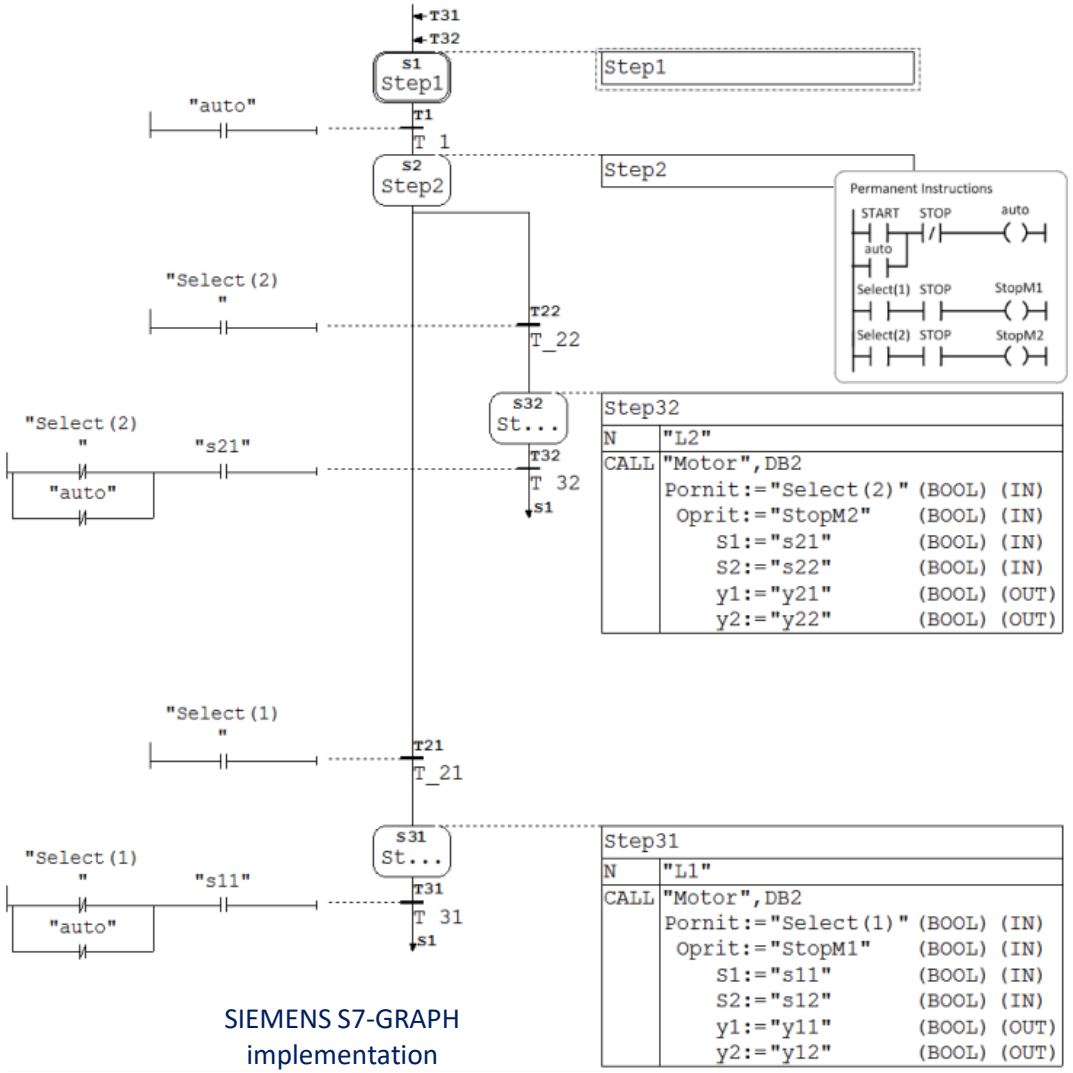
SIEMESN S7-GRAPH Example



Implementation graph using SFC rules



Description of the transitions



SIEMENS S7-GRAPH implementation

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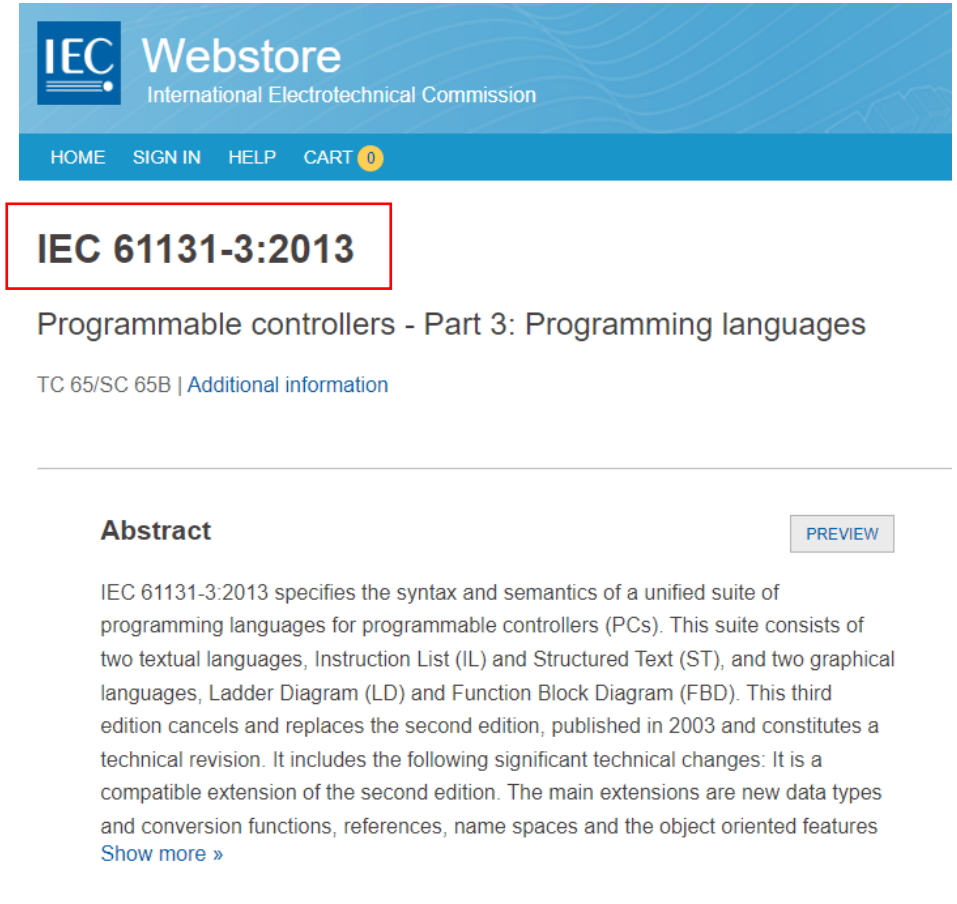
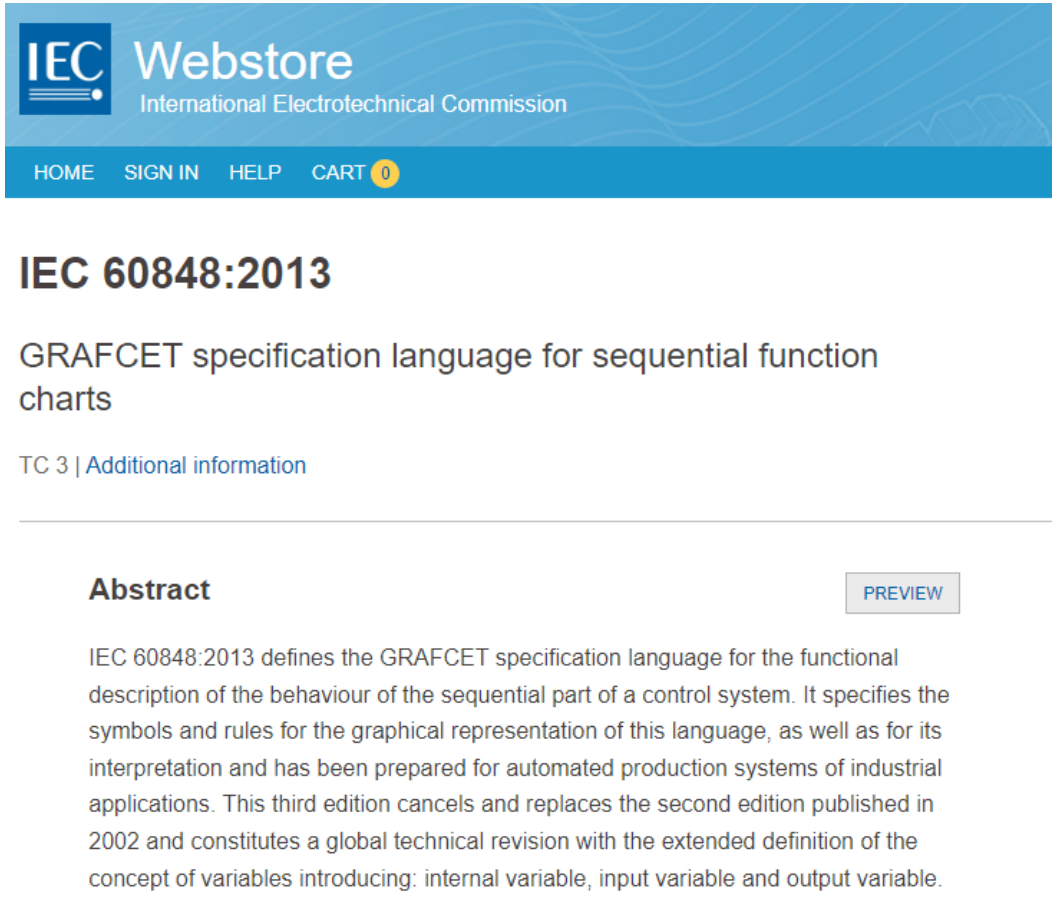
Further information





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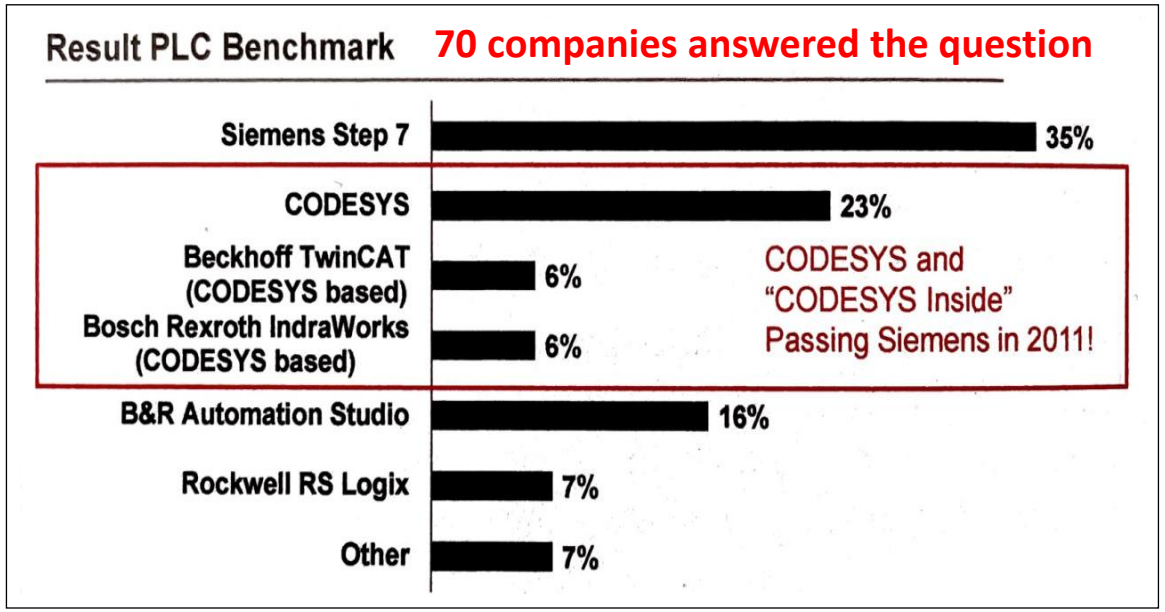
IEC 61131-3 and PLCs manufacturers

“Which development system do you use for programming your control system?”

Survey of “Computer & AUTOMATION” and two German Universities, 2011



Source: The Book of CODESYS: The ultimate guide to PLC and Industrial Controls programming with the CODESYS IDE and IEC 61131-3.

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SIEMENS and IEC 61131-3

How do you program the PLC with STEP 7 (TIA Portal) in compliance with the IEC 61131-3 standard?

Entry | Associated product(s)

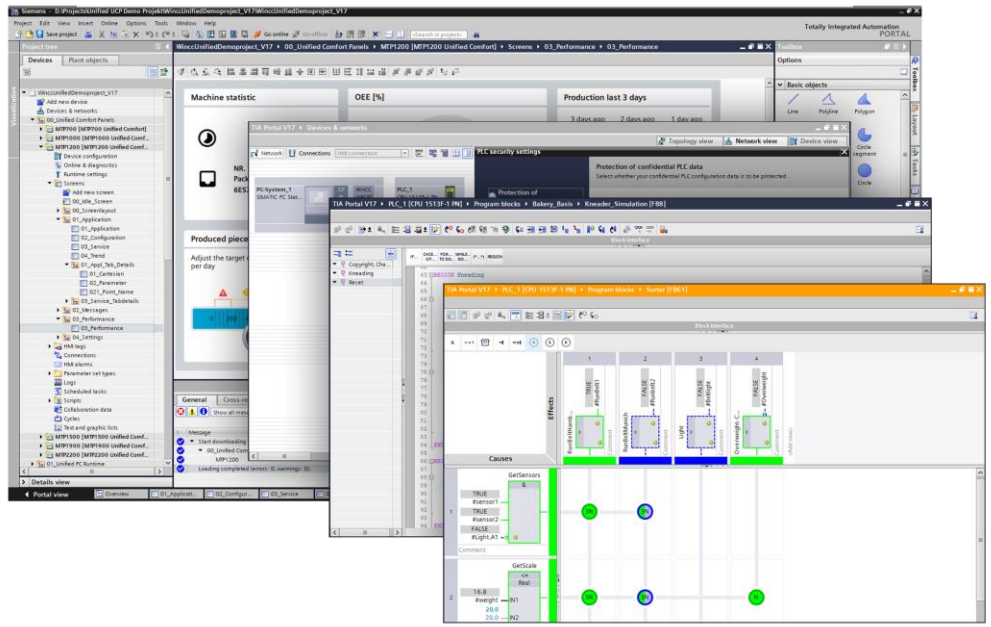
The attached PDF document gives you detailed information.

Description
The programming languages of SIMATIC STEP 7 (TIA Portal) meet the requirements of IEC 61131-3. The IEC 61131-3 standard is the only standard valid worldwide for the programming languages of programmable logic controllers.
The following table gives you an overview:

STEP 7 (TIA Portal)	IEC 61131-3 languages
Instruction List (AWL/STL)	Corresponds to IEC 61131-3 language "AWL/IL"
Ladder Logic KOP/LAD	Corresponds to IEC 61131-3 language "KOP/LD"
Function Block Diagram FUP/FBD	Corresponds to IEC 61131-3 language "FUP/FBD"
Structured Control Language SCL	Corresponds to IEC 61131-3 language "ST"*
S7-GRAPH	Corresponds to IEC 61131-3 language "AS/SFC"*

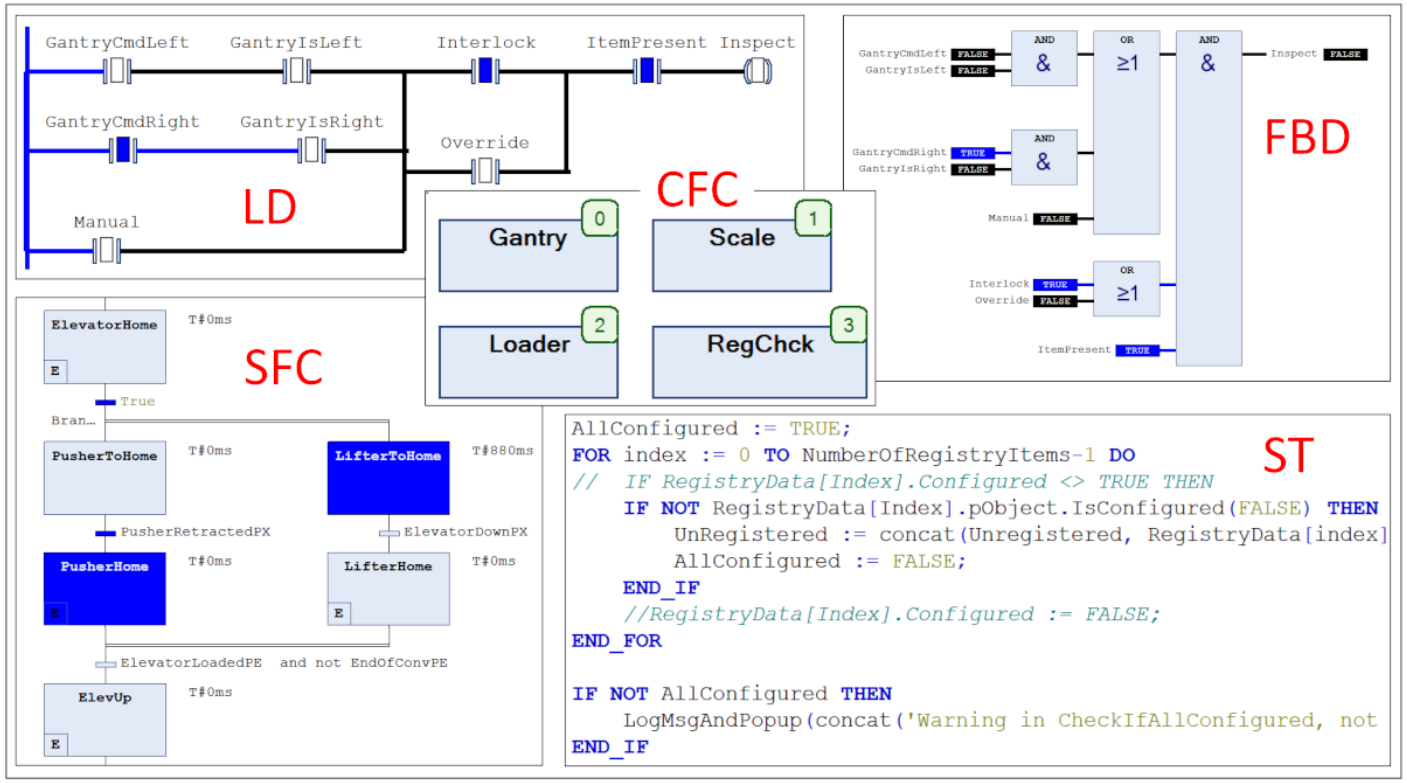
Detailed information is available in the "IEC_61131_Compliance" file.

IEC_61131_compliance_e.pdf (122 KB)



Source: https://support.industry.siemens.com/cs/document/8790932/iec-61131-3-and-simatic-s7?dti=0&lc=en-RO

CODESYS and IEC 61131-3



Source: https://www.codesys.com/news-events/publications/article/which-iec-61131-3-programming-language-is-best-part-1.html

PLC – based on CODESYS

- ABB (Switzerland)
- Schneider Electric (France)
- Beckhoff (Germany)
- Bosch (Germany)
- Festo (Germany)
- Lenze (Germany)
- IFM (Germany)
- Mitsubishi (Japan)
- HoneyWell (USA)
- Delta (Taiwan)

PLC – pure CODESYS

- Wago (Germany)
- Kendrion-Kunke (Netherland)
- Phoenix Contact (Germany)
- Hitachi (Japan)
- Eaton (USA)

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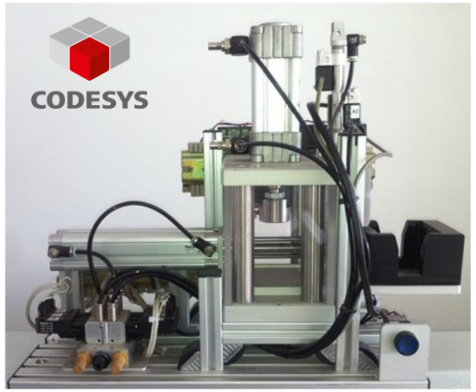

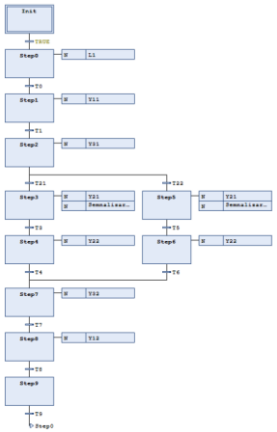

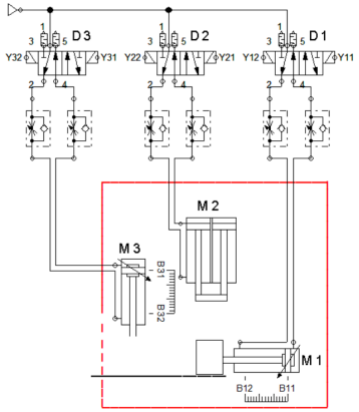

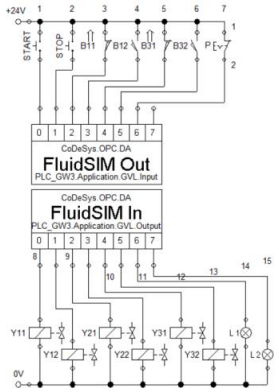

Industry case study – pneumatic press

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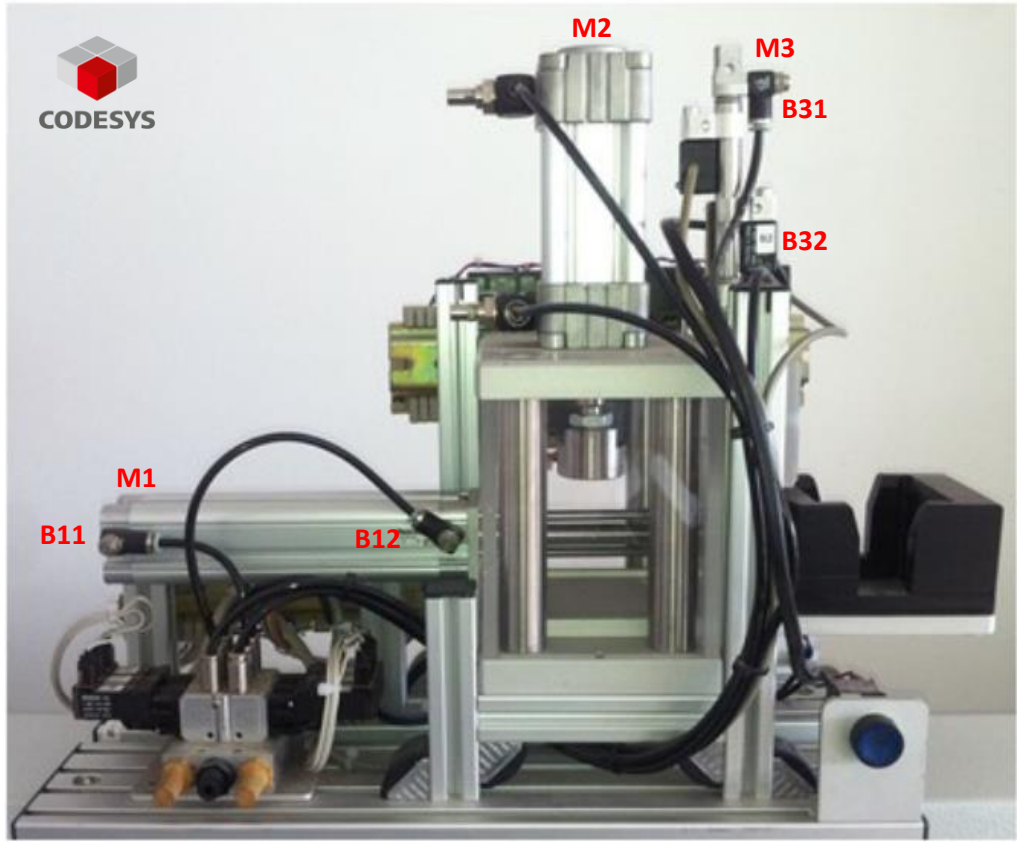
NextGEng

Industry case study – pneumatic press

An electropneumatic press is shown in the figure. It includes a press room, a feeding system and a sliding door for securing the press room. The actuating circuit is consisting of three linear pneumatic motors: M1, M2 and M3.

Technical description of the system:
- M1, M2, M3: linear pneumatic motors;
- P: part identification sensor (plastic (1); metal (0));
- B11, B12, B31, B32: position sensors;
- START/STOP: process control buttons;
- Y11, Y12, Y21, Y22, Y31, Y32: electromagnets;
- L1,L2: signal lights.



Pneumatic press

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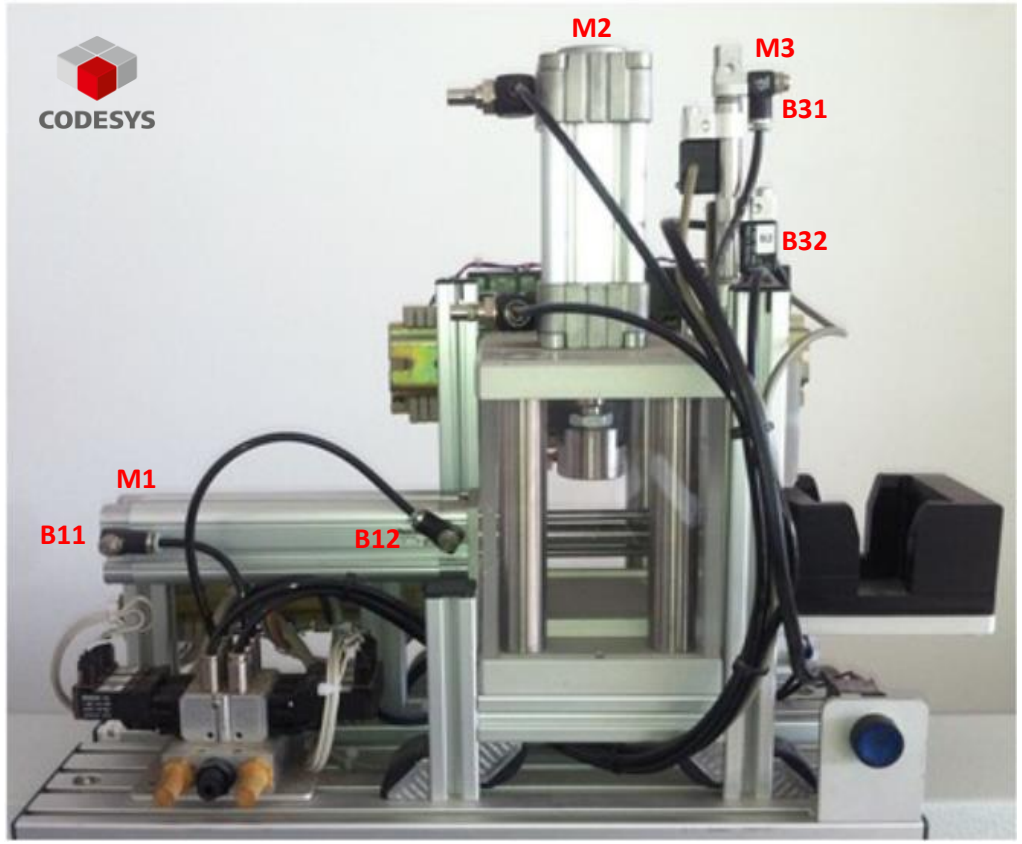
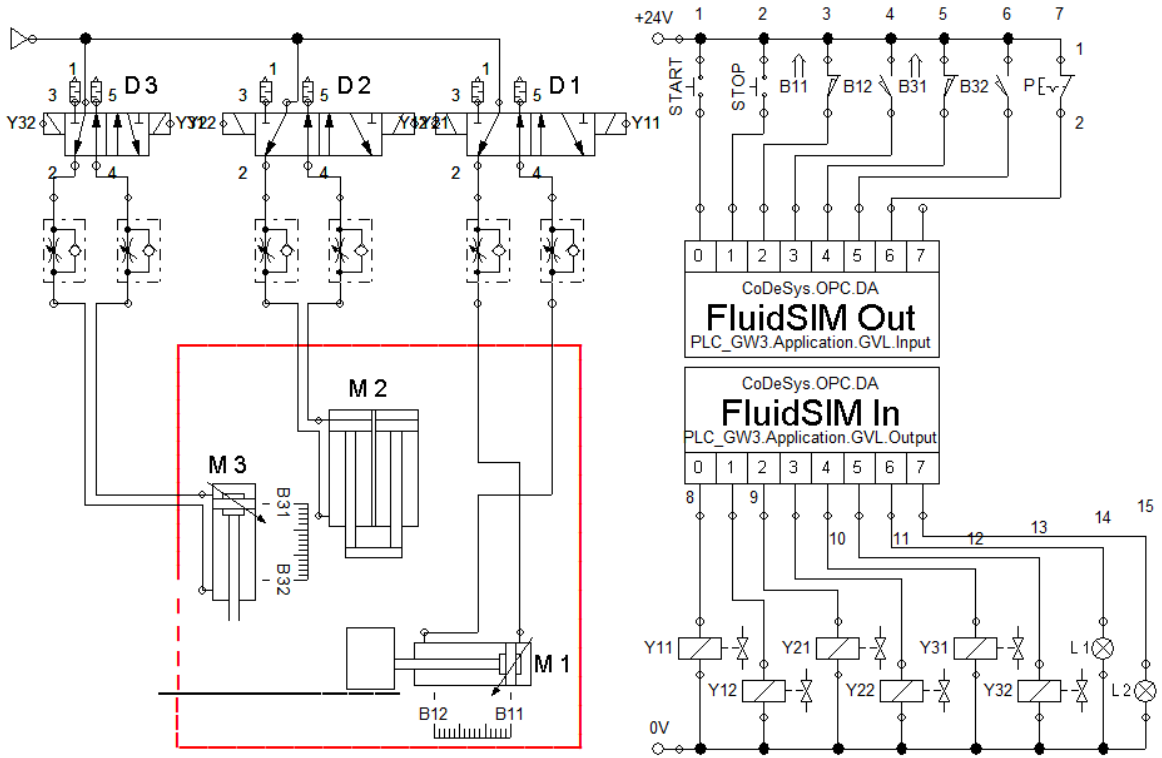
Industry case study – pneumatic press



Pneumatic press



Electropneumatic circuit

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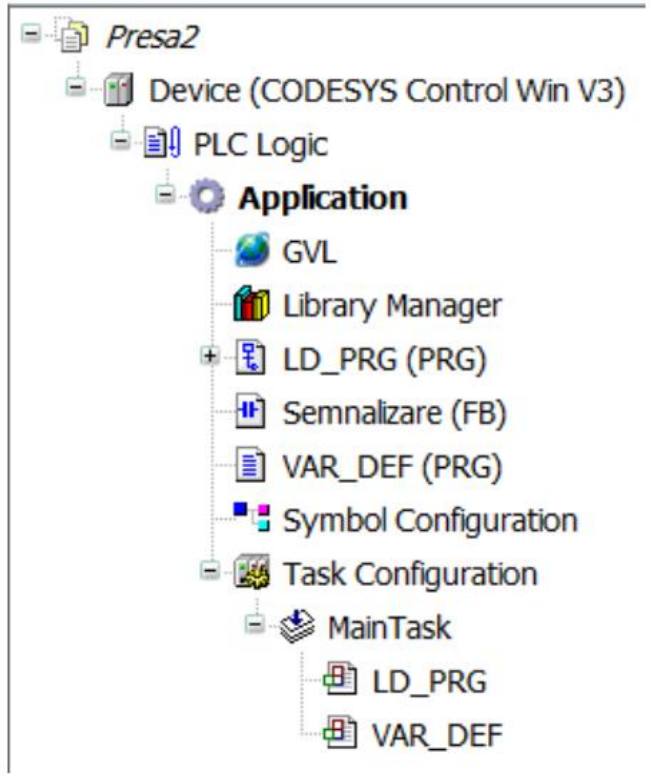
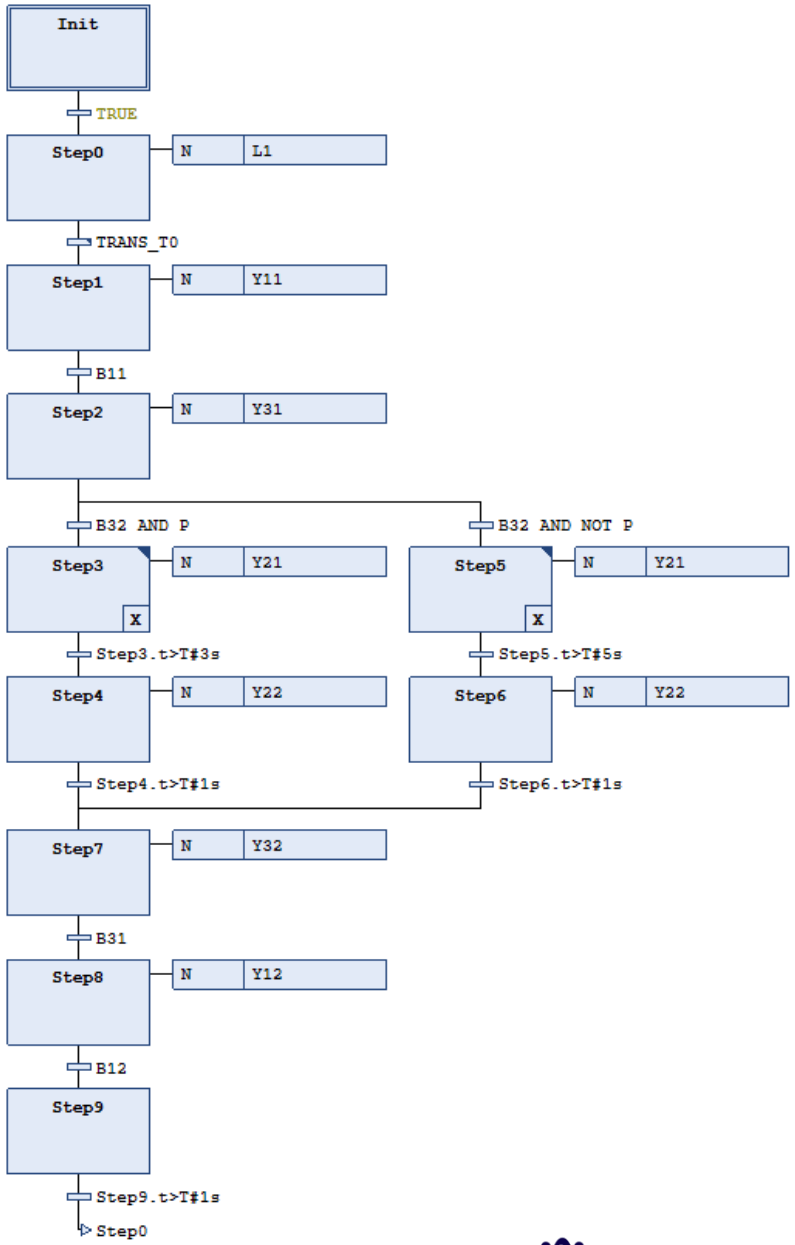
Task – Pressing process



CODESYS project

SFC implementation graph



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Summary

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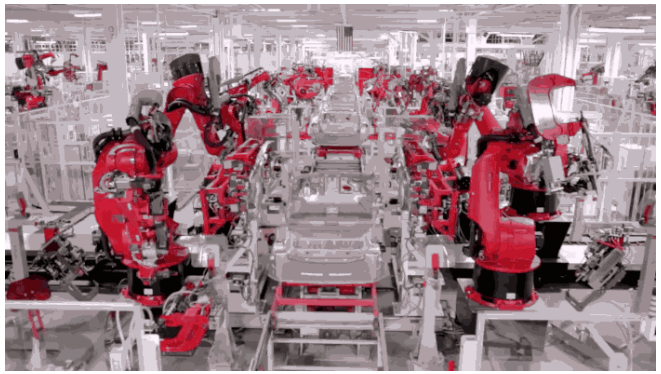
M2 - Structured Programming. Sequential Function Chart (SFC). GRAFCET

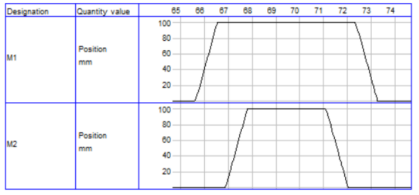
1 Industry 4.0 - Automation Reinvented

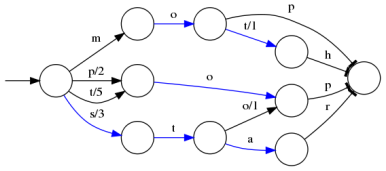


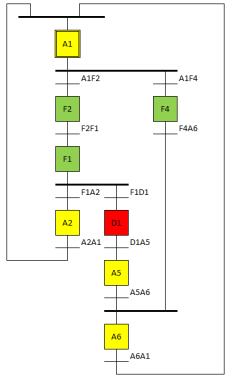
*"Tesla says the **Model 3** body line is now **95 percent automated**, including the transfer, loading, and welding of parts."*

Source: https://www.carrushome.com/en/tesla-model-3-body-line-now-95-percent-automated

2 Sequential Control Design



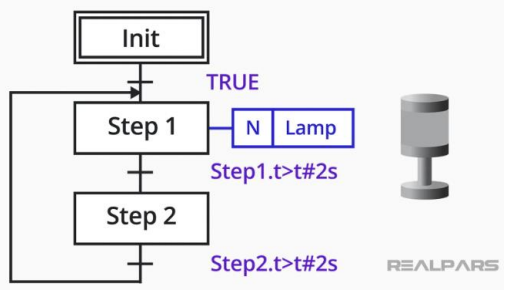




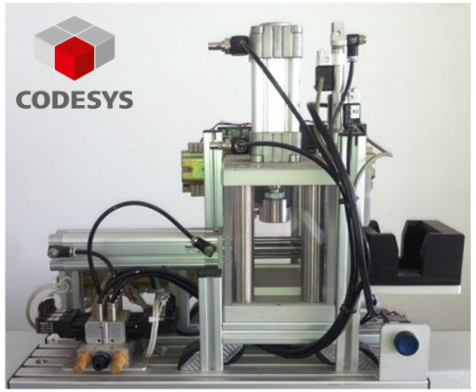
3 Structured programming using SFC

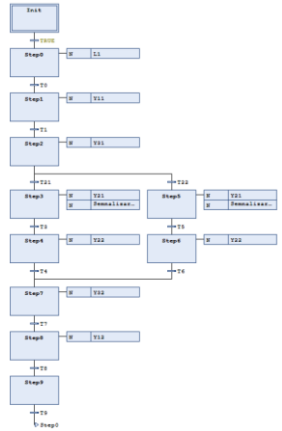
IEC 61131-3:2013

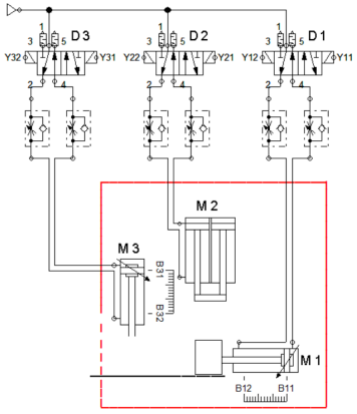
- Ladder Logic Diagram (LD)
- Function Block Diagram (FBD)
- Instruction List (IL)
- Structured Text (ST)
- Sequential Function Chart (SFC)

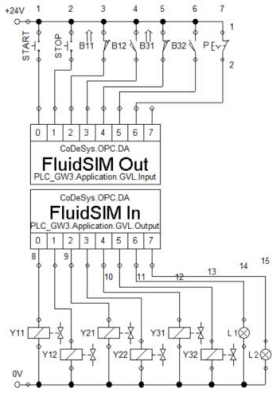


4 Industry case study – pneumatic press









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[1] Olimpiu Hancu, Ciprian R. Rad, *Controlere Logice Programabile – Programarea și Dezvoltarea Aplicațiilor Industriale*, UT PRESS, 1st edition, Cluj-Napoca, 2017, ISBN: 978-6067372328.

[2] Dag H. Hanssen, *Programmable Logic Controllers: A Practical Approach to IEC 61131-3 using CoDeSys,* Wiley, 1st edition, September 11, 2015, ISBN: 978-1118949245.

[3] Gary L. Pratt PE, *The Book of CODESYS: The ultimate guide to PLC and Industrial Controls programming with the CODESYS IDE and IEC 61131-3,* ControlSphere LLC, First Edition, October 25, 2021, ISBN: 978-1737821403.

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Thank you!

Kiitos!

Gracias!

Mulțumesc!

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C2 – Industrial Automation

M3 – DCS

JAMK University of Applied Sciences

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Content

- DCS in general
- Connections to Field
- Cases of study: Water Process & Software development tools
- Summary

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1

Topic 1 DCS IN GENERAL

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DCS – DISTRIBUTED CONTROL SYSTEM

- Common in heavy process automation (pulp, paper, power plants, dairies and food industry, chemical industry, cruise ships, etc.)
- Comprehensive system (process controllers, networking, SW+HW tools, user interface, historian, etc.)
- Very effective development tools for large applications
  - Typical IO-count ~ 1000-X0000
  - Very scalable
- Often proprietary, but with good connectivity
- Very long lifespan
- Slow cycle times if compared to a PLC
- Much easier to scale and manage big projects if compared to PLC-based systems
- Multiple operators
- Multiple sites can be networked and monitored from one control room if necessary

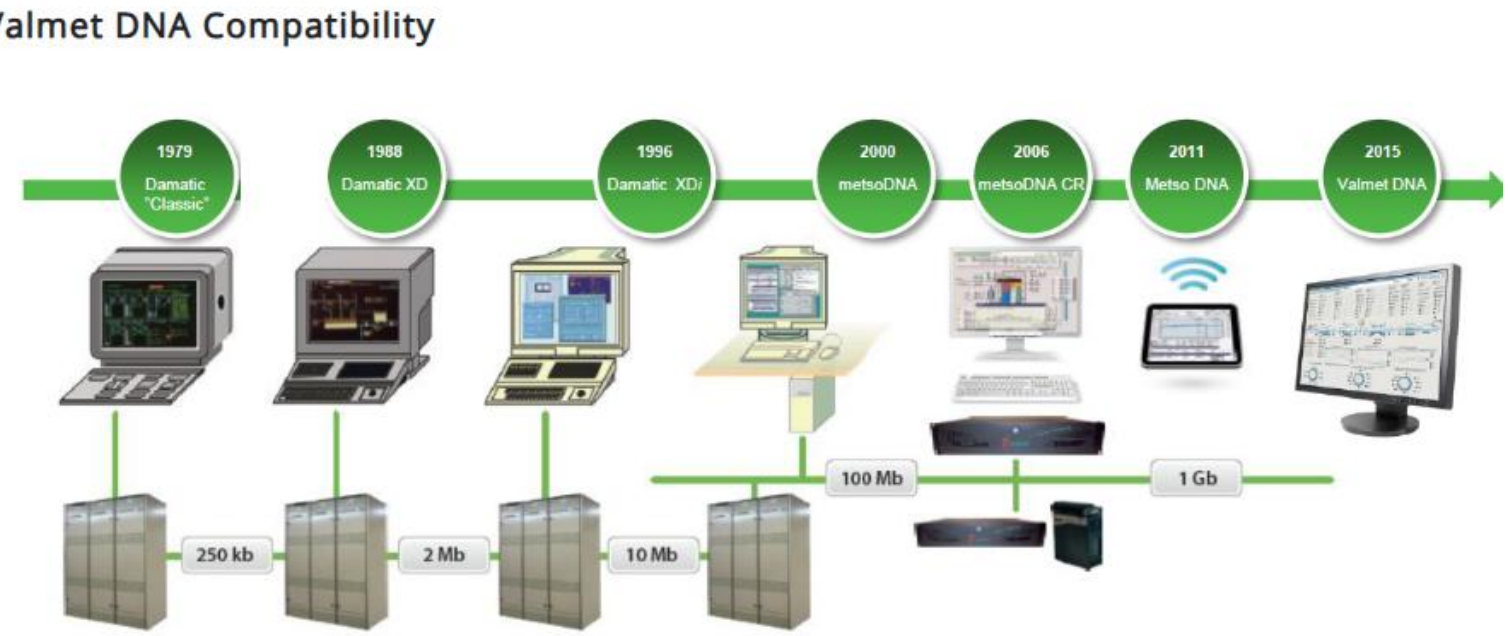

Image source: Valmet

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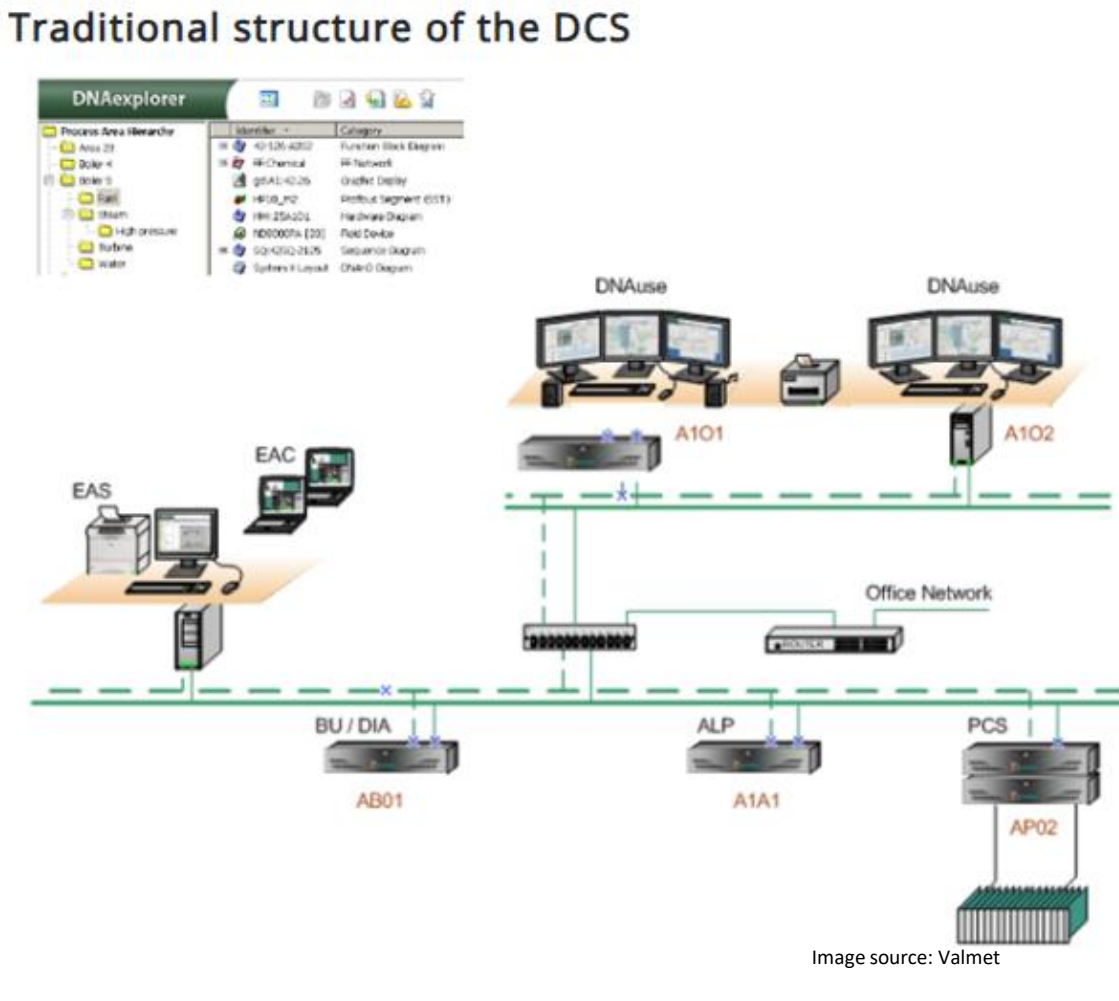
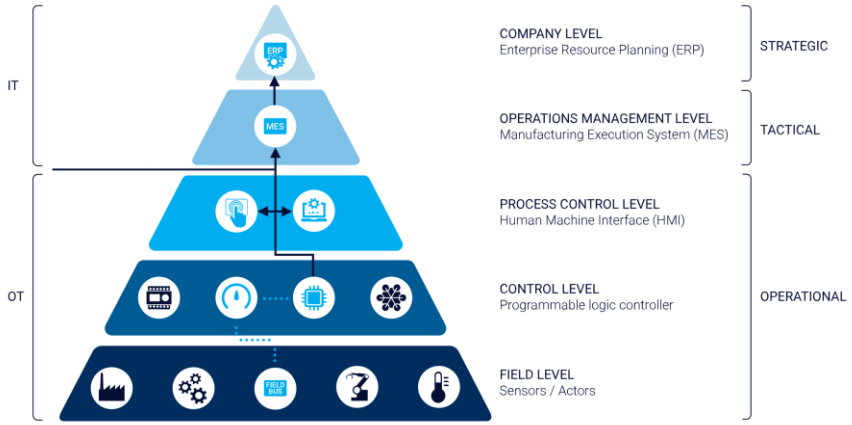
DCS – DISTRIBUTED CONTROL SYSTEM

- In the past DCS system contained many individual and physical networked servers
- Nowadays systems are typically cloud-based
  - On-premises! (usability and security)
  - Servers virtualized





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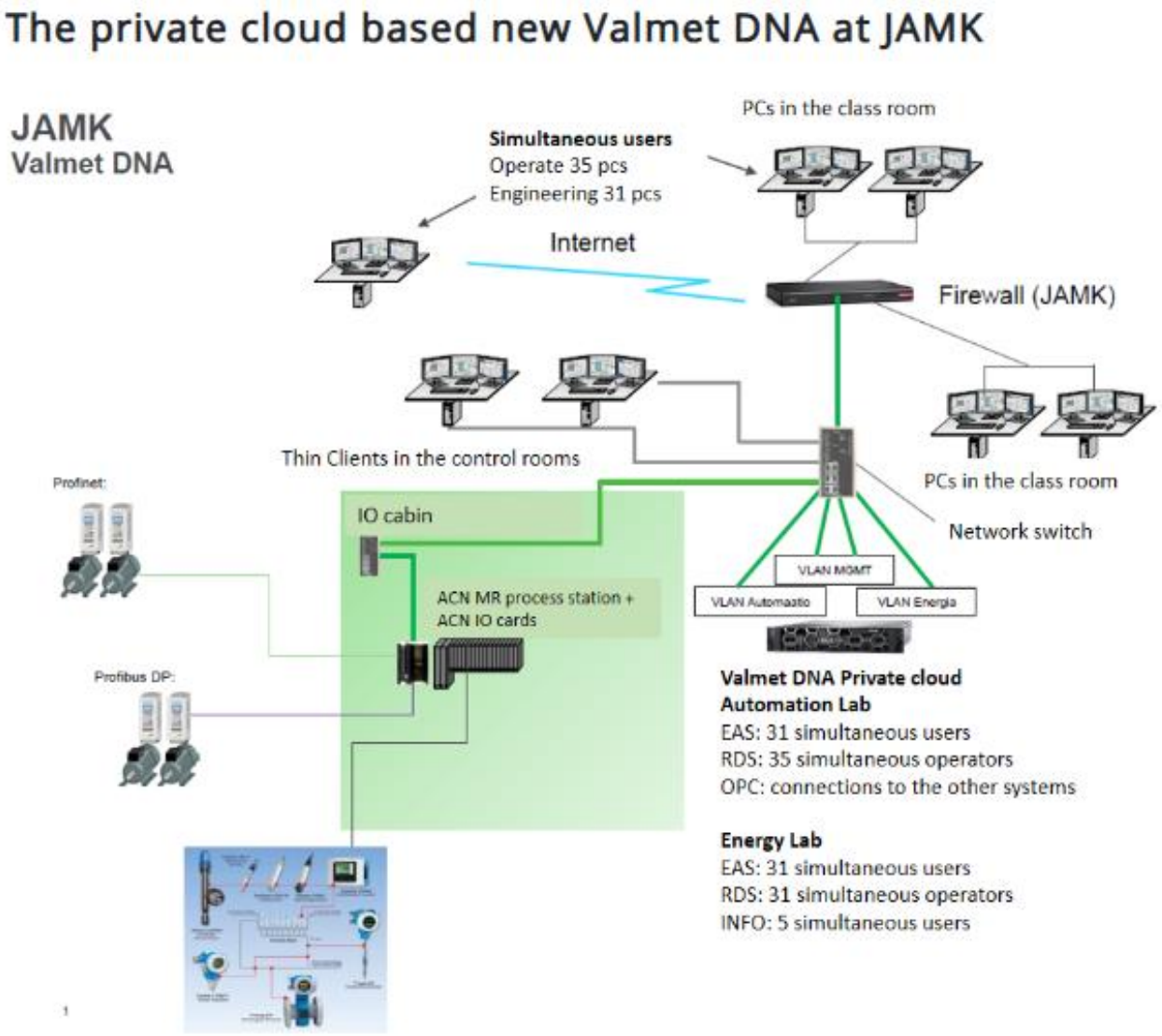
DCS – CLOUD-BASED



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DCS – SCALABILITY

Example site contains paper- and paperboad machines, other needed processes and even own powerplant. Site contains DCS systems from different decades (from Damatic Classic to DNA Network) –> Importance of the overall compatibility.

Note the scale of the site and the plant-wide DCS-system – it would be a struggle to create it and to maintain it (whole lifecycle) with a conventional PLC-based system!

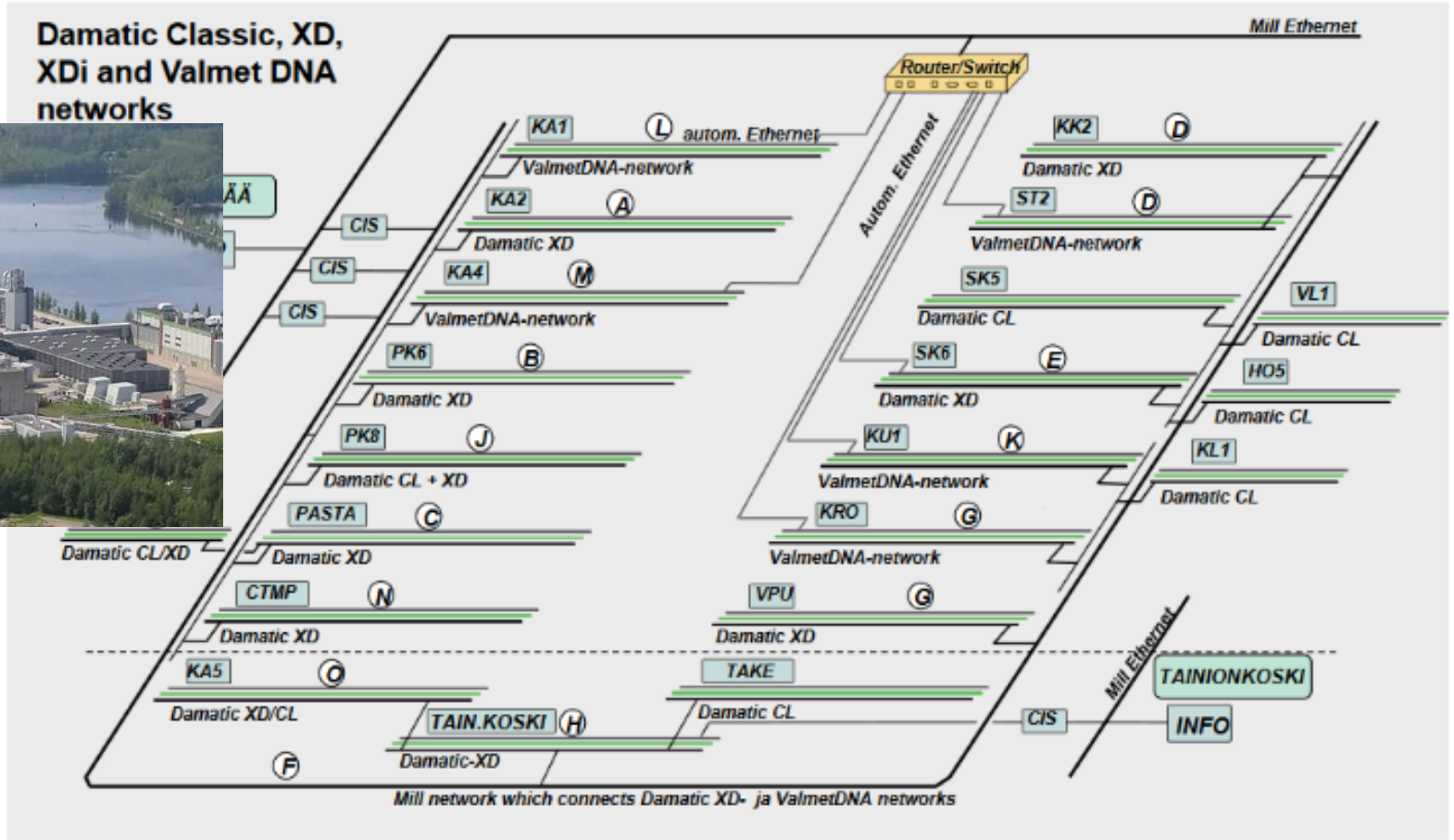

Image sources: Valmet

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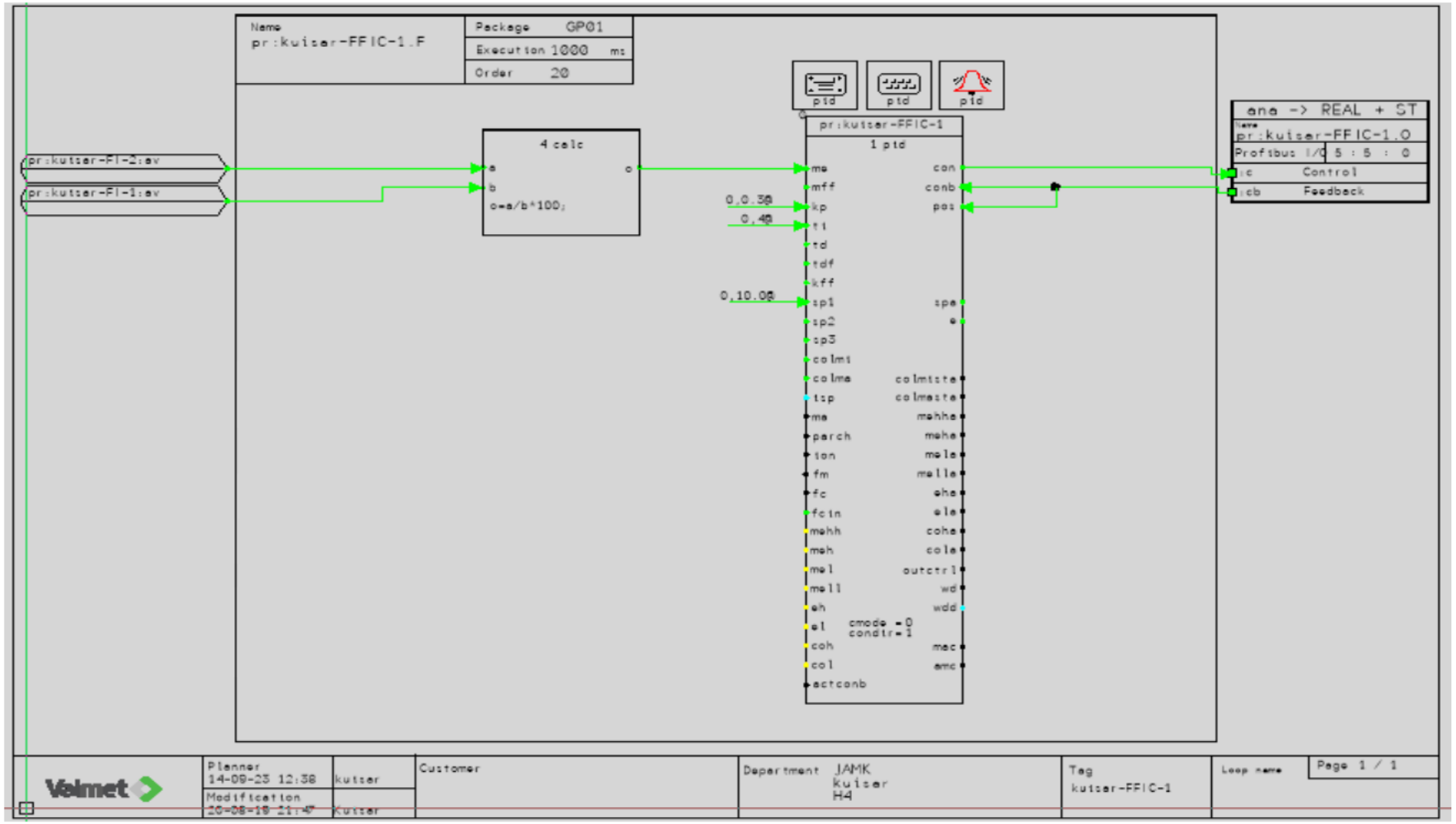
DCS – APPLICATION SOFTWARE

Appearance of the development tools for the DCS doesn't necessarily follow the IEC 61131-3 standard – but many principles are the same.

In the other hand some of the DCS systems are based on the certain PLC CPU's and are partially configured/programmed with the same tools than normal PLC's (e.g Siemens PCS7).



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Topic 2 DCS FIELD CONNECTIONS

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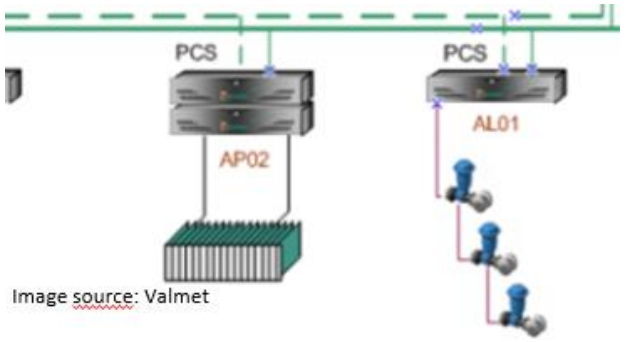
DCS – FIELD CONNECTIONS

Fieldbus connections or Traditional IO – both have pros and cons

Each connection has its own FieldBusController (master)

- IO-racks or Fieldbus devices are connected as slaves to certain FBC

- Fieldbus connections enables the features of the *intelligent field devices*. E.g integration of continuous device specific online diagnostics information to DCS tools for *preventive maintenance* (e.g. control valves) → Reduces unplanned downtime and environmental emissions caused by unexpected process disturbances. Cons: any changes to bus configuration usually demands controller reboot and single fault (in a device/segment) may bring the whole bus down.
- Well designed traditional IO system is robust, has an extremely long lifespan/compatibility, and it enables e.g. adding new measurements without rebooting DCS. Cons: more wiring and very limited possibilities to utilize the features of the intelligent field devices.



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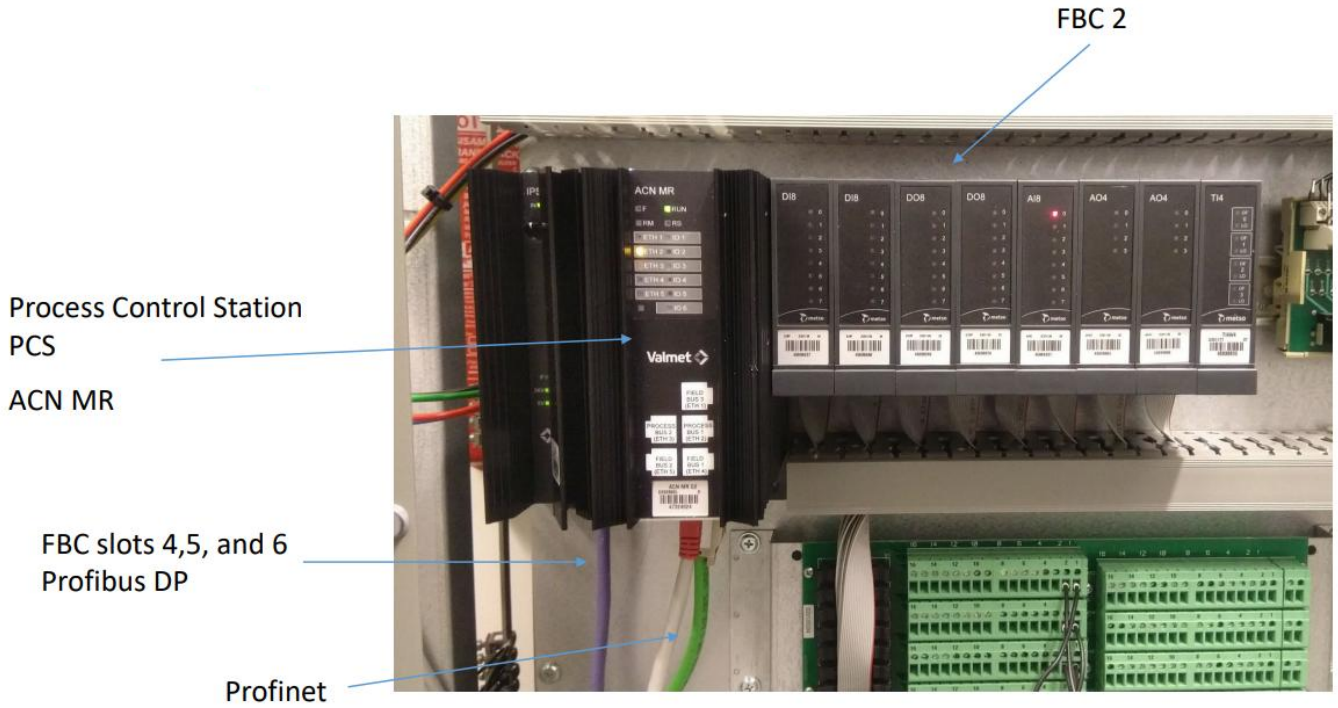

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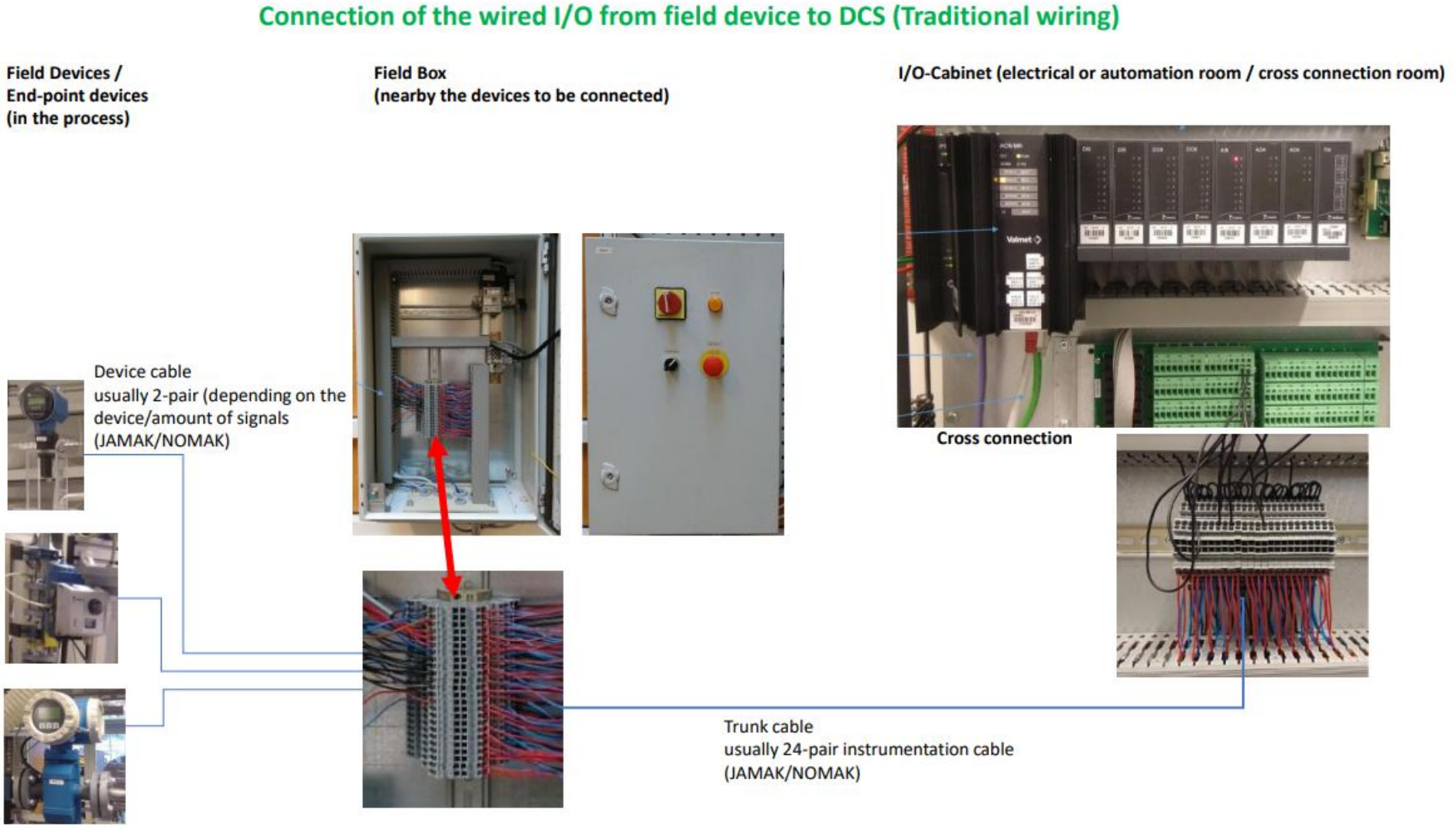
DCS – FIELD CONNECTIONS

Connection route from traditional IO-racks to field devices:

1. IO-modules in the rack (in the automation room)
2. Cross connection (in the automation room)
3. Trunk Cable
4. Fieldbox near the field devices (in the process room)
5. Device Cable
6. Field Device



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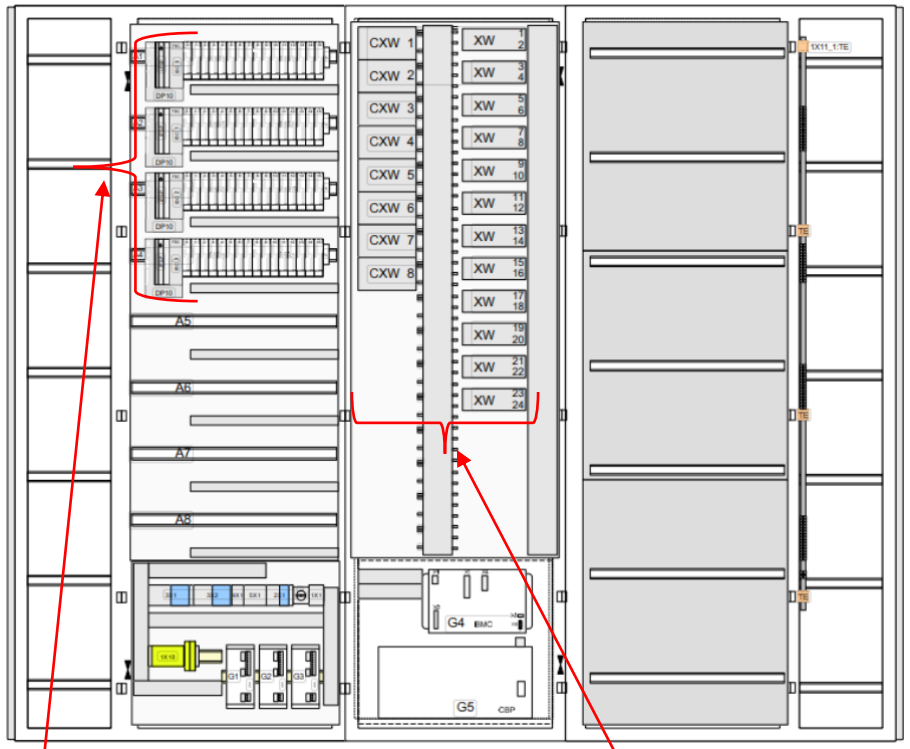
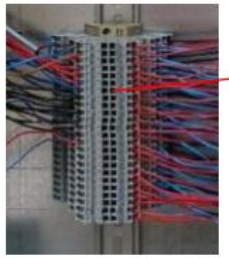
DCS – FIELD CONNECTIONS

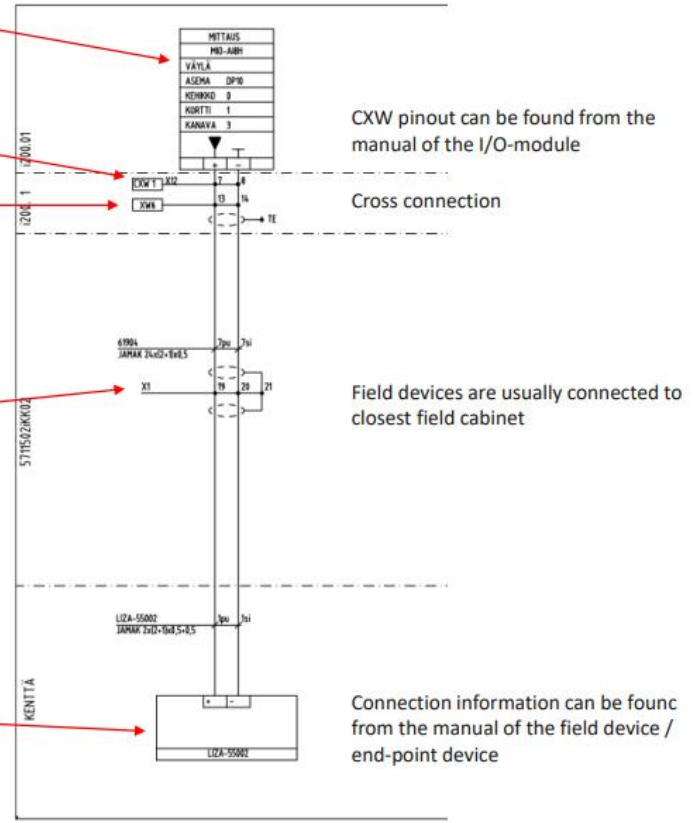


IO-racks with IO-modules in the IO-cabinet. Each IO-rack has a ”gateway” unit with slave address for addressing and connection to the FBC in the PCS. One process controller can utilize multiple IO-racks.

Cross connection boards (left) and terminals (right). Starting point for trunk cables to the Field.



Loop diagram descibing the connection (IO-module information, connector ID’s, wire colors, etc --> precise connection chain from IO-channel to field device)



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Topic 3&4 SW tools and Case of study

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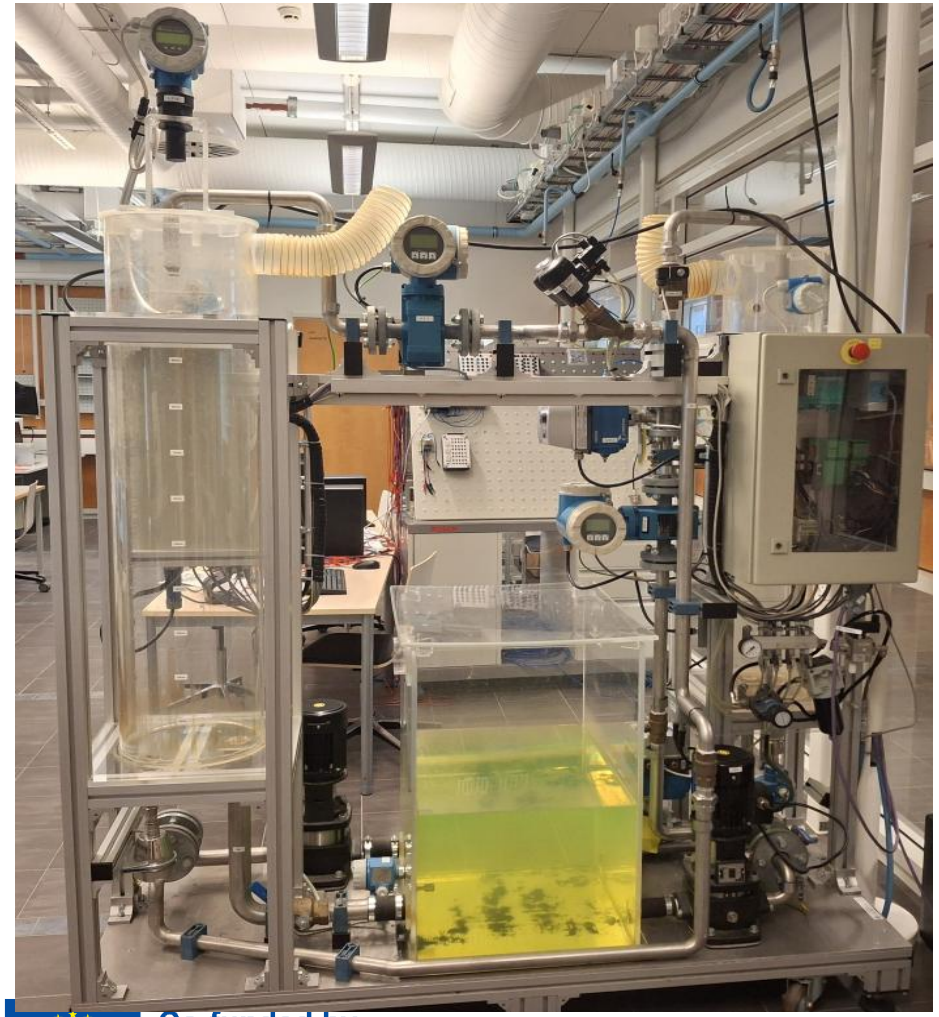
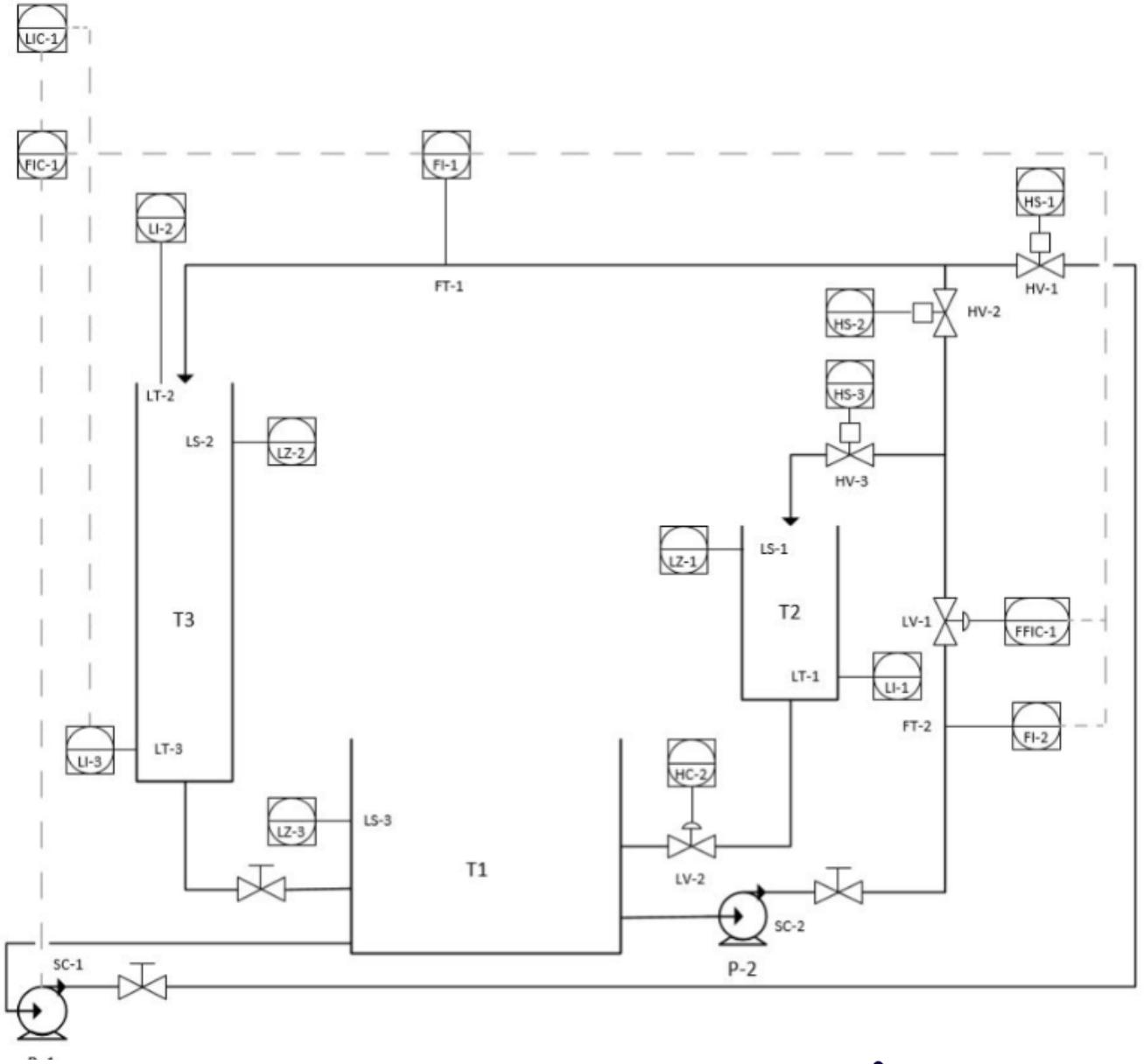
WATER PROCESS





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Summary

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Thank you!

Kiitos!

Gracias!

Mulțumesc!

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C2 – Industrial Automation

M4 – Operating interfaces (SCADA/HMI)

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- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

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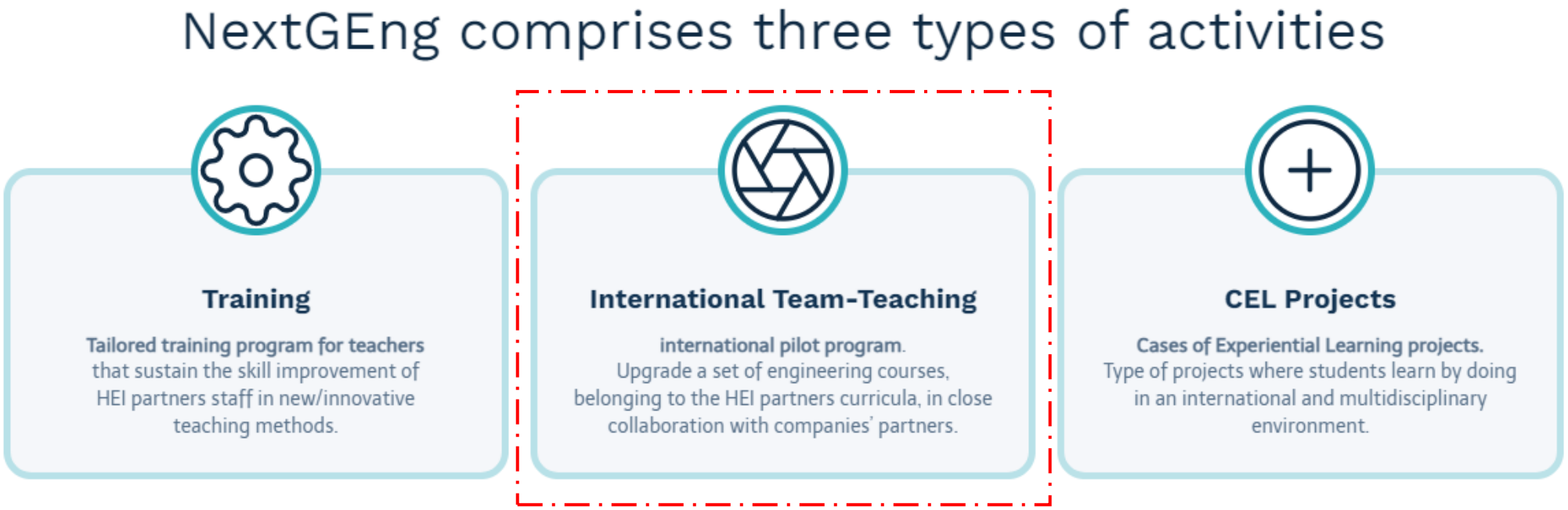
About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



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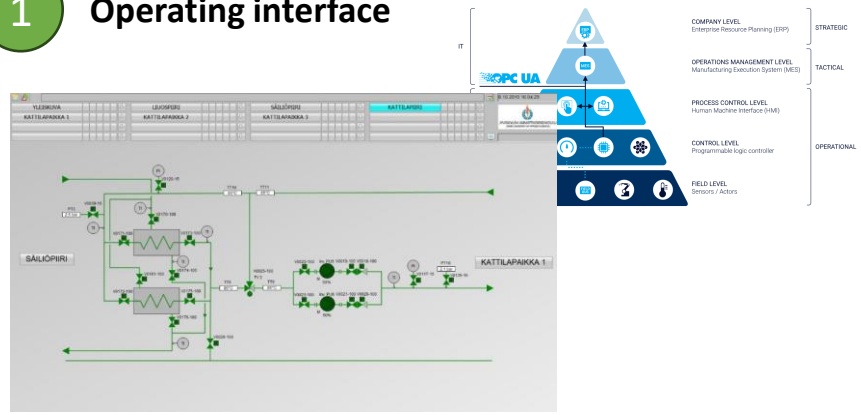
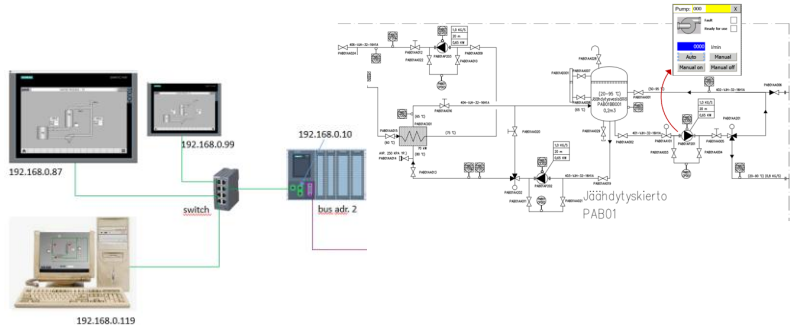
M1 – Operating interface (SCADA/HMI)

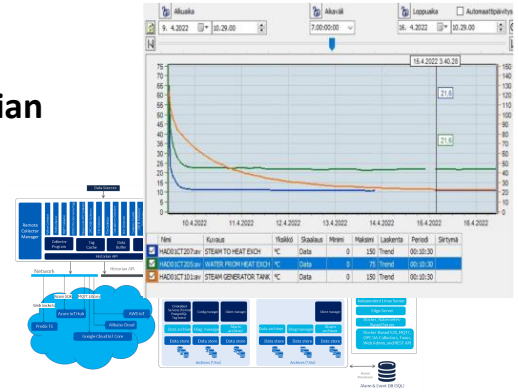
1 **Operating interface**



2 **Technical operation of the HMI**



3 **Historian**



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M1 – Operating interface (SCADA/HMI)

Upon completion of this module, the student will be able to:

1) Understand the basic concepts of operating interfaces in the context of industrial automation
2) Understand the basic features and principles of HMI and SCADA systems
3) Design and implement a simple user interface for a PLC-based system

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Content

- Introduction to Operating interfaces
- Technical operation of the HMI
- Historian
- Cases of study: Energy Process
- Summary

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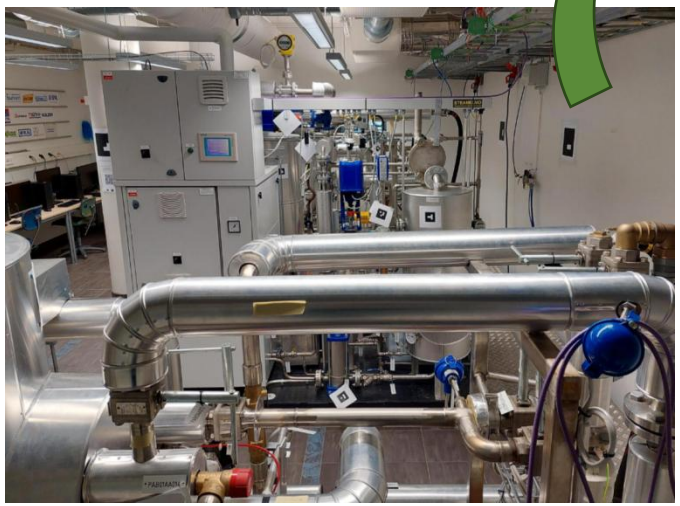

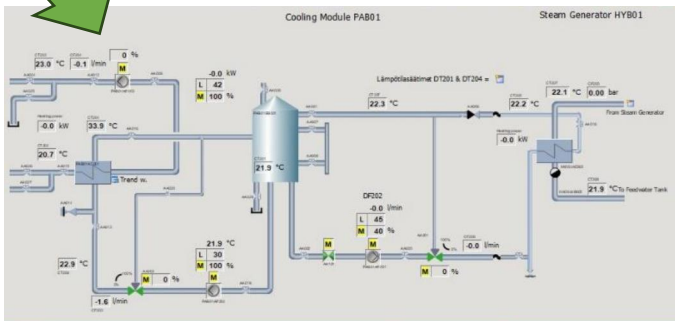

Topic 1 Operating interface

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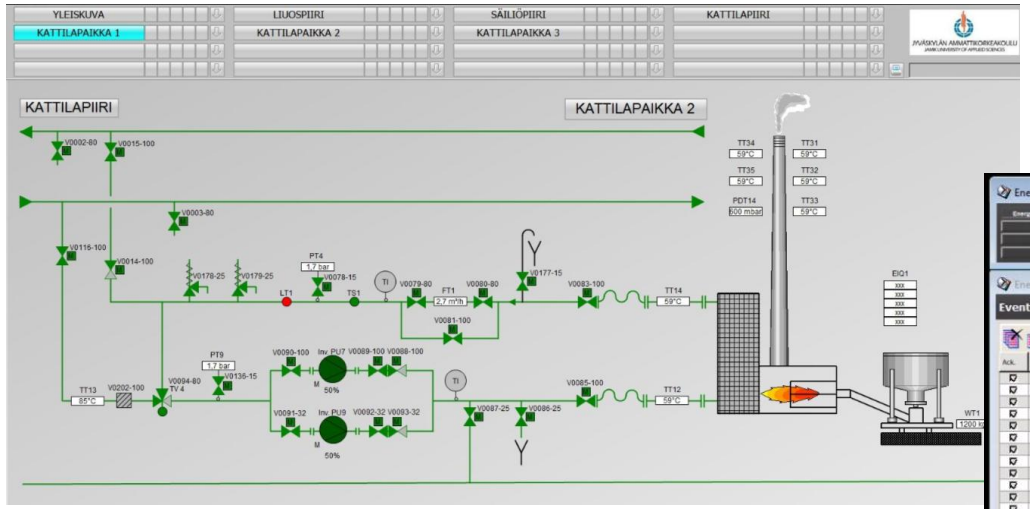
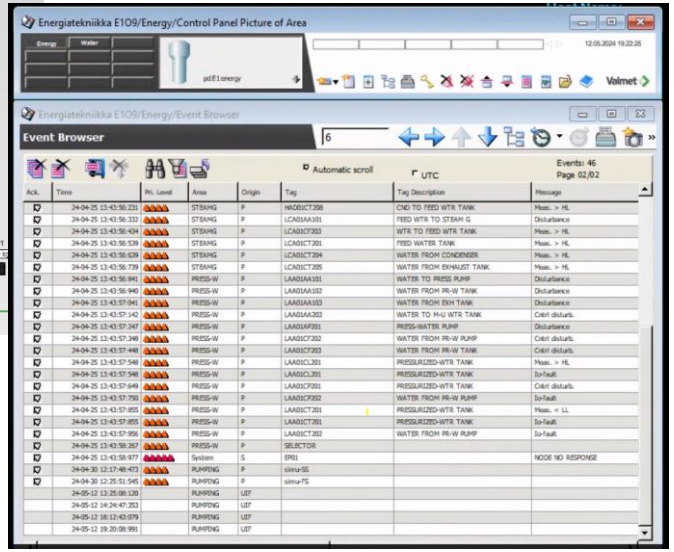
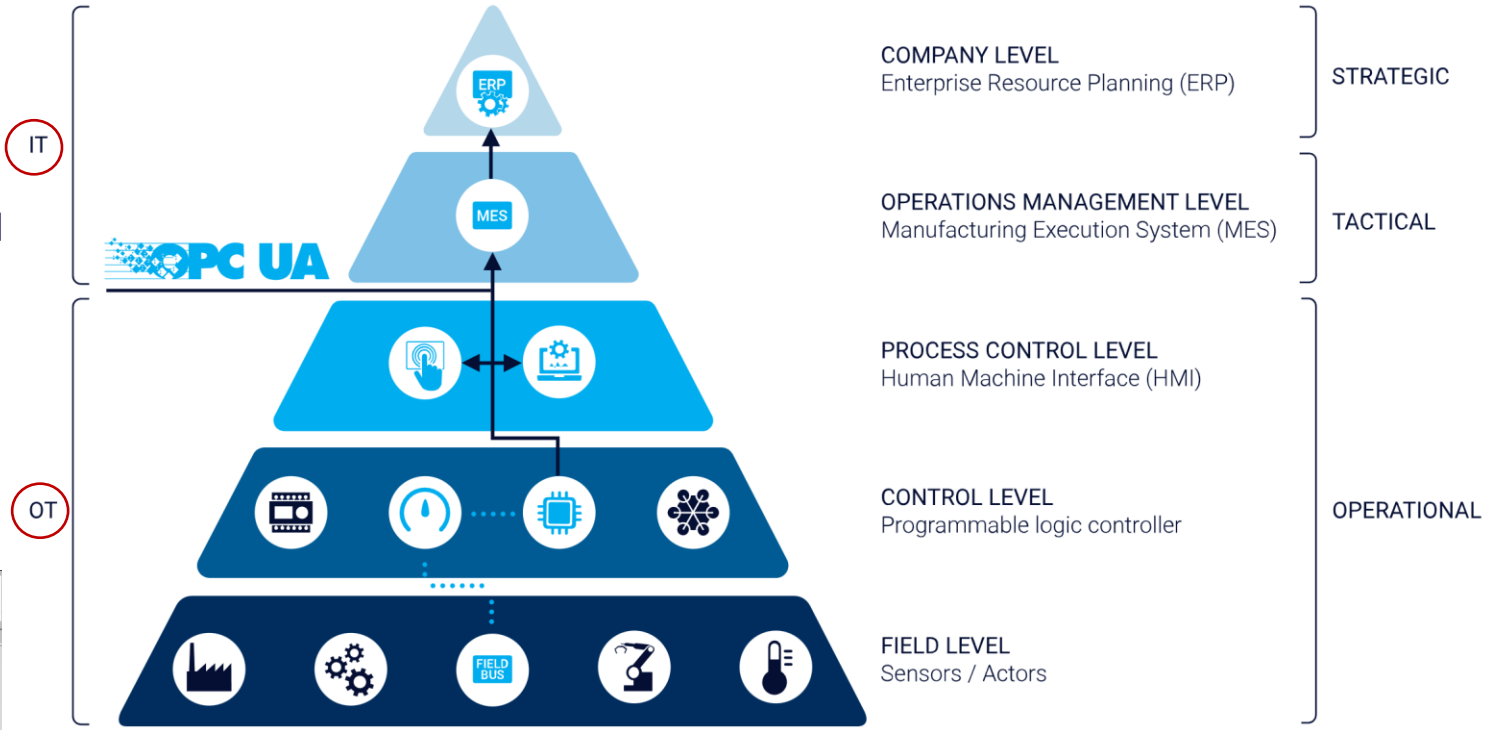
Operating interface

- Visualizing target system and providing a situational awareness
- Presenting values from the system
- Setting values to the system
- Detecting disturbances







Watching the watcher: keeping an eye on SCADA systems (paessler.com)

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Operating interface - SCADA and HMI

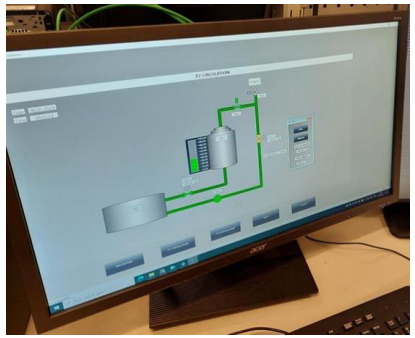
SCADA - Supervisory Control and Data Acquisition

a solution for monitor and control automated systems. Key features: UI including control and presentation, data collection, alarms and events, reporting, data communication, etc. Usually very comprehensive connectivity horizontally and vertically.

HMI – Human Machine Interface

HMI is a user interface between human and automated system. Terminology varies, but it's often considered that HMI is a simple local operating interface whereas SCADA is much more complex computer-based operating interface including also HMIs. Plain HMI could be a simple stand-alone operating panel or a part of a complex SCADA-system.

Source: Fortum (Suomenojan voimalaitos)



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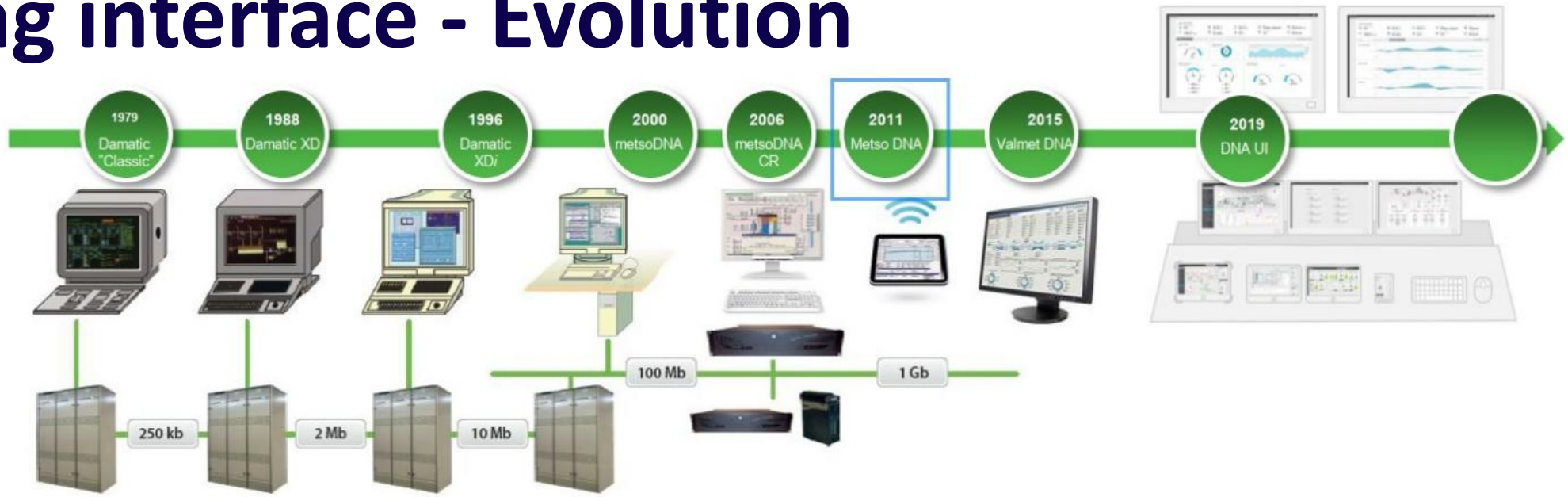
Operating interface - Evolution



Note - expected life cycles (very approximately):

Factory (heavy process industry): 30-40 years, power plant: 40+ Years

PLCs / RTUs / PCSs –> at least 15-30 years, serial-bus communication protocols from seventies still utilized, protocols from nineties (serial & ethernet-based) still very commonly utilized.

IT-solutions, servers and operating systems 5-10 years

Aspects: Cyber security? Compatibility with software used in 'office network'? Component replacements, continuity?

Long term HW & SW plan needed for many reasons – security, maintainability and compatibility!

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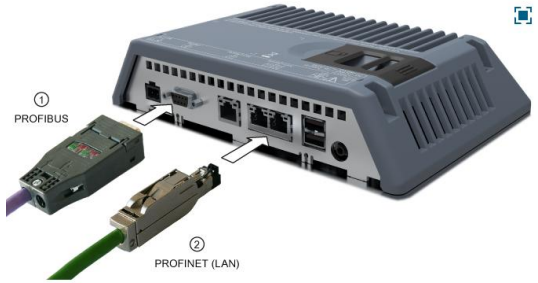
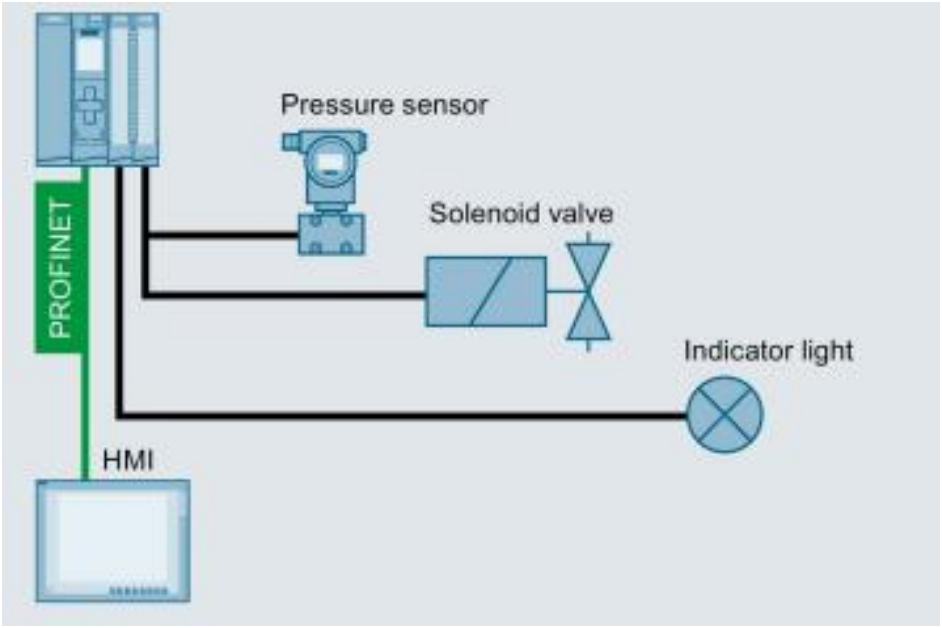
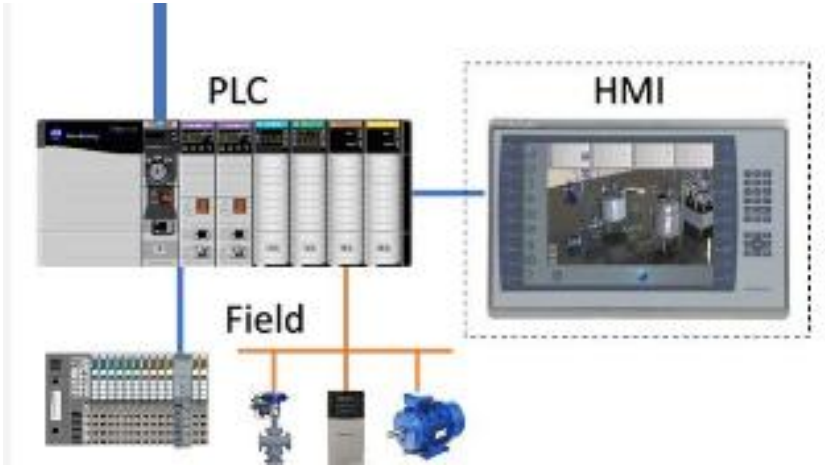
Operating panel





Pictures above: Siemens



What is SCADA? Supervisory Control And Data Acquisition – PLCynergy (modified)

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SCADA

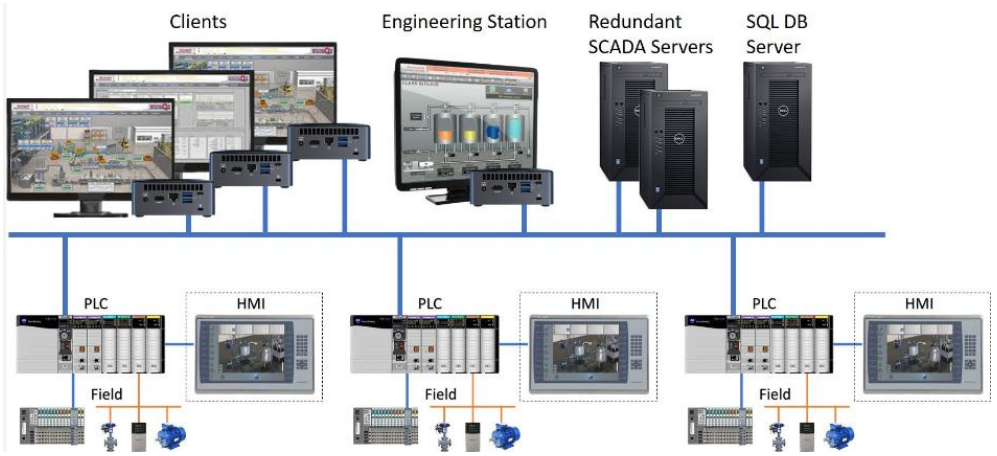
Supervisory Control and Data Acquisition

A Software-based control system architecture. Servers & Clients (Data Exchange, Historian, HMIs, etc)

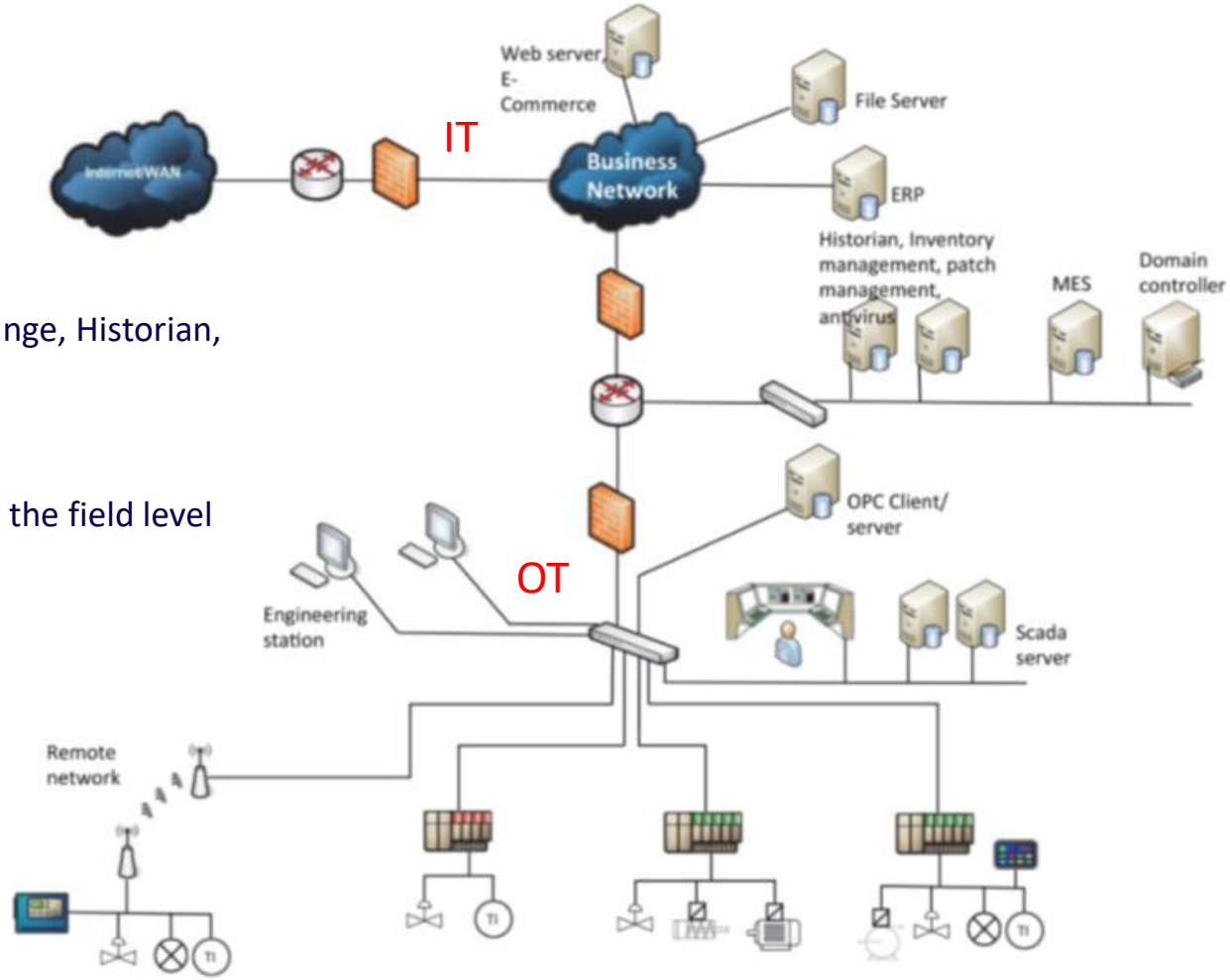
Non-proprietary

Communicates with PLCs, RTUs or equivalent for monitoring and controlling the field level

Local or geographically distributed system



What is SCADA? Supervisory Control And Data Acquisition - PLCynergy



Typical ICS architecture - Jean-Marie Falus - Cybersecurity of industrial systems 2019

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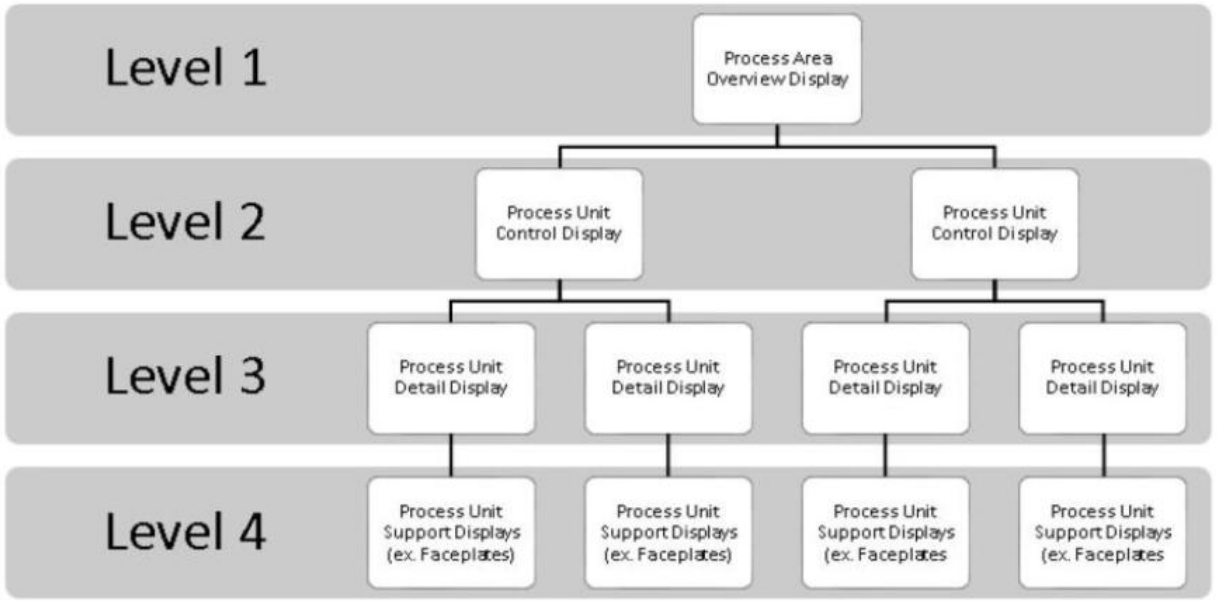
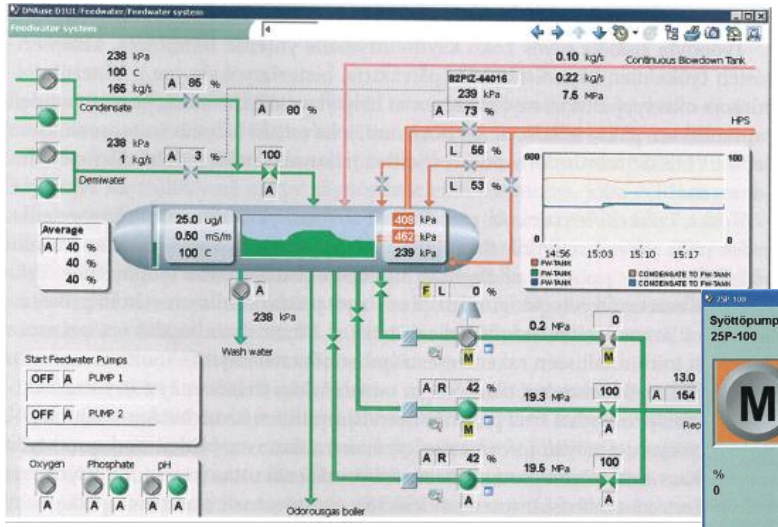
HMI IN SCADA



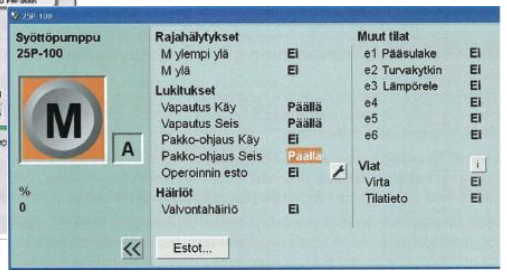
Display levels (source: Rockwell)

Level 1: Overview of the entire span of responsibility
Level 2: Primary display used during normal operations and monitoring
Level 3: Non-routine operations (process diagnostics etc.)
Level 4: Interlocks, diagnostics, Help, documentation etc. Usually popups.

Control room in a Powerplant (Source: Metso)



Supply water system in a Powerplant (Source: Metso)



Loop window (Source: Metso)

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DCS COMPARED TO SCADA

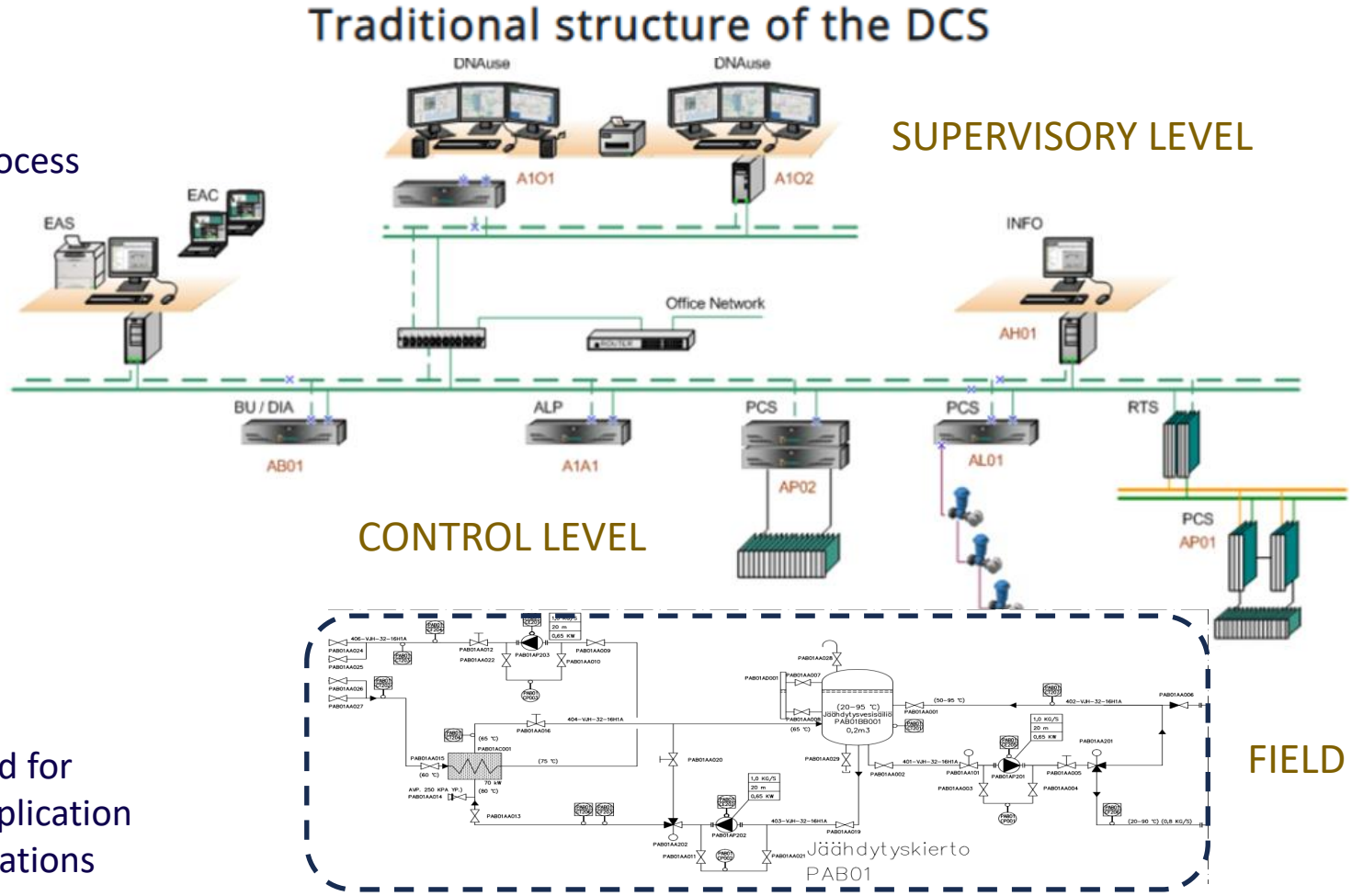
DCS – Distributed Control System

Proprietary automation systems used especially in process automation:

- Powerplants
- Paper mills
- Pulp mills
- Chemical industry
- Petrochemical industry
- Food industry (dairys etc.)
- Etc.

Also applications e.g. in marine sector.

DCS includes SCADA features and more. It's developed for certain fields of industry, and it contains extensive application libraries and is very scalable to extremely large applications



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Operating interface (SCADA and HMI)

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STANDARDIZATION

- Several separate standards for specific topics related to HMIs: ISA77.60, API 1185, ASM Consortium Guidelines Rev 3-2008, ANSI/HFES 100-2007, ANSI/HFES 200-2008, ISO 9241, ISO 11064, EEMUA 201, NUREG-0700 Rev. 2-2002, etc. For example, ISA77.60 “Human-Machine Interface” is focused on fossile power plant applications.
- ISA101-101.01-2015, “Human Machine Interfaces for Process Automation Systems” → ISA’s first HMI-standard including developing and maintaining HMIs. Philosophy, design, implementation, operation and maintenance. Afterwards several Technical Reports and sub-standards are provided by ISA. Builds and brings together threads from various sources. Took around 12 years to complete!
- ISA112, “SCADA systems” → is currently under construction.

Enterprises generally have, and should have, their own philosophies and guidelines for the design and implementation of the SCADA- and HMI-systems! (Maintainability, Scalability, Look&Feel for operators)

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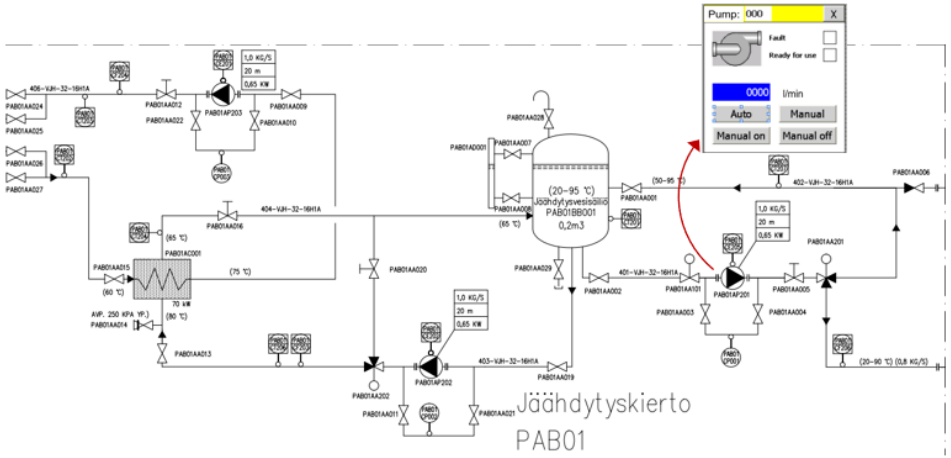
2



Topic 2 Technical operation of the HMI

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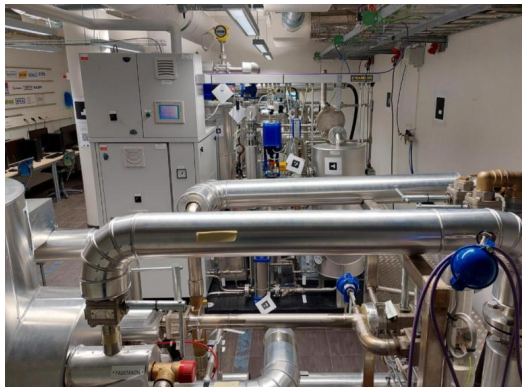
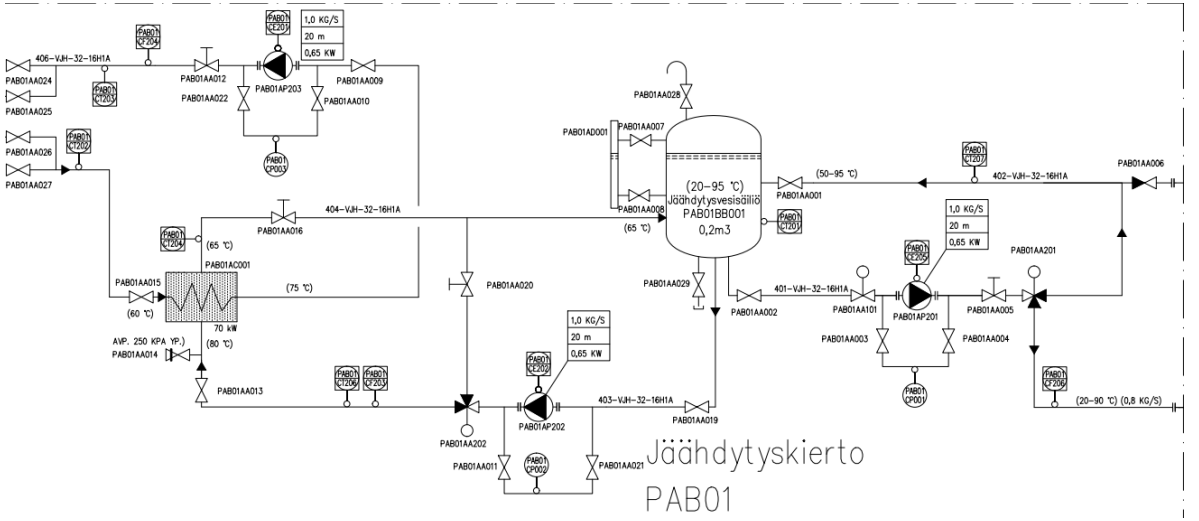
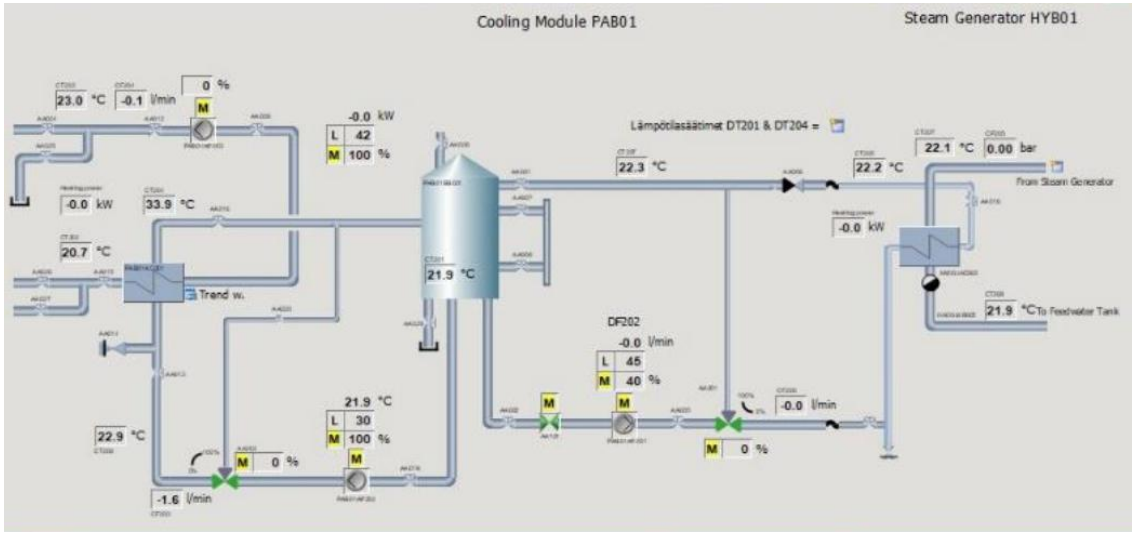
BASIC GRAPHICS

- Developed in a specific software
- Initial documents vary, but in process automation PI-diagram is very important among functional descriptions
- **STATIC** and **DYNAMIC** objects can be found in the library
- Dynamizations utilize tags (variables)
- Event-based and cyclical update
- Dynamization means that e.g color of the symbol changes according to the state of correspond field device (motor on = green, motor off = gray, etc) or the value of the numerical display changes
- Few basic objects/elements:
  - I/O Fields
  - Bars
  - Buttons
  - Symbolic I/O Fields
  - Alarm views and indicators
  - Static shapes and texts







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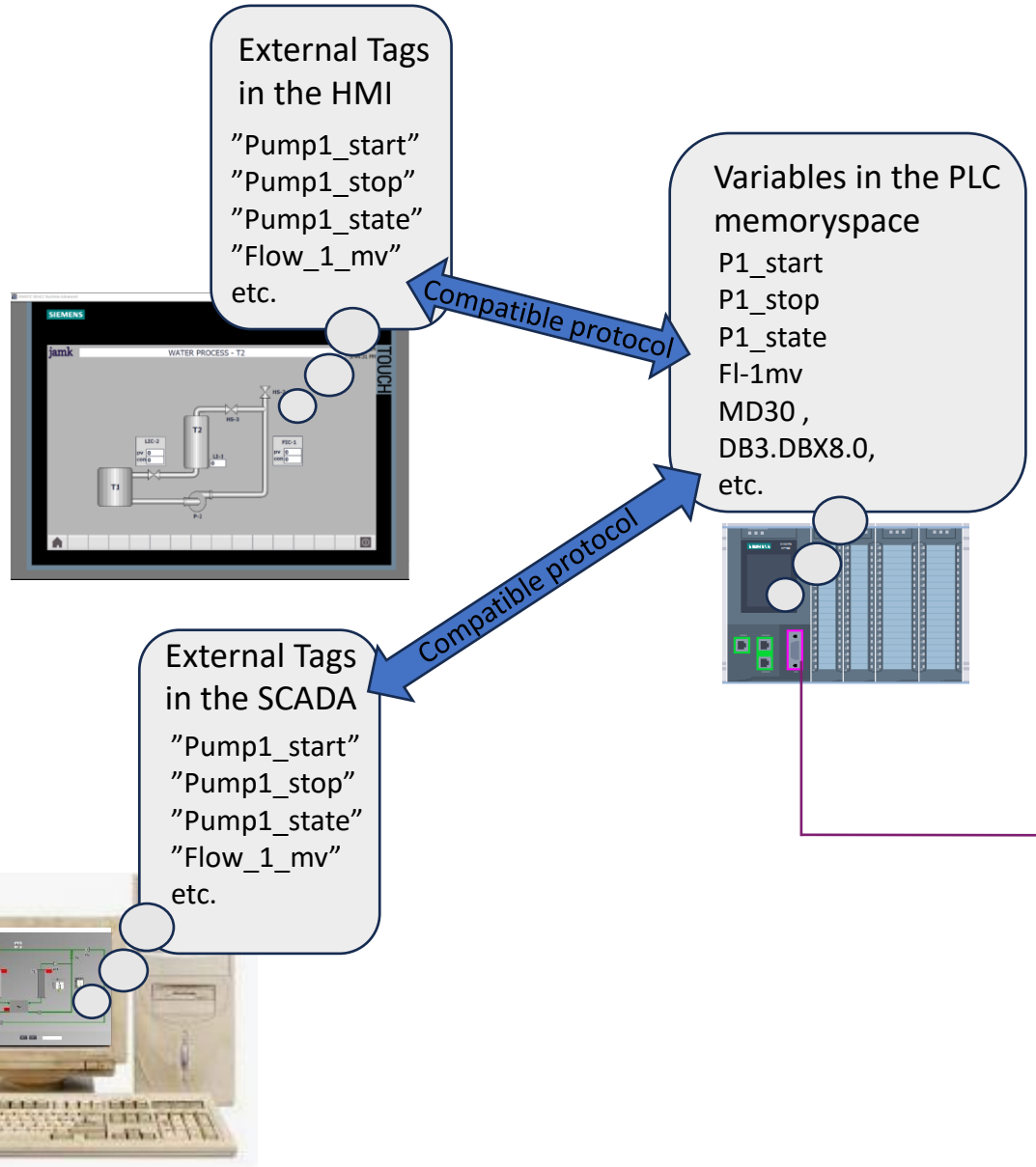
TAGS

HMI variables are called tags. There are two kind of tags: **Internal tags** and **External tags**. Internal tags can be used only inside the HMI (e.g in scripts, screen navigation, user management etc). External tags are used for data exchange with PLCs or RTUs

Values from the variables in the PLC memory are read to External Tags of the HMI (Input to HMI) and Values from the external tags of the HMI are written to variables in PLC's memory(Output from HMI)

External tags are configurated during the programming of the HMI/SCADA

Compatible **communication driver** is needed in the HMI/SCADA!



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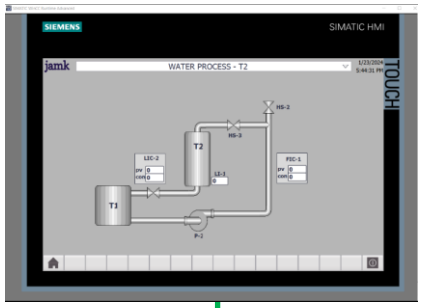
CONNECTIONS AND INTERFACES

PLC controls the process or machine (works independendly even when the HMI is unavailable)

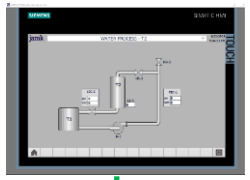
HMI / SCADA exchanges data with PLC via **physical medium**: ethernet utilizing certain **protocols** (common) or a serial bus (legacy)

Both ends must support the same protocol in order to exchange the data (drivers or IO-servers in a HMI/SCADA)

Implementation of LAN varies but normal networking rules apply.



192.168.0.87



192.168.0.99

192.168.0.10

bus adr. 2

switch

192.168.0.119

bus adr. 3 ...125

Profibus

Connection to the field level could be implemented via various different fieldbusses. This is only one example. Traditional IO-connections are also commonly used (DI,DO,AI,AO).

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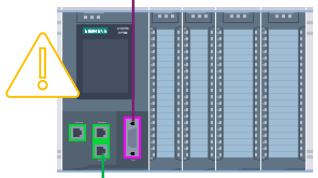
EVENTS & ALARMS



RT Simulator

SIEMENS SIMATIC HMI

SIEMENS SIMATIC HMI — Alarm Buffer — 1/31/2024 4:24:41 PM

Back

	No.	Time	Date	Status	Text
P1	3	4:24:30 PM	1/31/2024	I	LZ-1 HIGH ALARM
P1	4	4:23:30 PM	1/31/2024	I	FT-1 LOW ALARM
P1	2	4:23:08 PM	1/31/2024	I	M1 THERMAL RELAY
...	9	4:22:42 PM	1/31/2024	I	M1 Started
$	140000	4:20:46 PM	1/31/2024	I	Connection established: HMI_Connection_3, Station 192.1...
$	110001	4:20:46 PM	1/31/2024	I	Change to operating mode 'online'.
...	9	4:11:39 PM	1/31/2024	IO	M1 Started
P1	2	4:11:35 PM	1/31/2024	IO	M1 THERMAL RELAY
P2	5	4:11:33 PM	1/31/2024	IO	M2 SAFETY SWITCH
P2	5	4:11:03 PM	1/31/2024	I	M2 SAFETY SWITCH
P1	2	4:10:36 PM	1/31/2024	I	M1 THERMAL RELAY
...	9	4:09:58 PM	1/31/2024	I	M1 Started
$	140000	4:09:34 PM	1/31/2024	I	Connection established: HMI_Connection_3, Station 192.1

TOUCH

F1 F2 F3 F4 F5 F6 F7 F8

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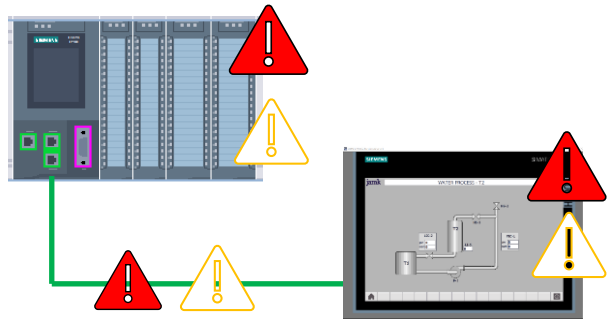
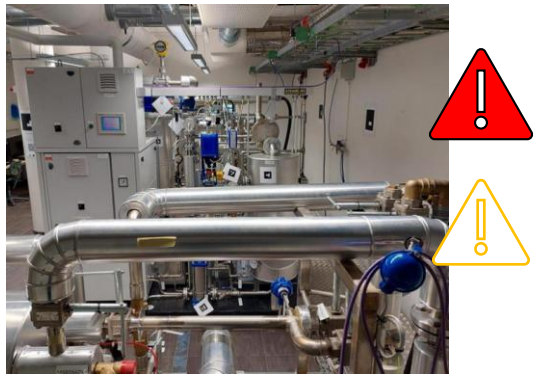
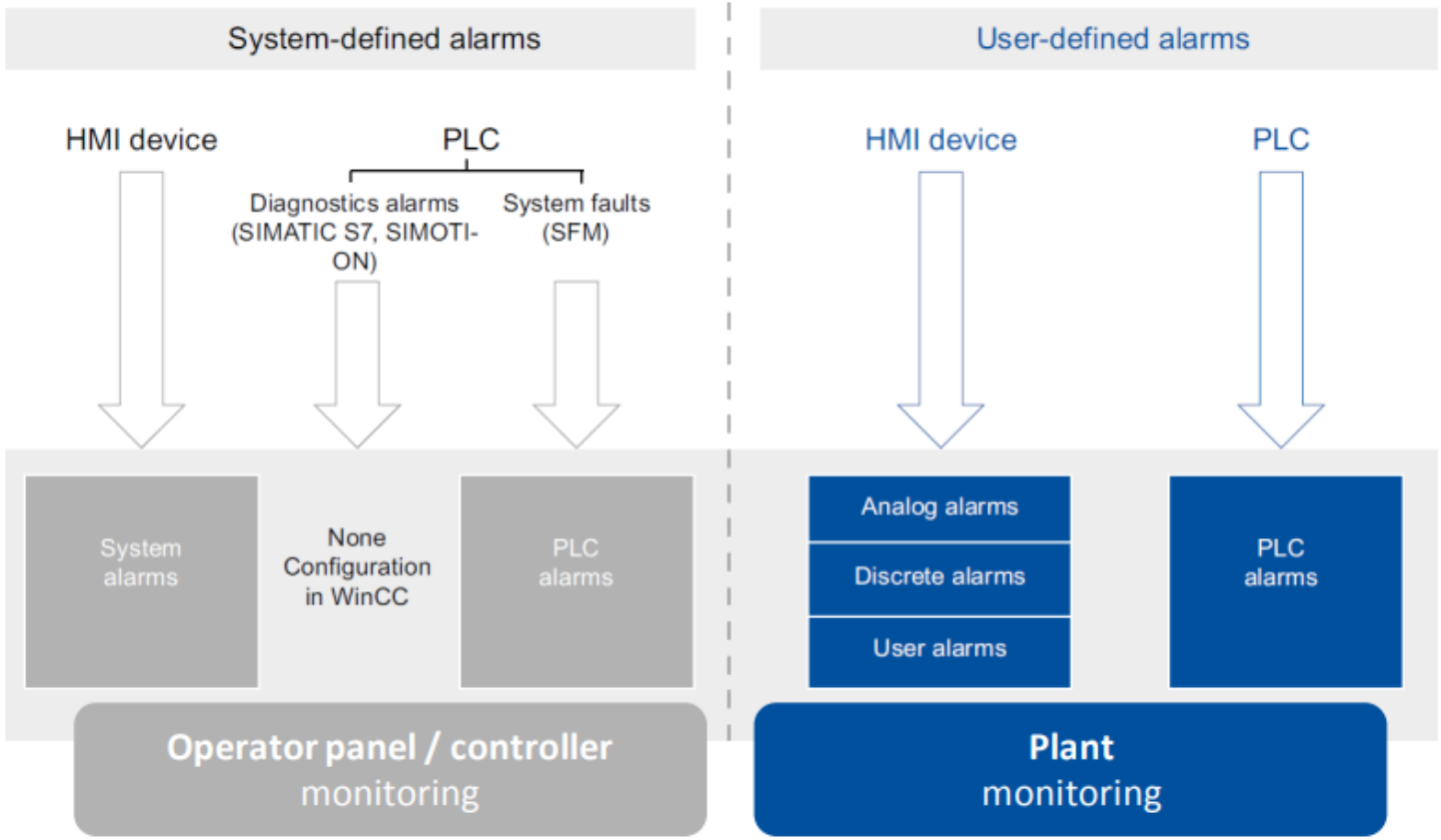
MESSAGING SYSTEM

Alarms and important events:

- Process
- System







Source: Siemens

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BIT MESSAGE PROCEDURE

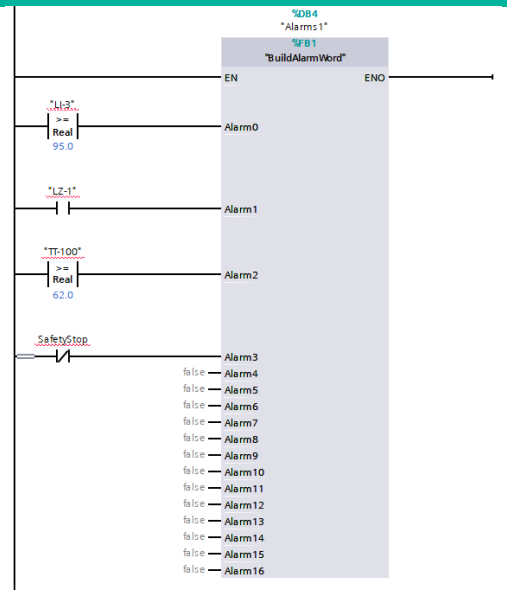
Message or alarm words are defined and written in the PLC

Corresponding message / alarm tags are created in the HMI

Each bit corresponds to a certain alarm or event

Message texts / alarm texts are configured in the HMI

HMI polls the alarm or message variable in the PLC memoryspace



bits

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

Alarm word in the PLC, bits are controlled by the user application

Data exhange

bits

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

Alarm Tag in the HMI

Message / alarm texts in the HMI

- LI-3 High Alarm
- LZ-1
- TT-100 High Alarm
- Safety Stop activated
- Etc.

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HMI – Hands on

Basic level: P-1 Operating interface

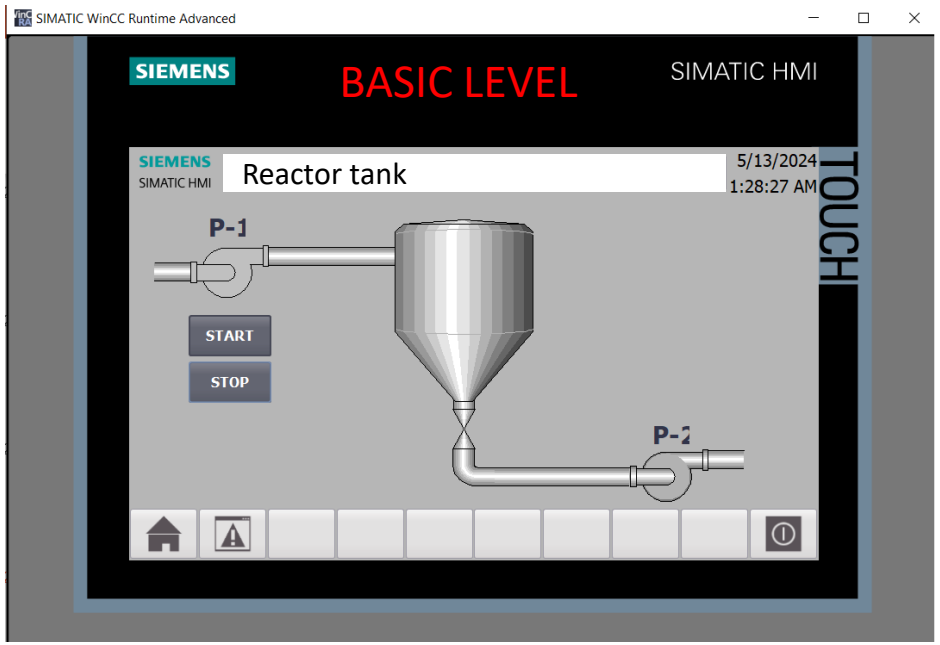
1. Create a **HMI panel** project (e.g TP900)
2. Create **connection** with wizard when adding the panel
3. Add **objects and elements** to the screen
   -note: simplify the picture!
4. Create **tags**
5. Create **Events** and **bind tags** to start and stop the pump
6. Add **Animations** for displaying the state of the pump (**dynamization**)
7. Add **IO Field for** presenting the RPMs of the pumps
8. Simulate

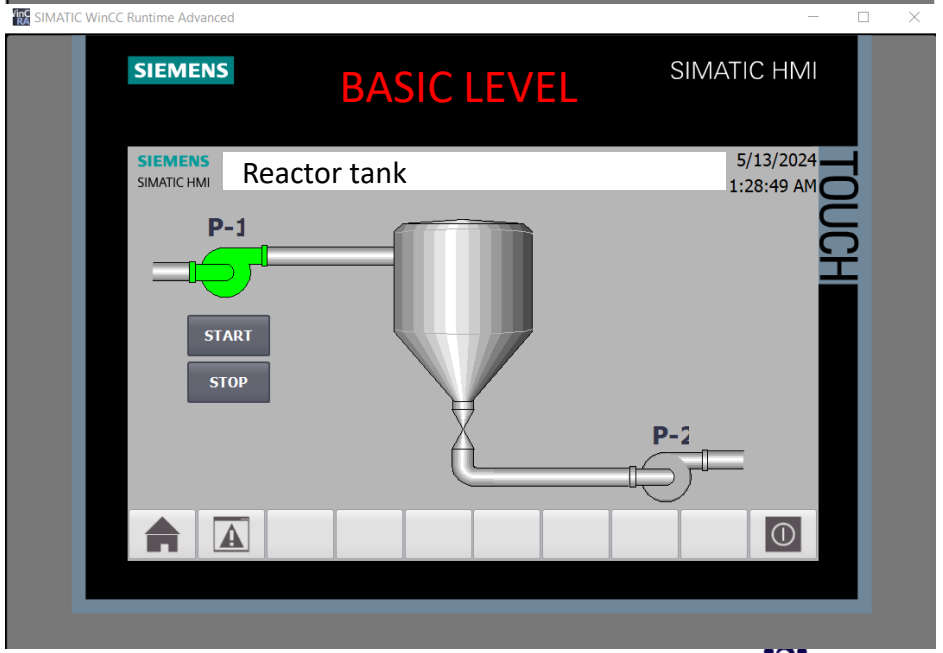
Intermediate:

1. Add **IO Fields** presenting the RPMs of the pumps
2. Create also necessary elements to control and visualize the P-2
3. Configure messaging system

Advanced level:

Utilize **Faceplates** and **Popup** windows to produce detailed view to the pumps (lower hiearchy level displays)





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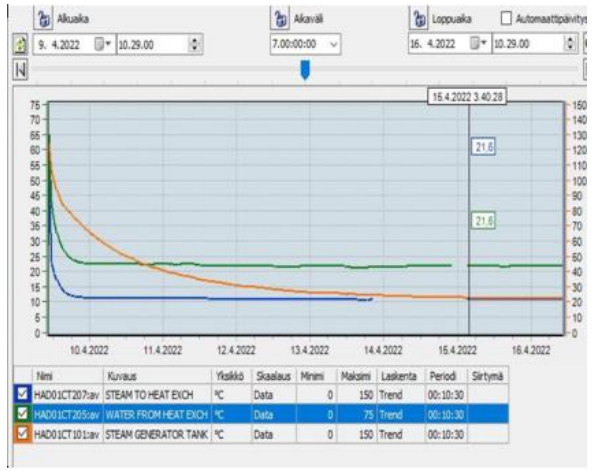
3



Topic 3 Historian

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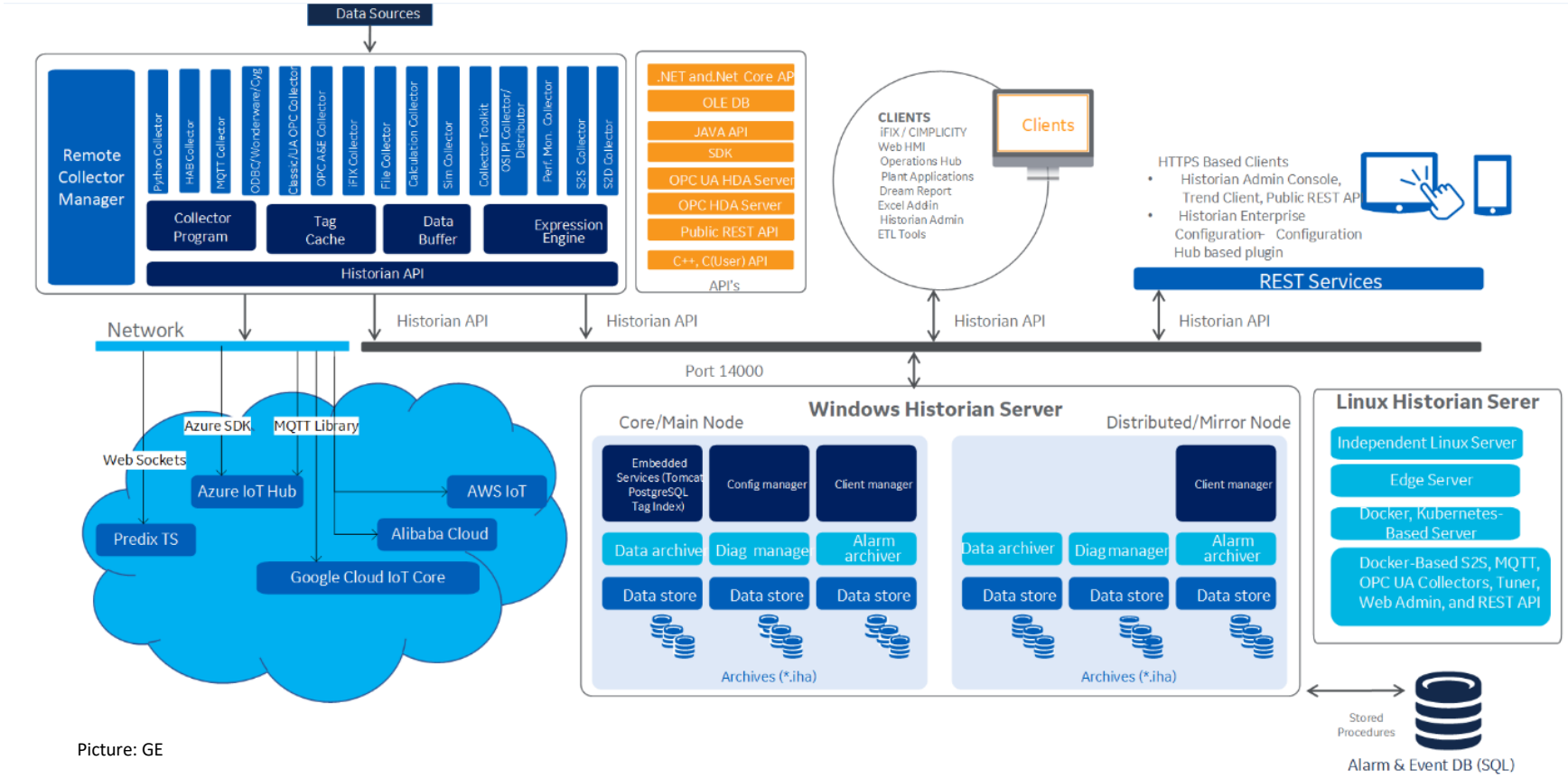
HISTORIAN

Tag logging is used to archive selected tag values with configured interval to a data base. Tag logging may be done also into a .csv or a text-file e.g. in simple operating panel projcets (not actual Historian)

• This enables historian and other applications where data stored to a data base is utilized

• Tag logging is important part of real-life projects! Normally there is a need for archiving at least the most important process variables for later use.

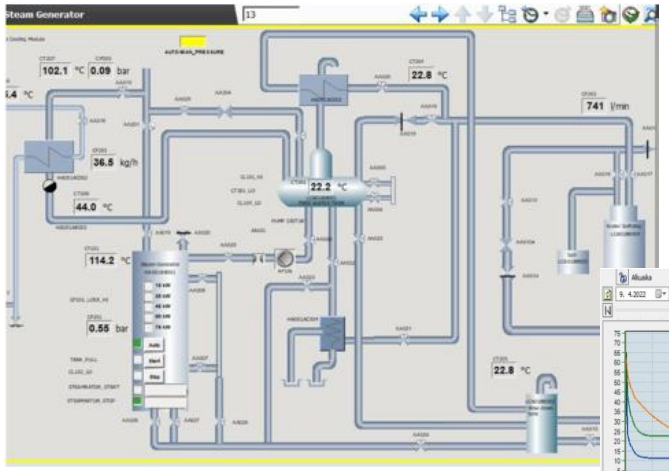
Important features: capacity, available logging intervals, connectivity,

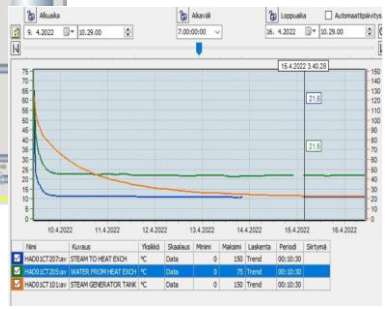


Picture: GE

UTILIZATION OF THE HISTORIAN

- Tracers / Historical trends
- Creating reports (energy, materials, faults, emissions, etc.)
- “Replaying” past time in the operating interface
- Data-analysis
- Etc.





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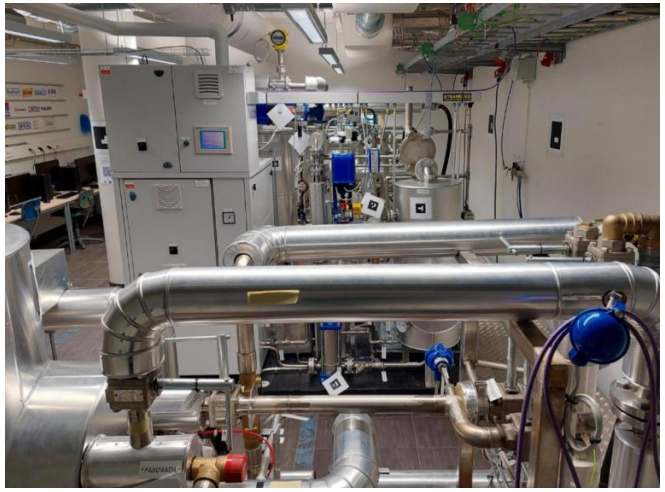
4



Topic 4 Case of study – Historian in energy process

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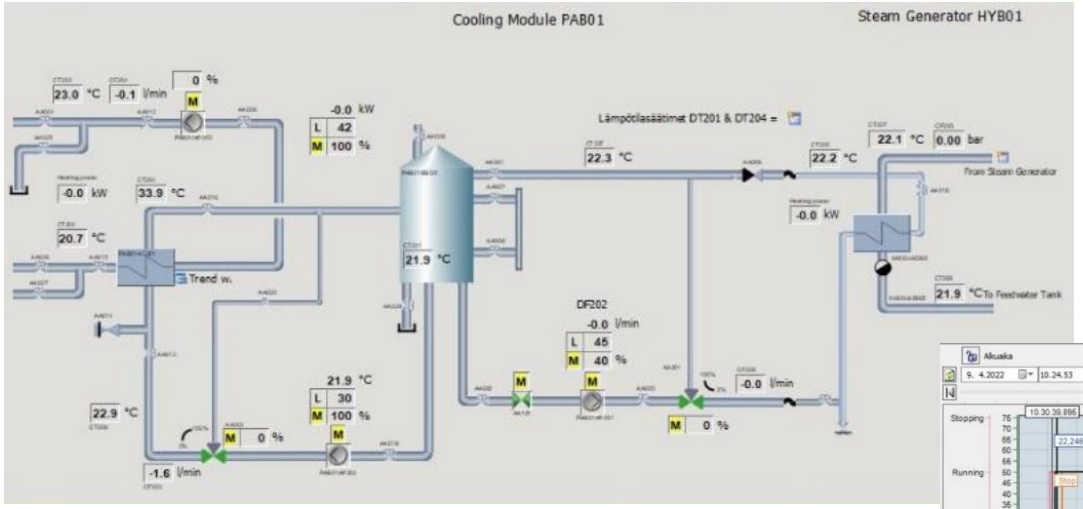
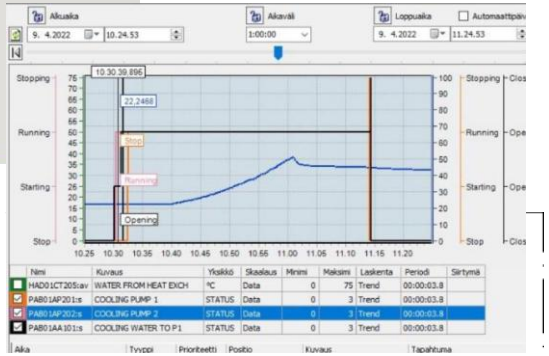
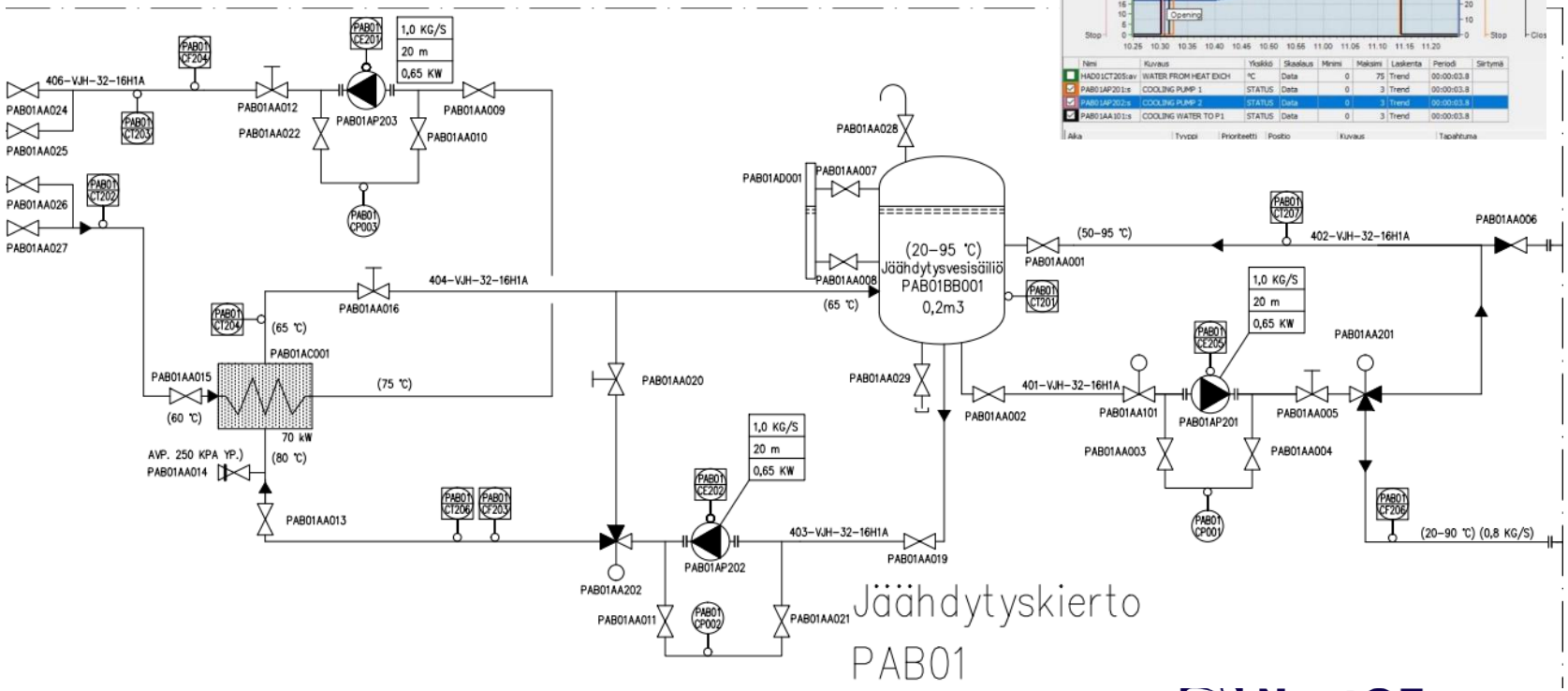
ENERGY PROCESS

- Valmet DCS process control including Historian (INFO-system)







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Summary

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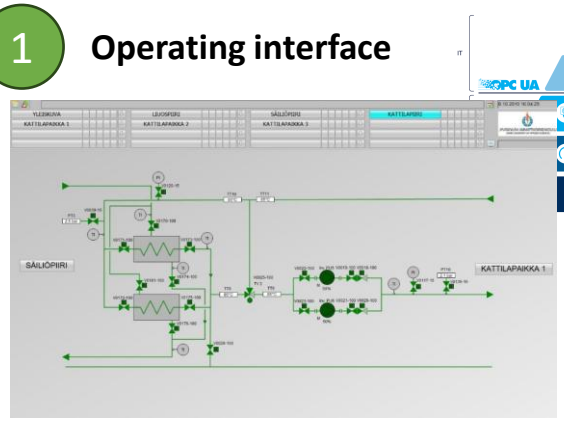
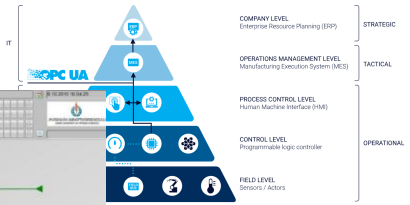
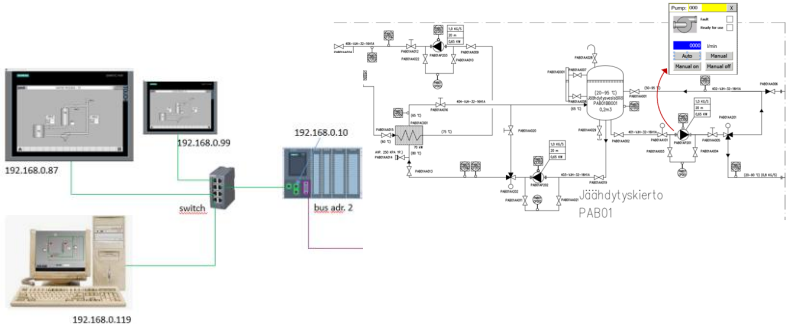
M1 – OPERATING INTERFACES (SCADA/HMI)

1 Operating interface

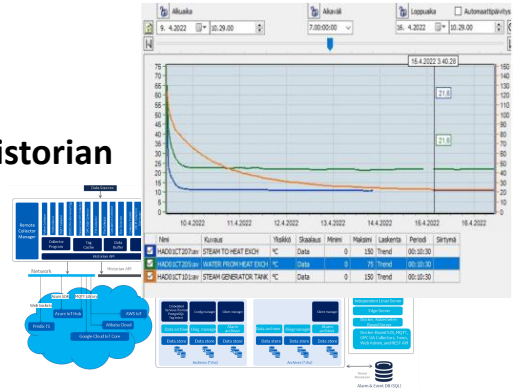




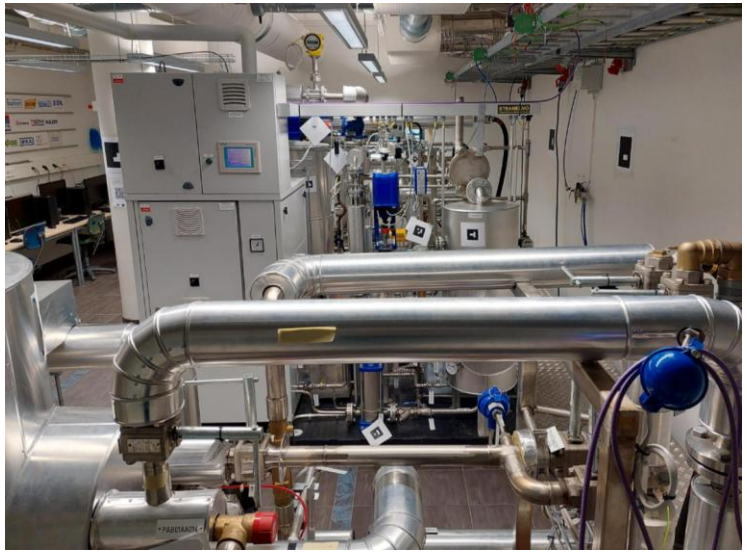
2 Technical operation of the HMI



3 Historian



4 Case study: Historian in energy process



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Thank you!

Kiitos!

Gracias!

Mulțumesc!

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C2 – Industrial Automation

M5 – Programmable Logic Controllers (PLCs). GRAFCET

University of Jaén

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Integracion Sensorial y Robotica

Jamk University of Applied Sciences

Valmet Technologies Oyj

University of Jaén

Rober Bosch SRL

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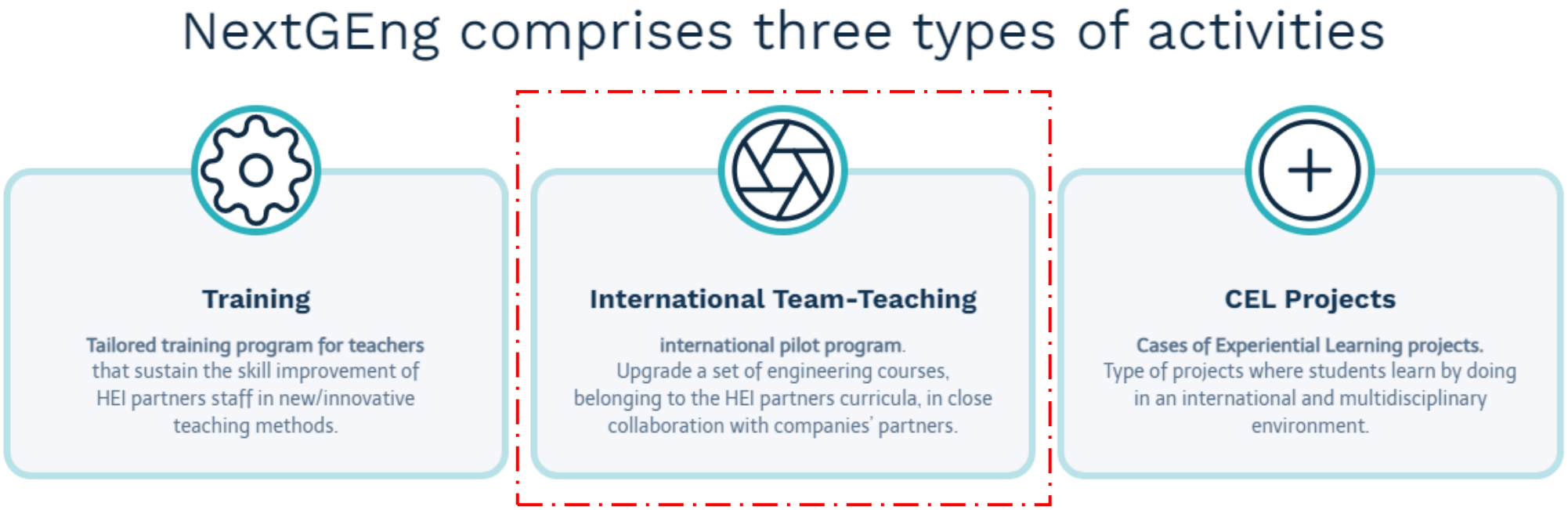
About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



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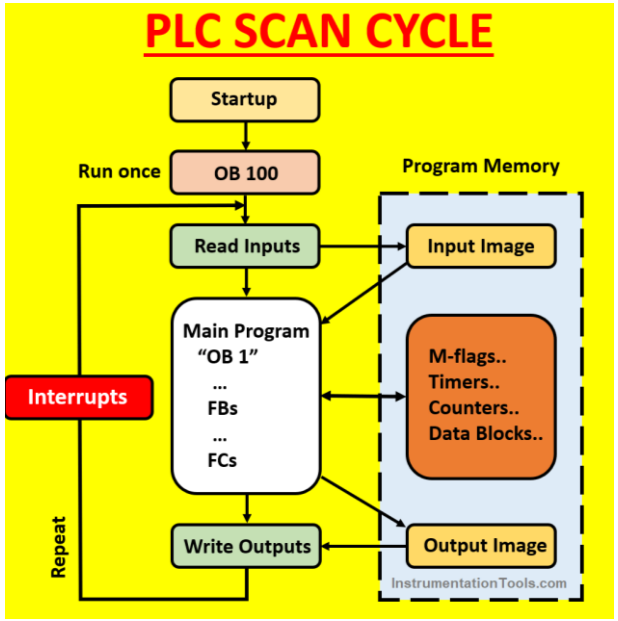
M1 – Programmable Logic Controllers (PLCs). GRAFCET

1 **Role of Industrial Automation in Global Challenges**

2 **Foundations of PLCs & discrete event system design**

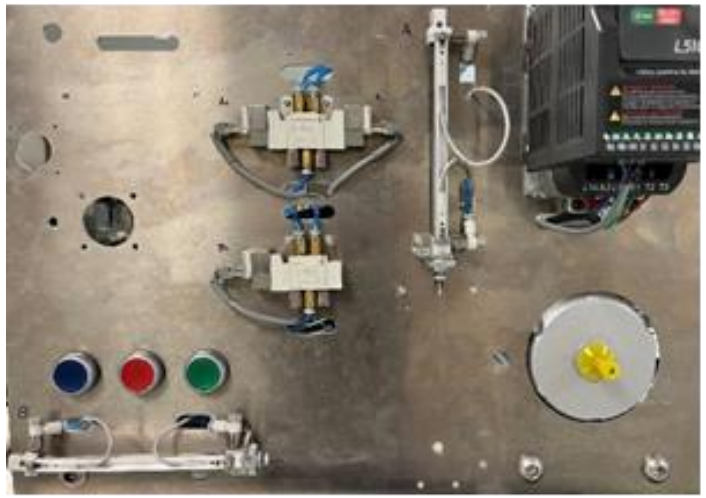


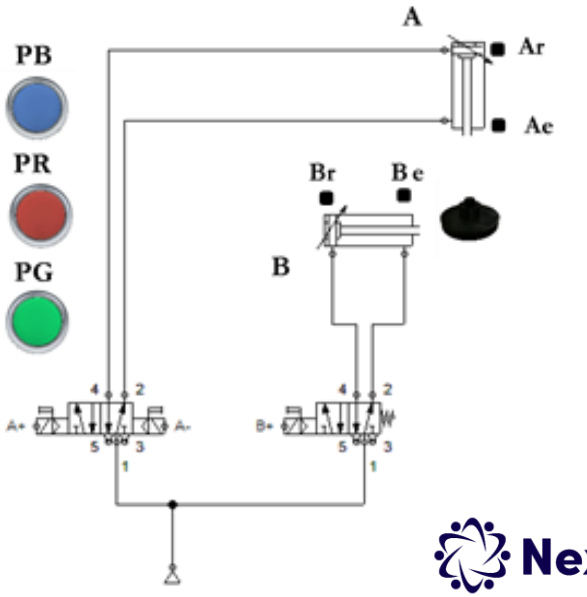
3 **Structured programming using ladder (timers, counters and emergency stop)**

IEC 61131-3

- **Ladder Logic Diagram (LD)**
- Function Block Diagram (FBD)
- Instruction List (IL)
- Structured Text (ST)
- Sequential Function Chart (SFC)

4 **Case study – pressing batch of parts**





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Programmable Logic Controllers (PLCs). GRAFCET

Upon completion of this module, the students will be able to:

1) Gaining knowledge of how new technologies and paradigms can contribute to **global challenges**
2) Understand and know the **foundations of programmable logic controllers**
3) Design the control system of **basic industrial processes** (discrete event systems)
4) Basic knowledge about **structured programming using Ladder** (timers, counters)

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Content

- Contributing to global goals → Digital Twins in Industrial Automation
- Foundations of PLCs & discrete event system design (GRAFCET)
- Structured programming using Ladder
- Cases of study: Pressing batch of parts
- Results in a real system

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1 **Role of Industrial Automation in Global Challenges**

Industrial Automation in Global Challenges

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Industrial Automation in Global Challenges

United Nations

In September 2015 UN adopted the Sustainable Development Goals (**SDGs**), also known as the Global Goals, with the aim to transform our world by addressing **global challenges** like poverty, inequality, climate change, and environmental degradation, with the goal of achieving a better and more sustainable future for all by 2030.

Lines of action: What should be supported? / What should be reinforced?

- Optimization in energy use
- Promotion of renewable energy
- Minimization of waste generation
- Development of new and more efficient practices and technologies
- Higher and optimized productivity

- Efficient use of materials
- Innovative technologies to promote inclusive, safer, and smart waste management

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Industrial Automation in Global Challenges

Focuses on "**Industry**, Innovation, and Infrastructure," aiming to build resilient infrastructure, promote inclusive and **sustainable industrialization**, and **foster innovation.**

Reasons to support

Industry increases productivity, job creation and generates income, thereby contributing to poverty eradication and addressing other development goals, as well as providing opportunities for social inclusion, creating decent employment for the youth**. As industry develops**, it drives an increase of value addition and **enhances** the application of science, **technology and innovation**, therefore encouraging **greater investment in** skills and **education**, and thus **providing the resources to meet broader**, inclusive and sustainable **development objectives**

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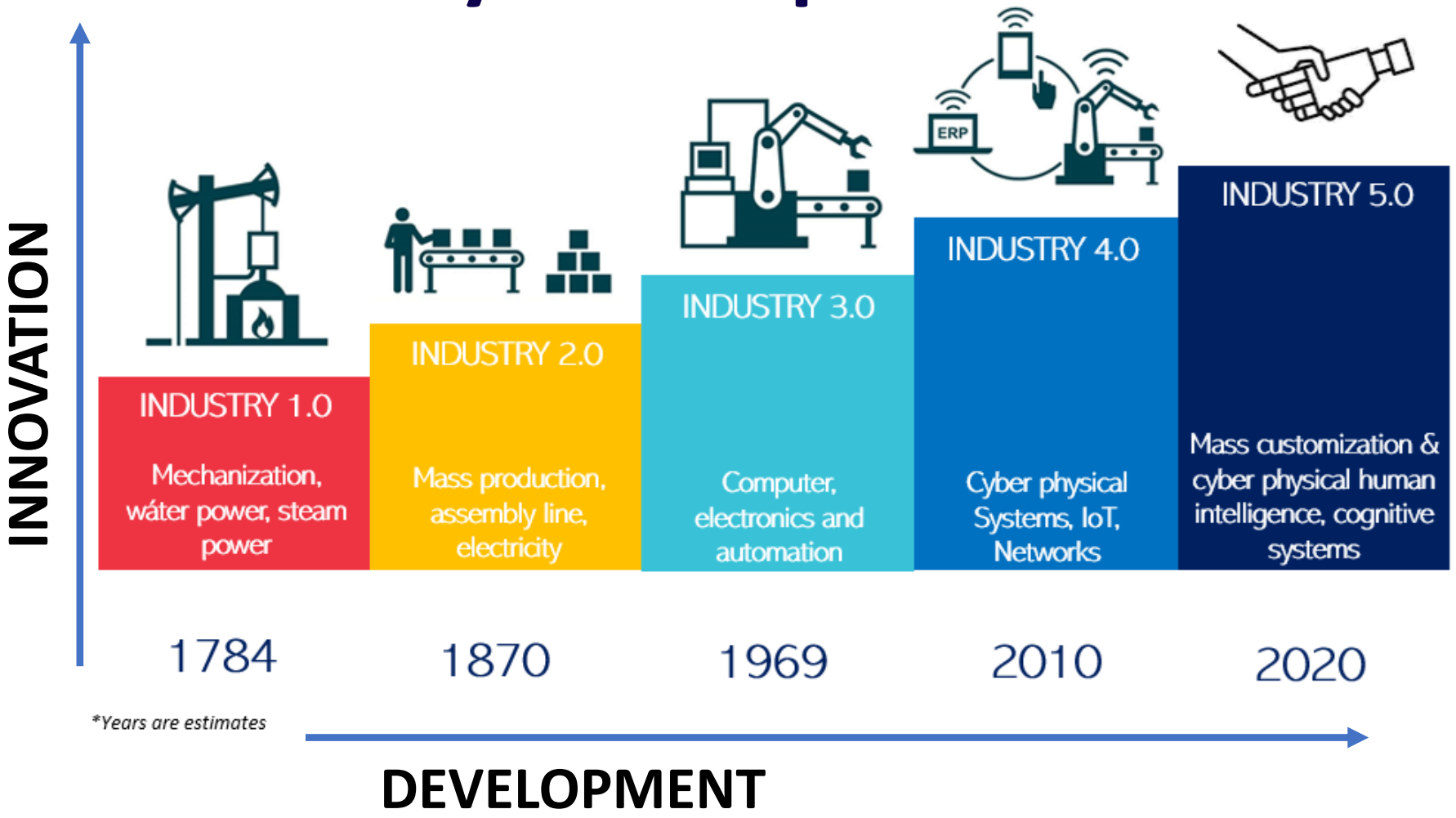
As Industry develops ….



Industry 5.0 envisions a future where industry goes beyond efficiency and productivity, focusing on human-centric, sustainable, and resilient production, integrating advanced technologies while prioritizing worker well-being and societal value.

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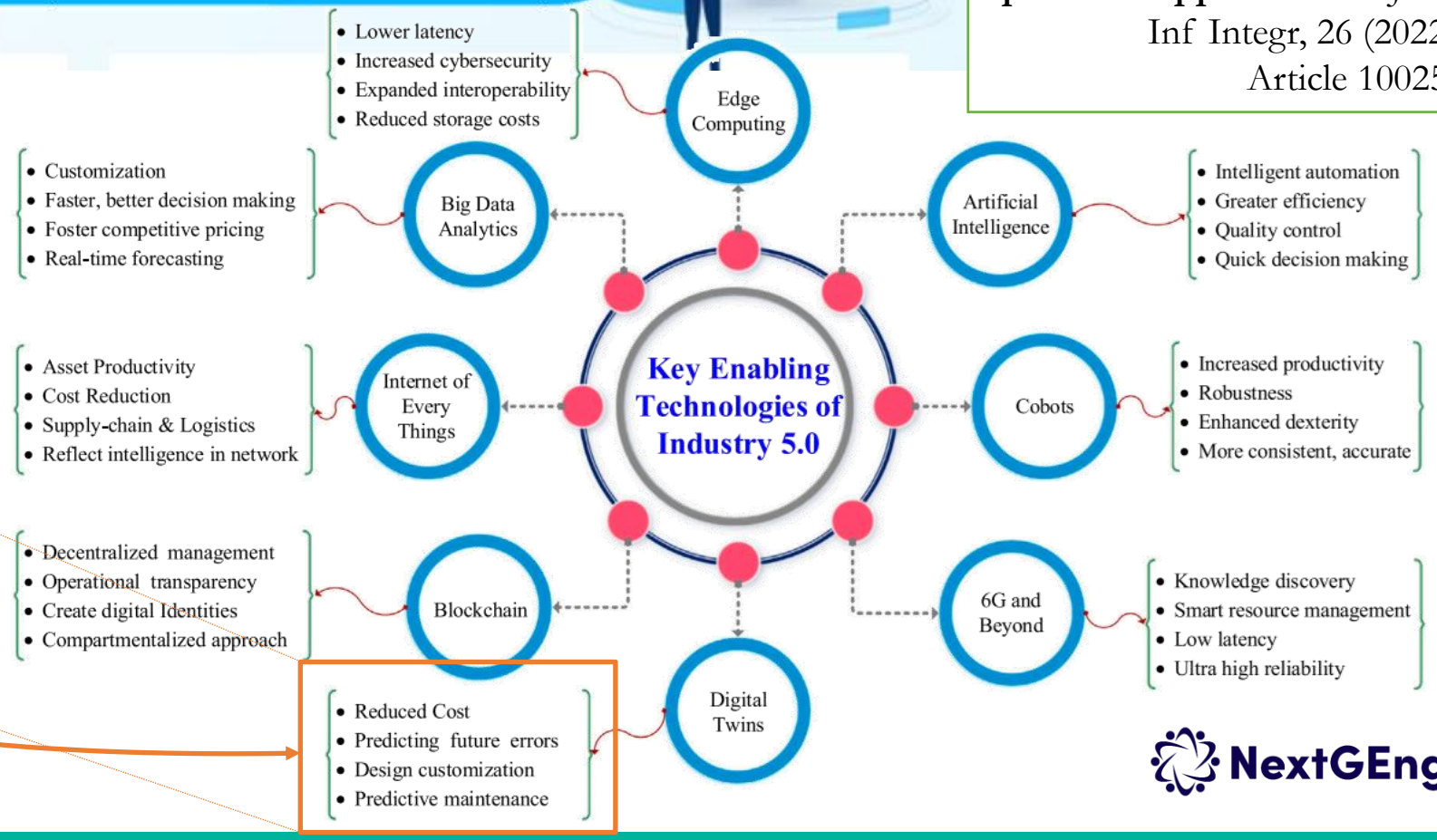
From Industry 4.0 to Industry 5.0

P.K.R. Maddikunta, *et al.*. "**Industry 5.0: a survey on enabling technologies and potential applications**". J Ind Inf Integr, 26 (2022), Article 100257

- Reduced cost
- Predicting future errors
- Design customization
- Predictive maintenance



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Digital Twins → A definition

Despite the multitude of definitions, a DT can be defined as:

"a digital copy of a physical object or system that is connected and shares functional and operational data, allowing the historical and real-time data collected to be used to assess the conditions of the physical asset and support the execution of simulation and data analysis techniques to **allow the optimization and improvement of the physical object**"

DTs offer a promising approach to achieving the Sustainable Development Goals (SDGs) by enabling data-driven modeling, optimizing resource management, and facilitating informed decision-making across various sectors like urban planning, transportation, **industry** and energy

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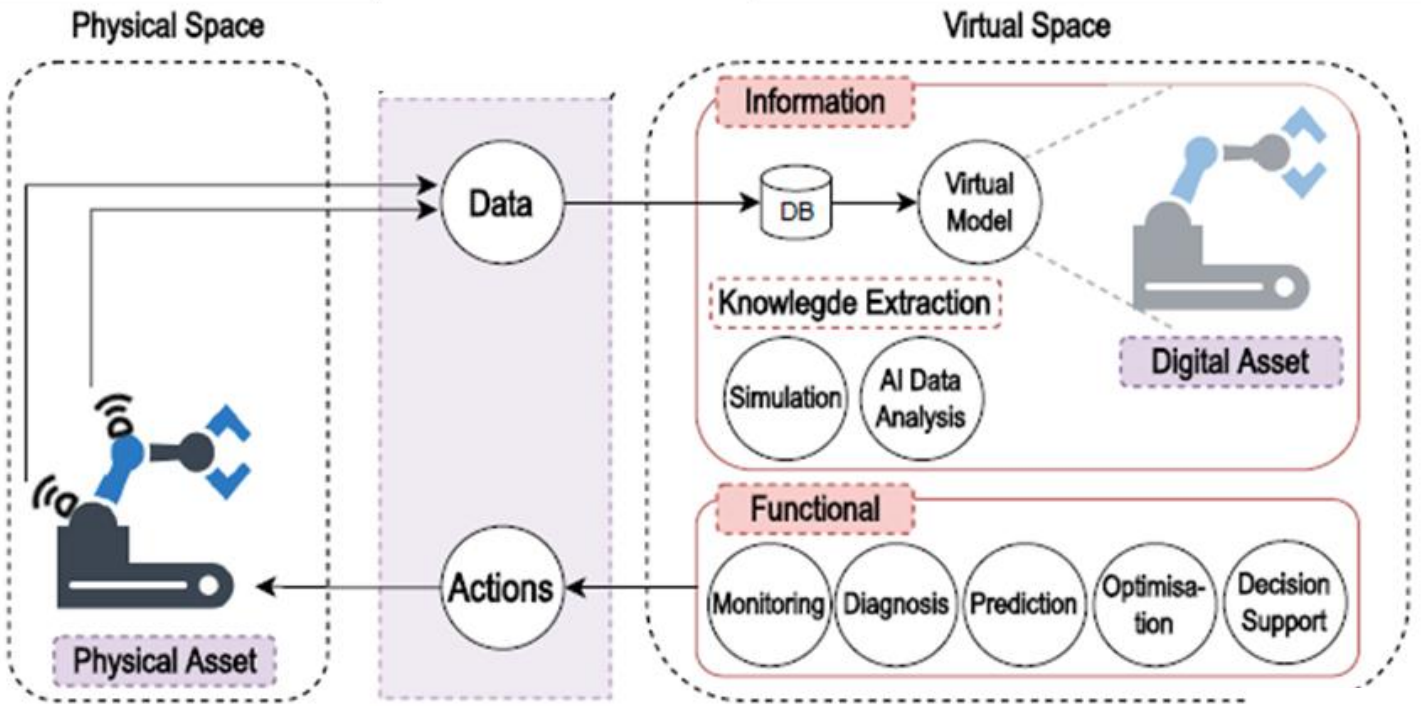
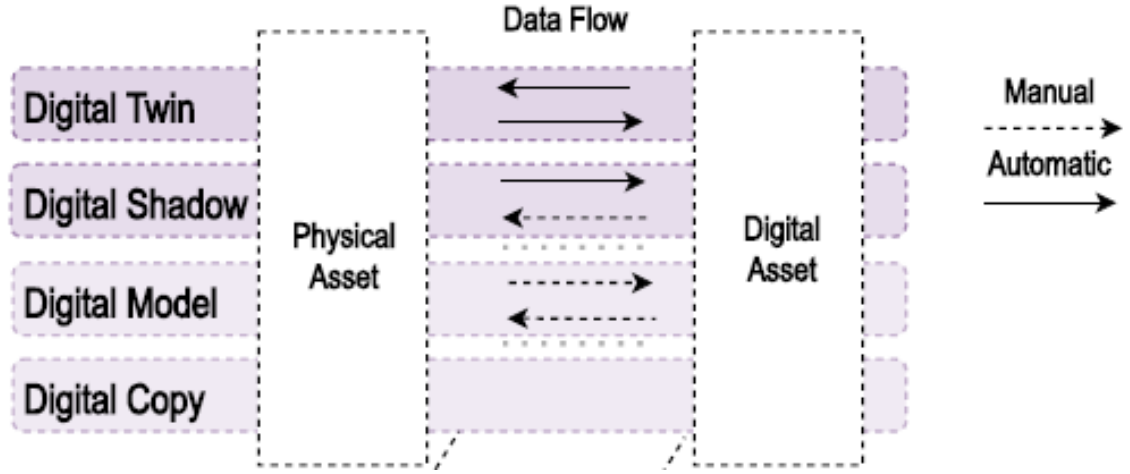
Digital Twins



Depending of the level of data integration between the physical and digital counterpart there are different categories of this concept:



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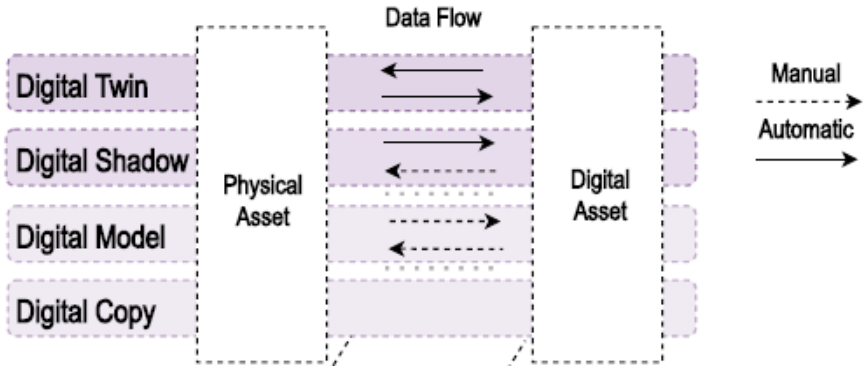
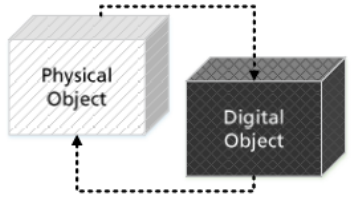
Digital Twins



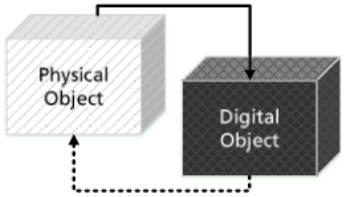
Depending of the level of data integration between the physical and digital counterpart:

Level 1. Digital Model



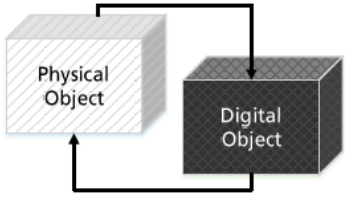
Digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object. A change in state of the physical object has no direct effect on the digital object and vice versa.

Level 2. Digital Shadow



When exists an automated one-way data flow between the state of an existing physical object and a digital object. A change in state of the physical object leads to a change of state in the digital object, but not vice versa.

Level 3. Digital Twin



When the data flows between an existing physical object and a digital object are fully integrated in both directions.

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Digital Twins in Industrial Automation

Integration of digital twins with automation significantly boosts **efficiency** and **controllability** of industrial processes

ONE EXAMPLE → PREDICTIVE MAINTENANCE

1

When industrial equipment breaks, the **resulting problem** often is not the cost of replacing that equipment but the forced **downtime**

2

Performing **regular maintenance** can help avoid unplanned downtime, but it does not guarantee that equipment will not fail.

3

What if the machine could indicate when one of its parts was about to fail?

What if the machine could even tell you which part needed to be replaced?

PREDICTIVE MAINTENANCE **GOAL**: avoiding downtime by using sensor data to predict when maintenance is necessary.

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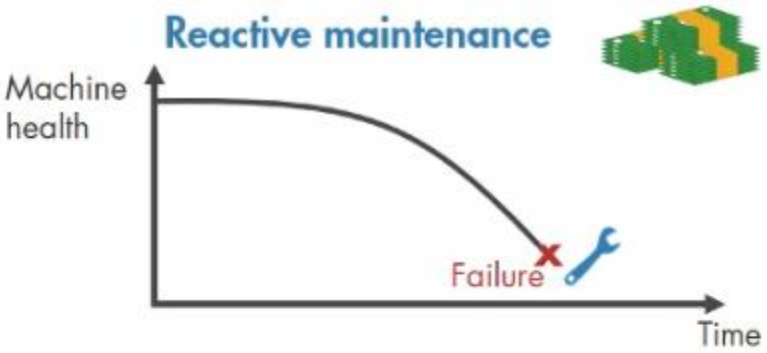
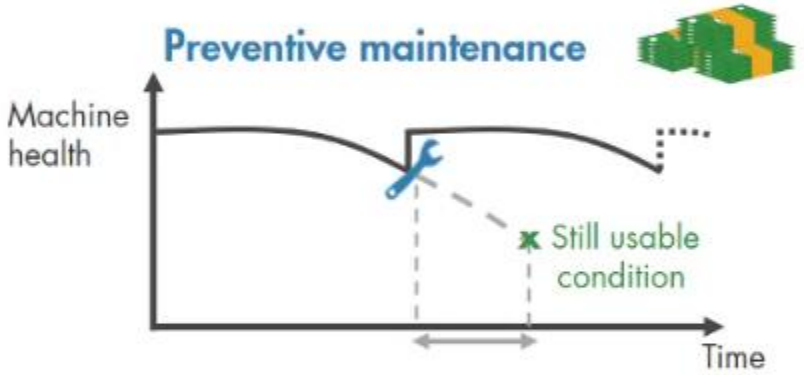
Digital Twins in Industrial Automation

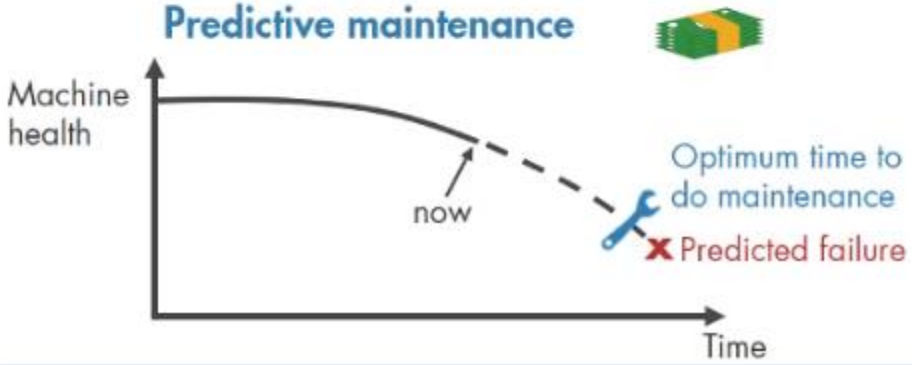
Real Asset. Triplex pump

A reciprocating pump design that utilizes three separate drive rods to drive the pumps plungers or pistons

Commonly used in the oil and gas industry







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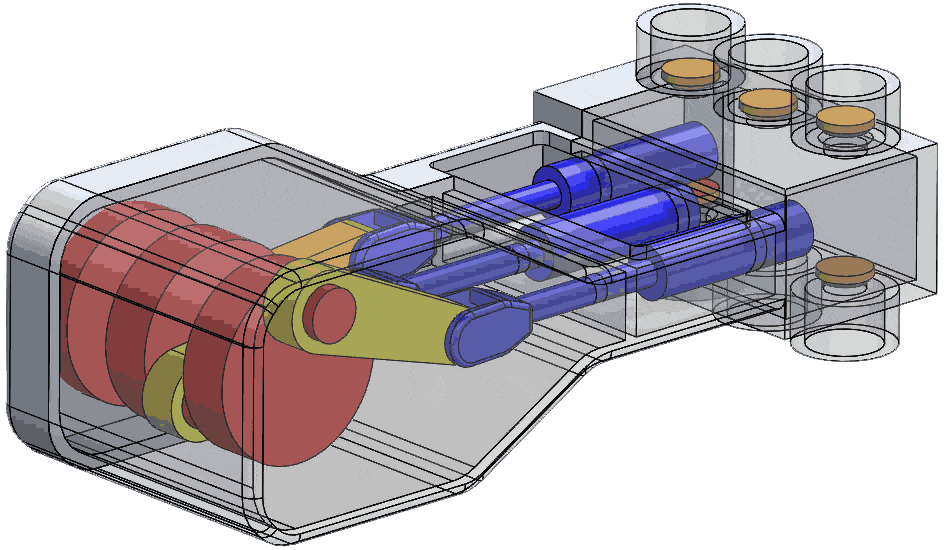
Digital Twins in Industrial Automation

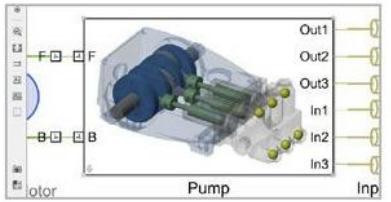
Real Asset.
Triplex pump



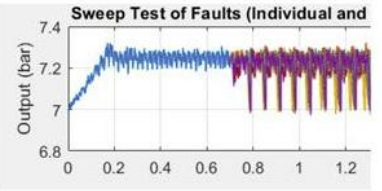
Temperature, flow, pressure

Sensor Data

Build Digital Twin



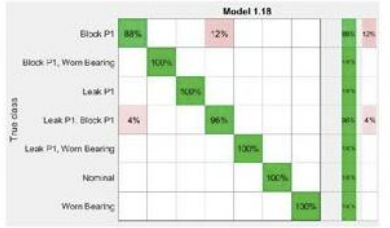
Obtain and Explore Data



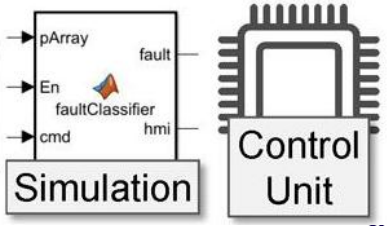
Preprocess Training Data

Run	Freq_1	Peak_1	Freq_2	Peak_2	
1	0.0021	0.0062	0.3152	0.0006	Le
2	0.0021	0.0062	0.3361	0.0006	... Le
3	0.0021	0.0063	0.3319	0.0006	Le
⋮					
31	0.0021	0.0104	0.3319	0.0073	Blc
32	0.0021	0.0107	0.3319	0.0075	... Blc
33	0.0021	0.0109	0.3319	0.0077	Blc
⋮					

Develop Predictive Model



Deploy Algorithm



Optimum time to do de maintenance

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GREAT POTENTIAL IN ALL FIELDS

Applications of digital twins for advancing the specific targets that span the 17 SDGs

Source

https://www.nature.com/articles/s41893-022-00923-7

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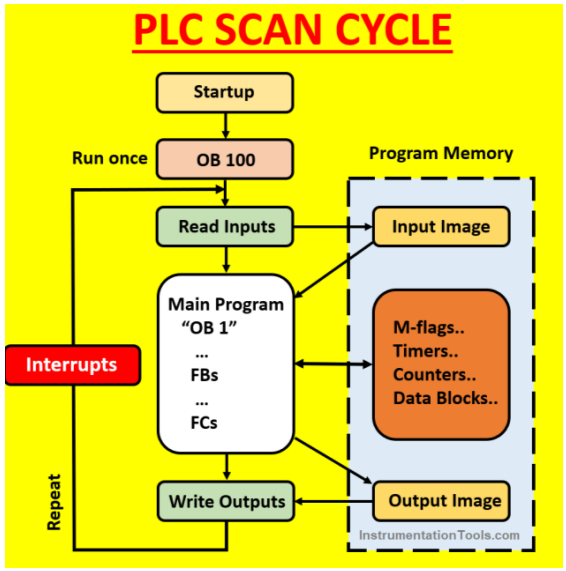

Foundations of PLCs & discrete event system design

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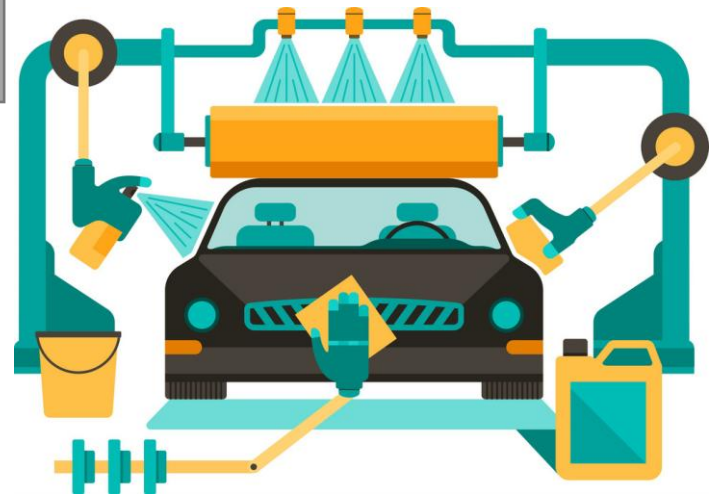
Previous concepts

Discrete event systems (discrete automation)

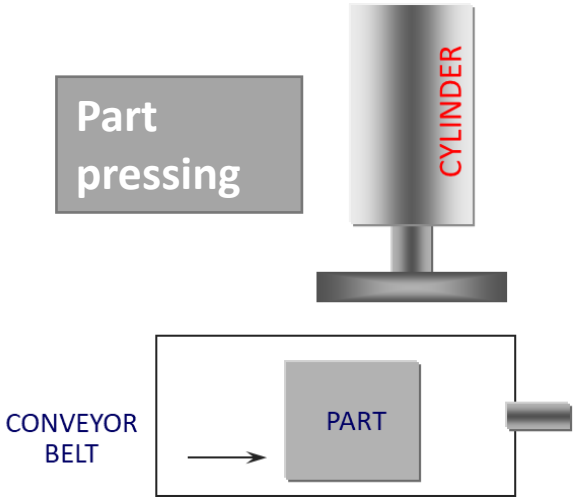
- ✓ Many processes involve discontinuous elements
- ✓ Some of its variables only take an integer number of values
- ✓ The values of some variables only change at certain time instants (events)
- ✓ Logic and sequential control problems

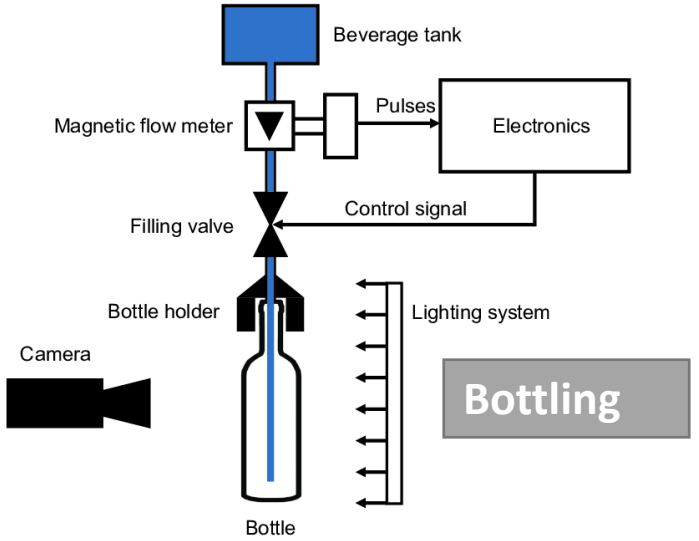
Automatic Car Wash



Traffic lights

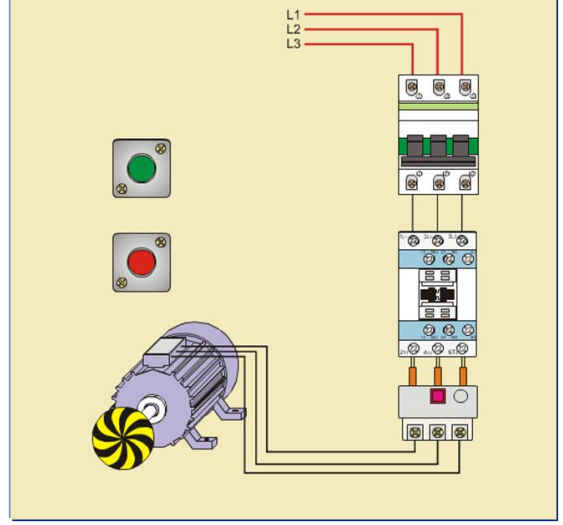
Part pressing





Bottling

Direct start of a motor



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Programmable Logic Controllers (PLCs)

What are PLCs?

Programmable Logic Controllers (PLCs) are industrial computers, with various inputs and outputs, used to control and monitor industrial equipment based on custom programming

PLC Basics

Source YouTube: https://www.youtube.com/watch?v=PbAGl_mv5XI

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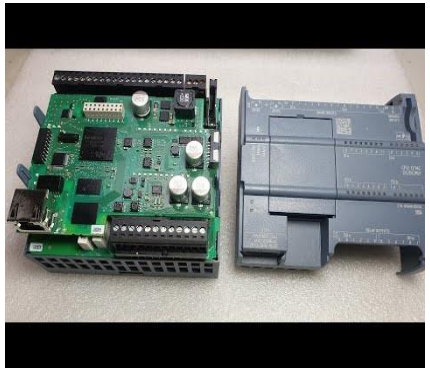
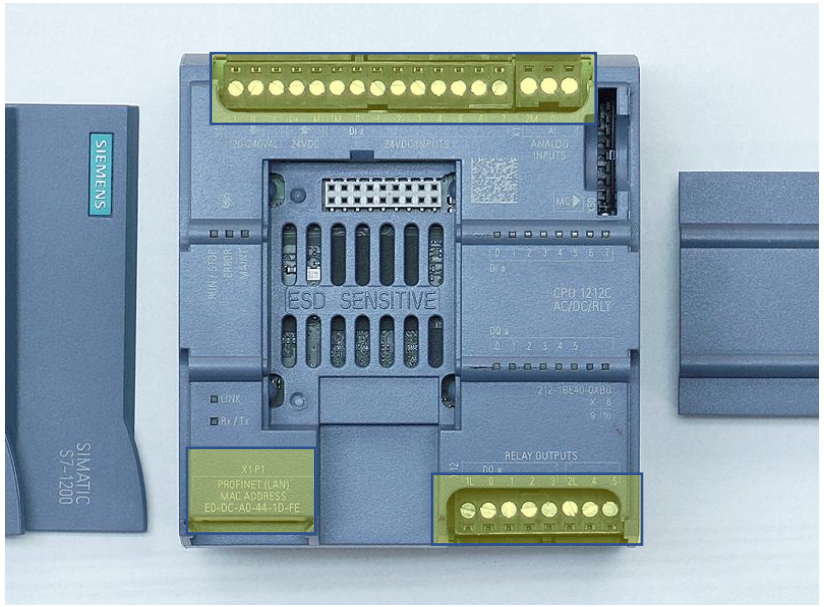
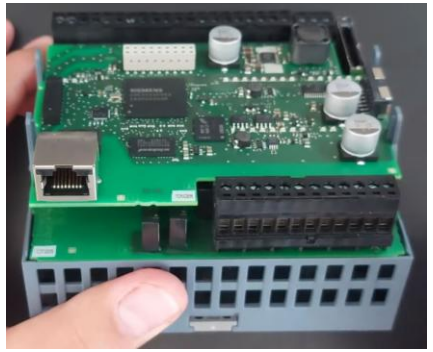
Inside the PLC

Siemens S7-1200

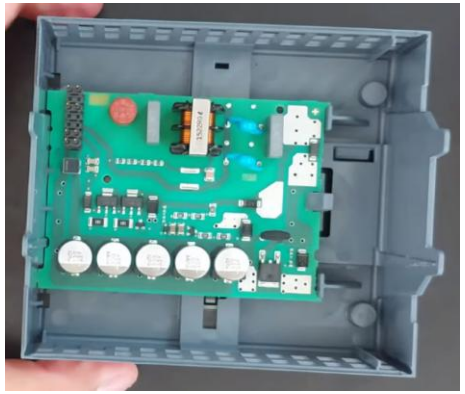






CPU

I/O module



Power supply

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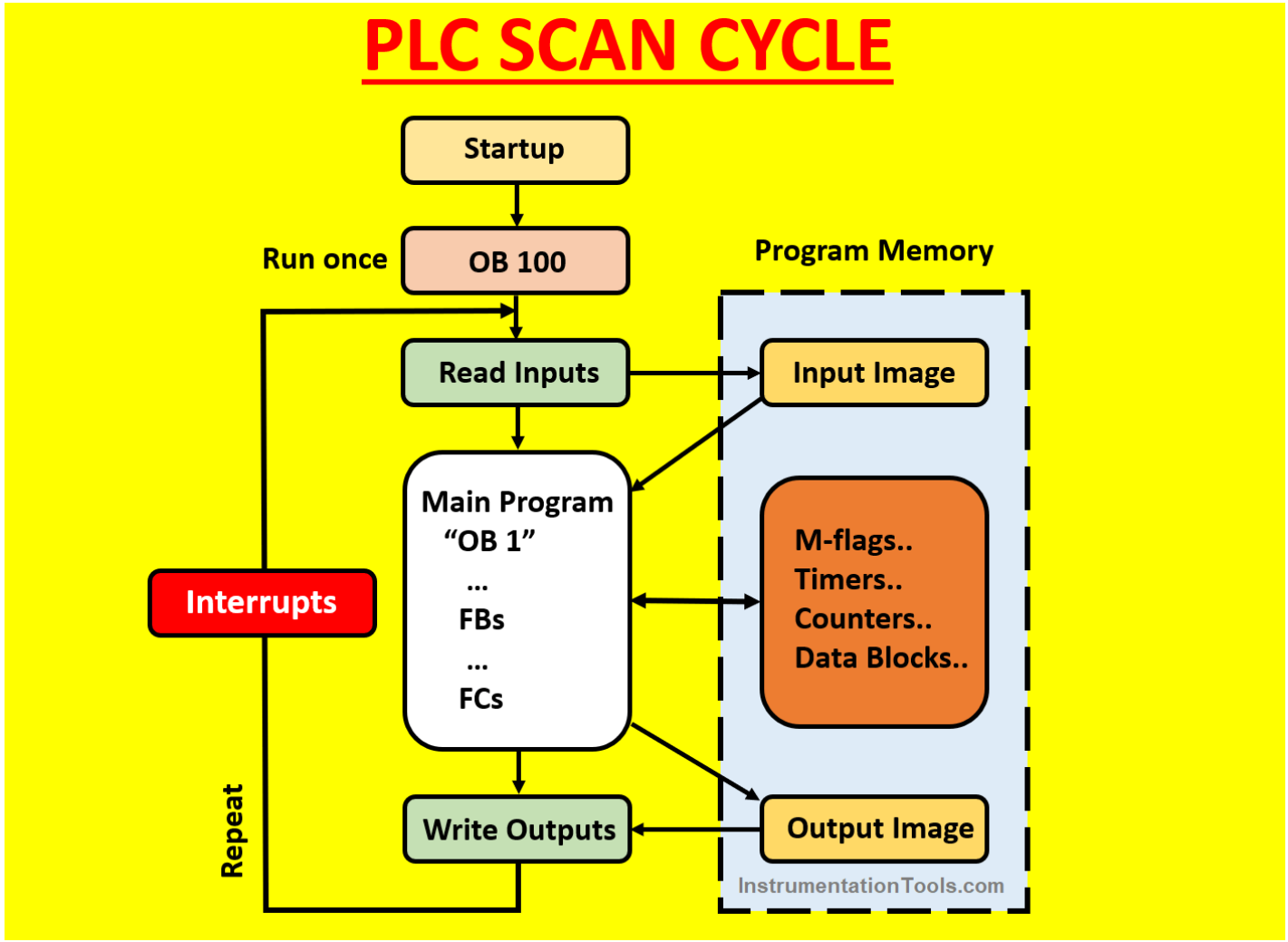
How a PLC works



It depends on:

- Hardware and software characteristics of the PLC itself.
- The number of inputs and outputs involved.
- Length of the user program.
- Number and type of peripherals connected to the PLC.

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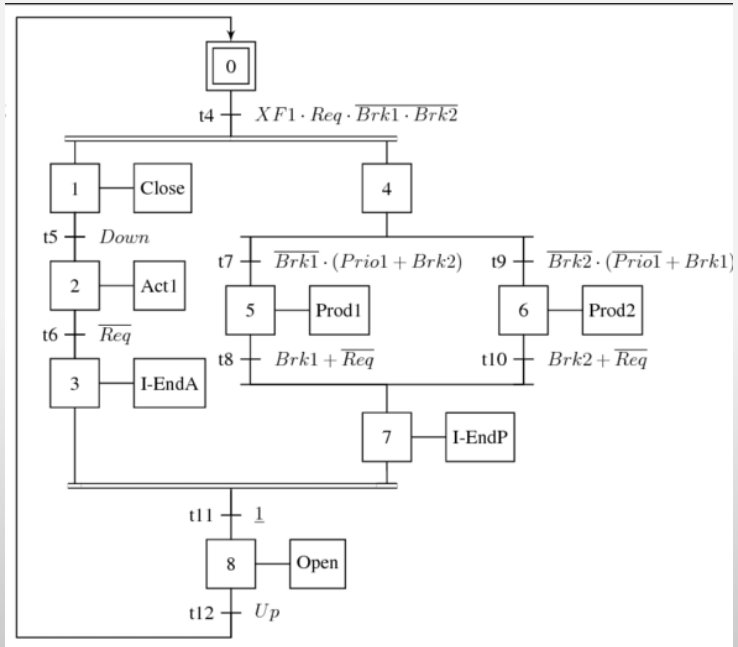
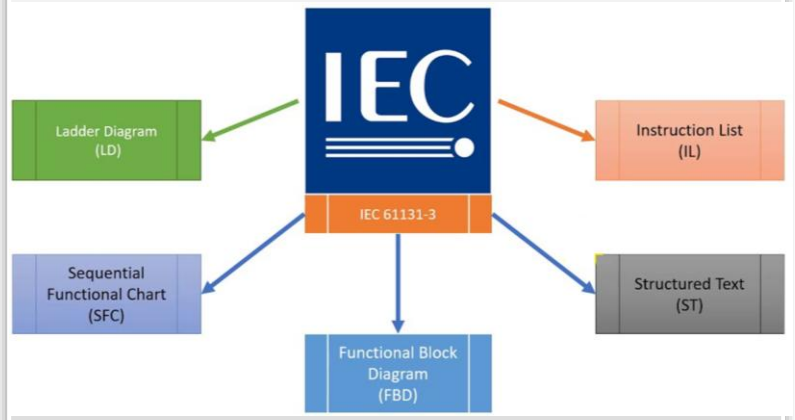
Programming a PLC

AUTOMATISM DESIGN

GRAFCET

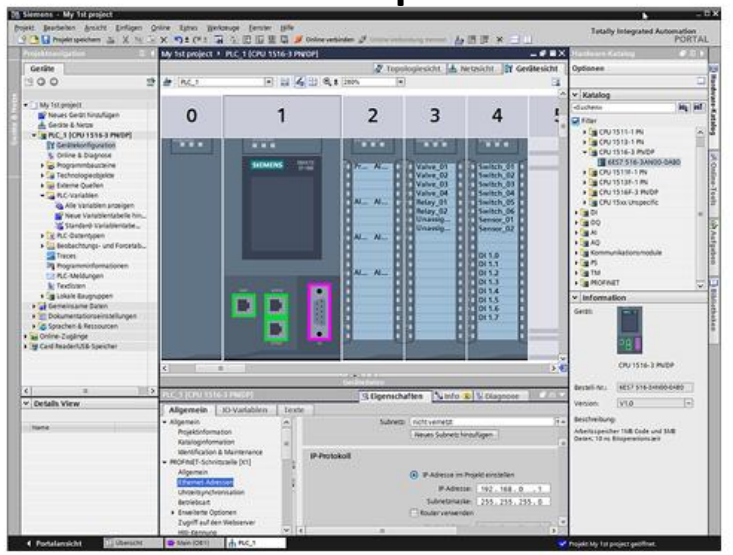


PROGRAMMING



TEST

Siemens TIA portal



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Discrete event system design. GRAFCET

❑ Definition

It is a method for representing the operation of logical systems independent of their technological implementation.

❑ History

- The GRAFCET - Functional Chart for Control of Stages and Transitions - emerged in 1977 in a working group of the AFCET (French Association for Economic and Technical Cybernetics) created in 1975.
- There was a need to unify and rationalize the language for describing logical systems and in particular the sequential part of them.

❑ Main characteristics:

- Describes any system whose evolutions can be expressed sequentially.
- Can be used for the description of combinatory processes because it allows them to be treated sequentially, in an easy-to-understand and analyze way.
- Characterizes the operation of the automation with complete independence of the components with which it will be built.

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GRAFCET

IEC 60848

Edition 3.0 2013-02

INTERNATIONAL STANDARD

NORME INTERNATIONALE

GRAFCET specification language for sequential function charts

Langage de spécification GRAFCET pour diagrammes fonctionnels en séquence

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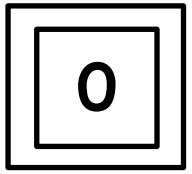
GRAFCET

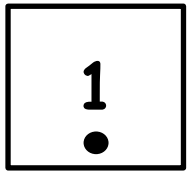
❑ Basic elements

- **Step:** represents a partial state of the system and can be active or inactive

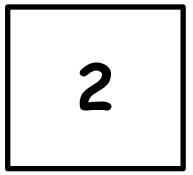
Initial



Active

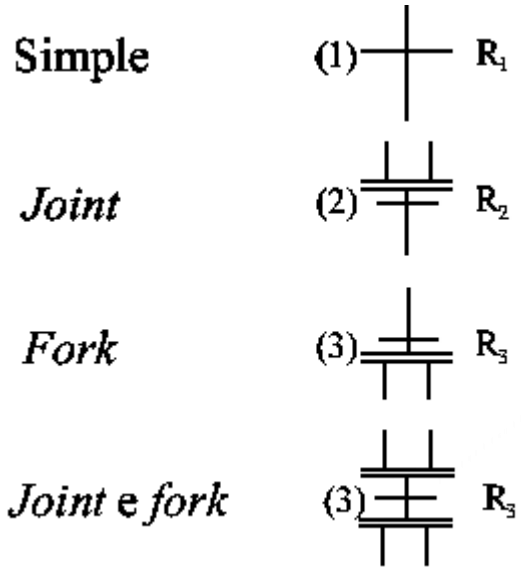


Inactive



- **Actions**: can be associated with Steps

- **Transition**: links the previous step (one or several) of any transition and the following step (one or several)



A logical receptivity function can be associated with each Transition

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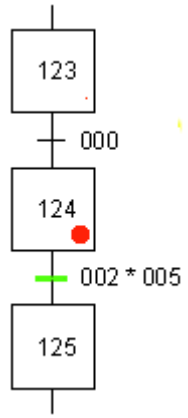
GRAFCET

❑ State Evolution



- Rule 1: Initial State

  It is characterized by the active Steps at the beginning of operation (at least one)

- Rule 2: Transposition of a Transition

  (2a) A Transition is active or enabled only if all the Steps at its input are active (if not it is inactive).

  (2b) A Transition can only be transposed if it is active and its associated condition is true (receptivity function).

- Rule 3: Evolution of active Steps

  The transposition of a Transition leads to the deactivation of all the Steps on its inputs and the activation of all Steps on its outputs.

- Rule 4: Simultaneous transposition of Transitions

  All active Transitions are transposed simultaneously

- Rule 5: Simultaneous activation and deactivation of a Step

  In this case the activation has priority.

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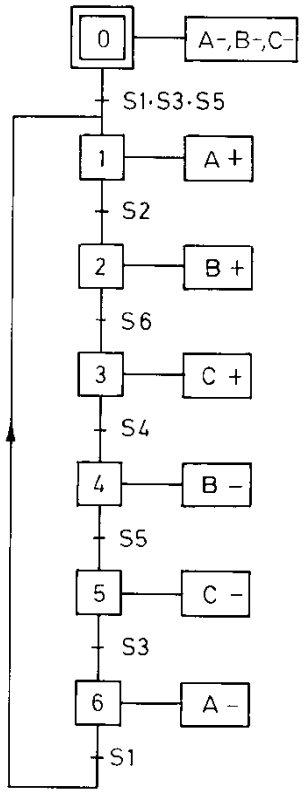
❑ Structures

✓ *Linear*



☑ It is the simplest one

☑ Several steps joined by transitions

- In a linear structure only one step should be active in a stable state
- One step will be active if the previous step is active and the associated condition of the transition between both is true
- The activation of one step leads to the deactivation of the previous
- A linear structure can be part of a more complex structure.

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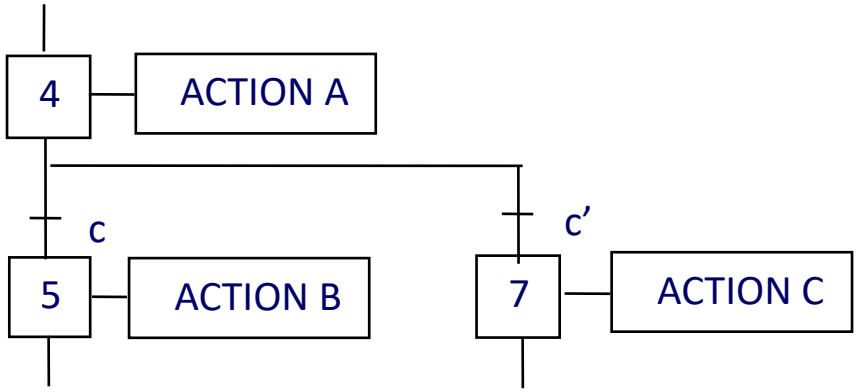
❑ Structures

✓ *Convergence/Divergence "OR" – exclusive sequences*



- Several alternative sub-processes are initiated with an OR divergence
- These sub-processes may include other types of structures
- The sub-processes has to finish in an OR convergence

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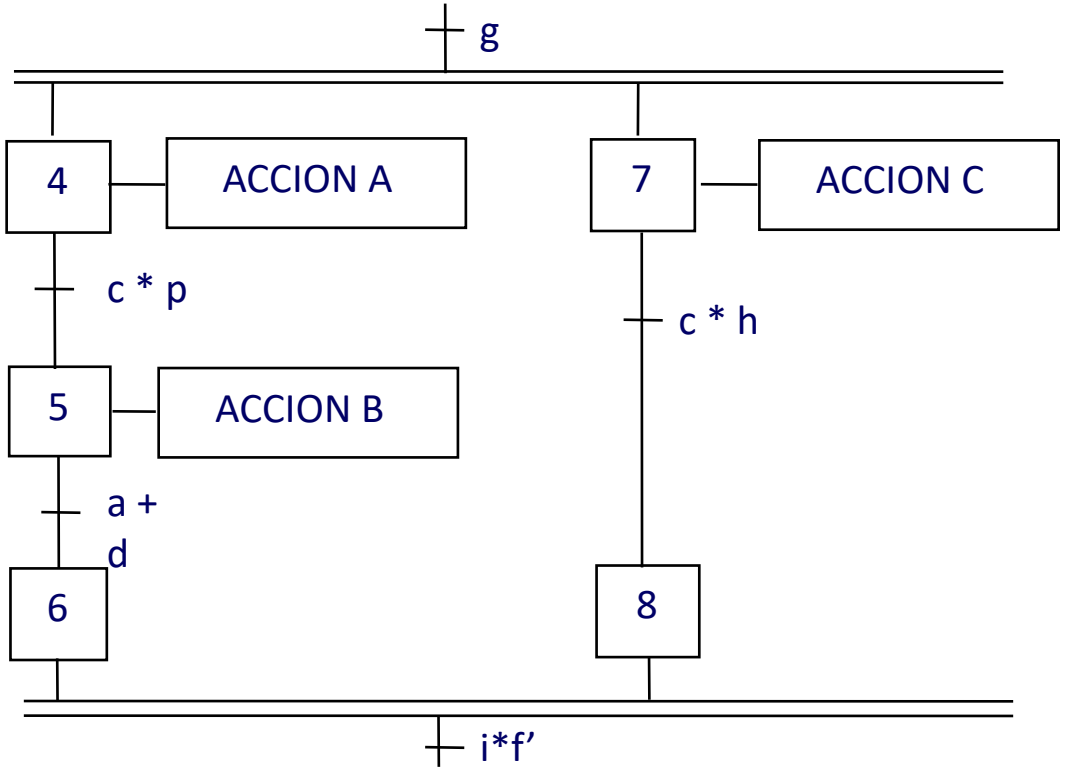
❑ Structures

✓ *Convergence/Divergence "AND"*



① Several sub-processes are simultaneously initiated with an AND divergence once C9 is true

② These sub-processes may include other types of structures.

③ The sub-processes has to finish in an AND convergence

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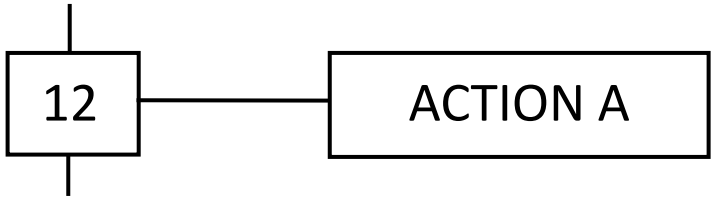
❑ Type of actions

✓ *Continuos action*

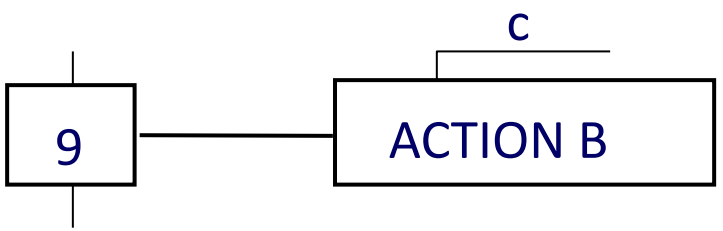
The execution of the continuous action occurs while the stage to which it is associated is active.



ACTION A= step 12

✓ *Conditioned action*

It is a continuous action whose execution is subject to a logical condition; if this logical condition is fulfilled, the action is executed.

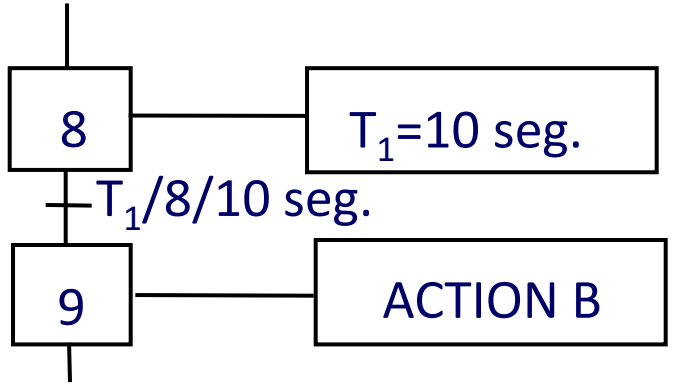


ACTION B = step 9 * c

✓ *Time-phased action*

It is expressed by the notation : *t / i / q*

ACTION B is excuted if 10 seconds have passed since step 8



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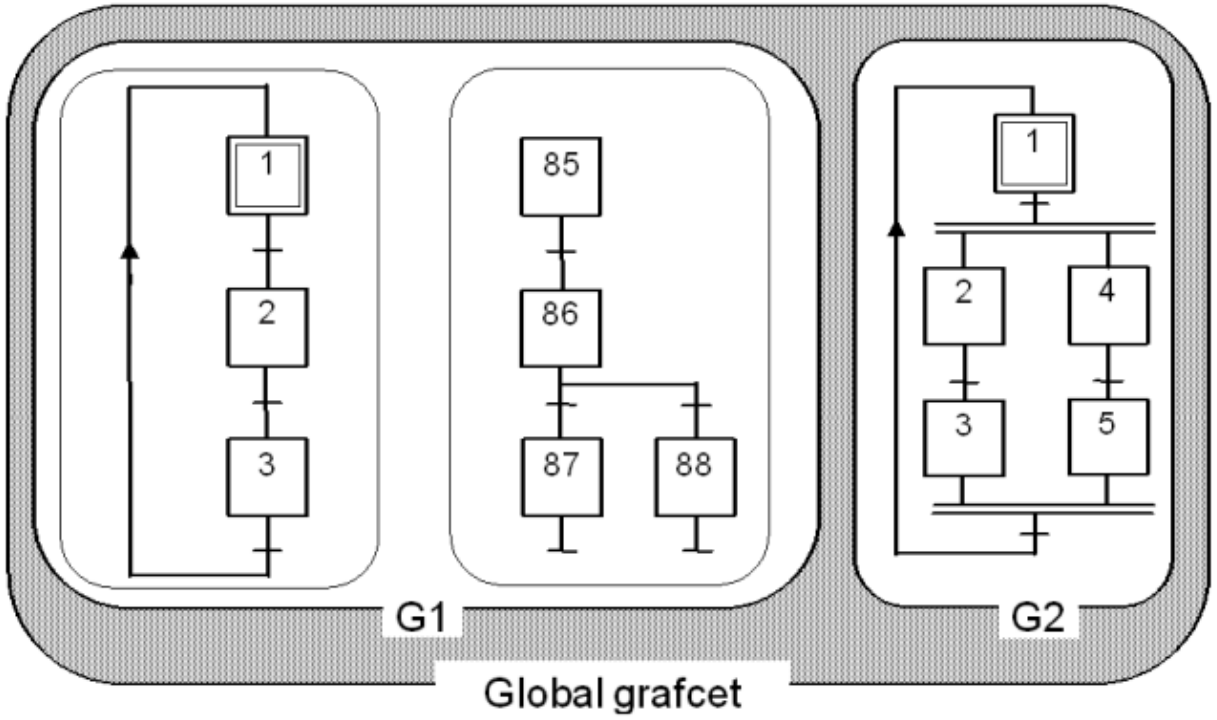
NextGEng

GRAFCET

❑ Partial GRAFCETs

Formed by one or several connected GRAFCET charts, a partial GRAFCET chart will results from the division of the global GRAFCET chart describing the behavior of the sequential part of a system, according to the methodological criteria.



EXAMPLE: Partition of a global grafcet:

The global grafcet is made of the partial grafcets G1 and G2. The partial grafcet G1 is made of two connected grafcets.

- G#: # replaces the name of the partial GRAFCET
- G#{}: empty situation. None of its steps is active in G#
- G#{INIT}: Initial situation of a partial GRAFCET. Initial step is active in GRAFCET #
- G#{… , …, …}: Indicates which steps are active in GRAFCET #

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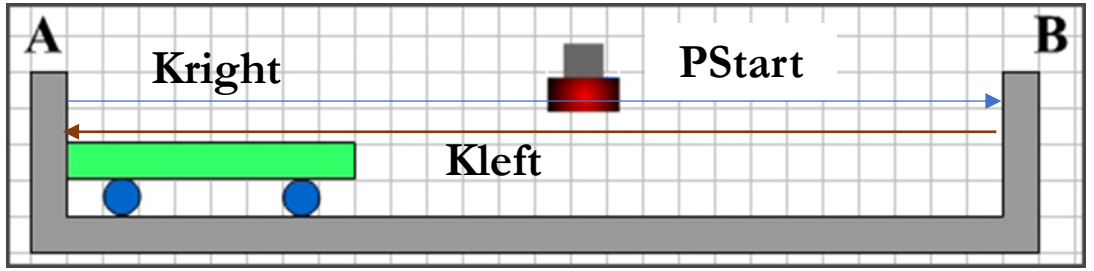
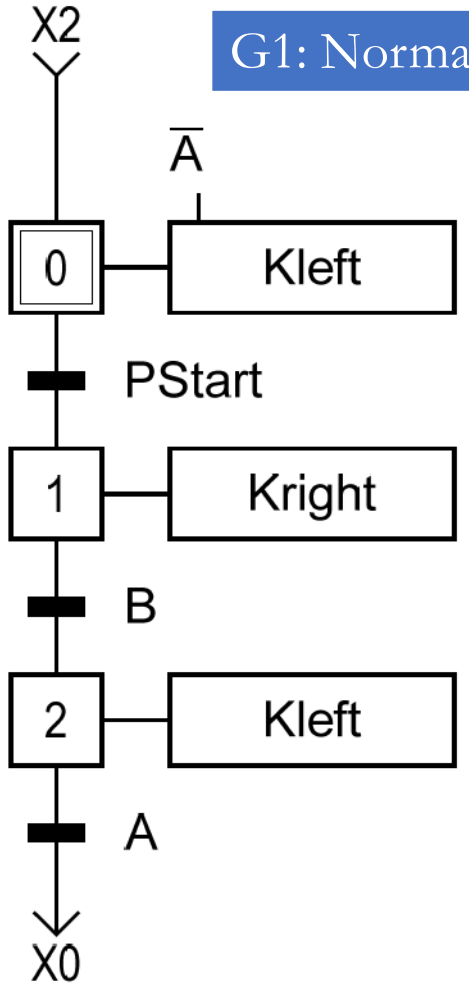
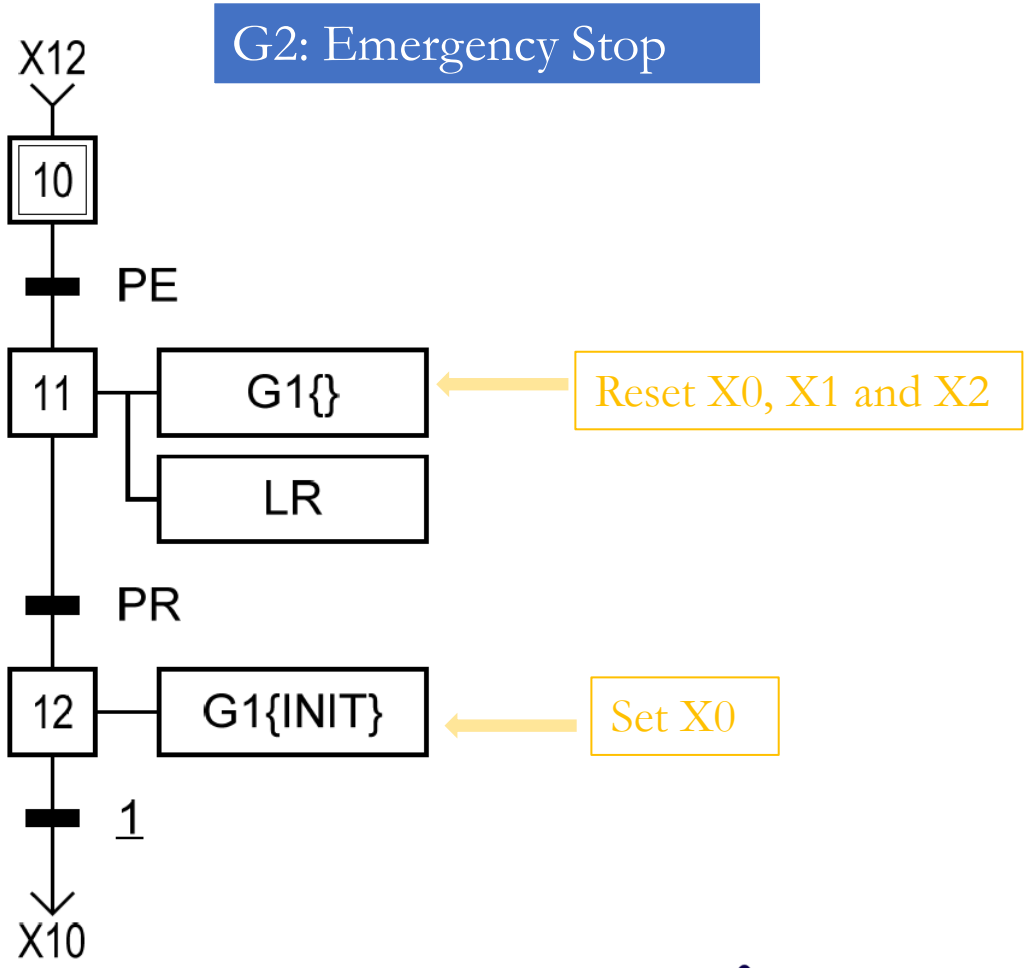
NextGEng

GRAFCET

- Emergency stops with partial GRAFCETs







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NextGEng

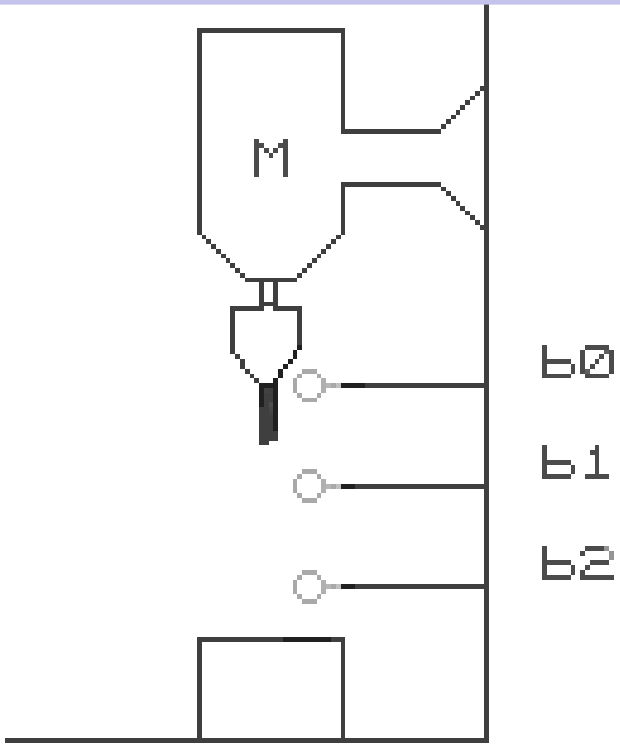
GRAFCET

❑ Example

The electric drill bit is rotating during the drill movement.
Drill movement is controlled by five contactors: (*)

- D: Go down
- S: Go up
- Vh: High speed
- Vl: Low speed
- Md: Bit drill movement

b0, b1 and b2 are limit switches



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NextGEng

GRAFCET

❑ Example

1. Input / Output identification

Control

D	Go down
S	Go up
Vh	High speed
Vl	Low speed
Md	Bit drill movement

Output

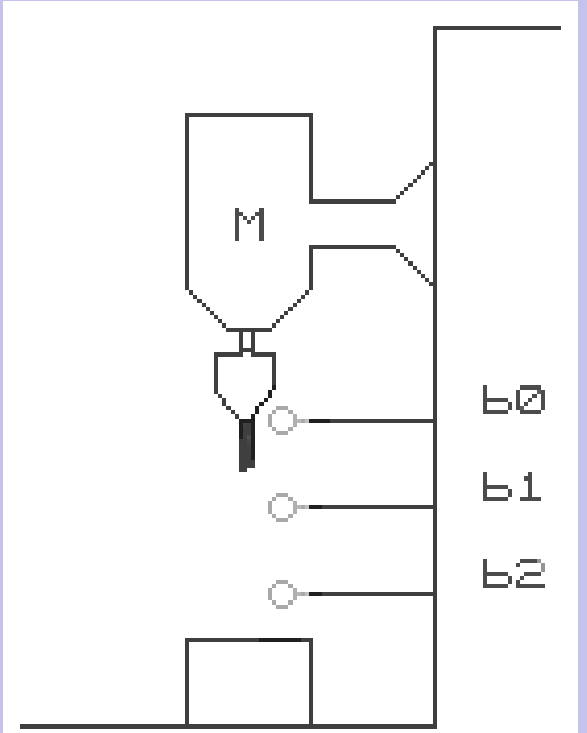
Input

Input

Output

b0	Limit switch pos 0
b1	Limit switch pos 1
b2	Limit switch pos2
Start	Start button

Process



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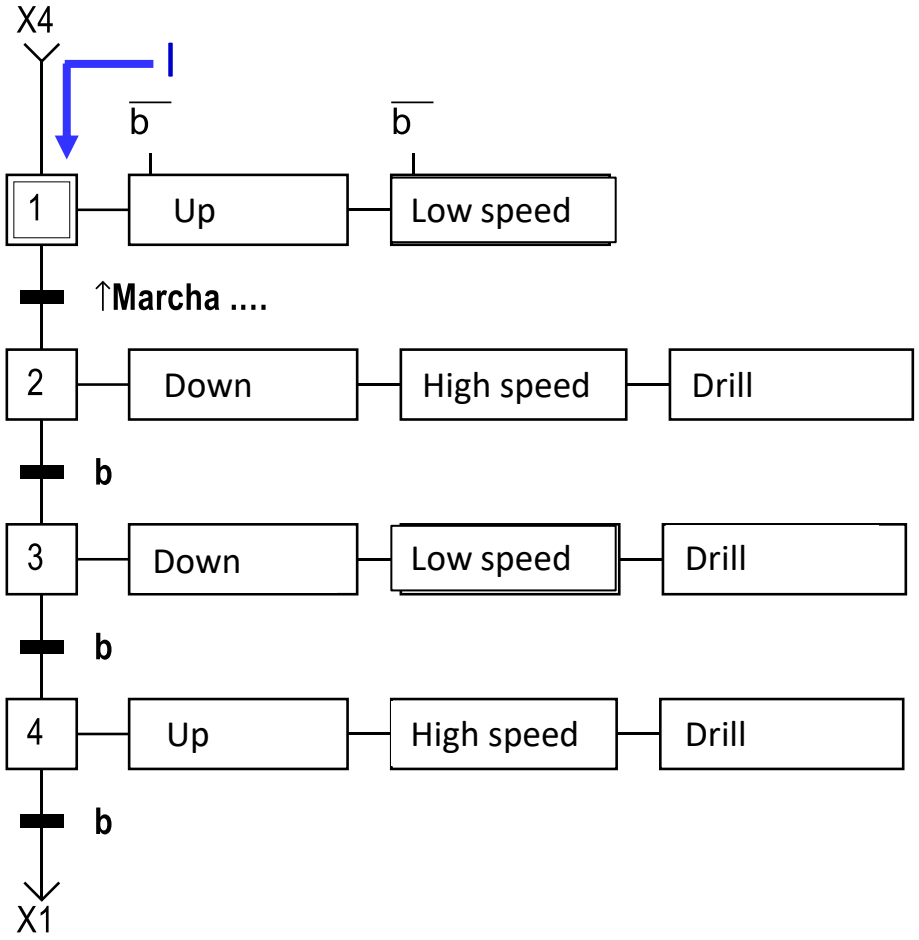
NextGEng

GRAFCET



START-UP

SET	RESET
X1	X2, X3, X4

SEQUENTIAL

	SET	RESET
X1· Marcha·b0	X2	X1
X2·b1	X3	X2
X3·b2	X4	X3
X4·b0	X1	X4

COMBINATORIAL

Down = X2 + X3
High Speed = X2 + X4
Low Speed = X1 . b0 + X3
Up = X1 . b0 + X4
Drill = X2 + X3 + X4

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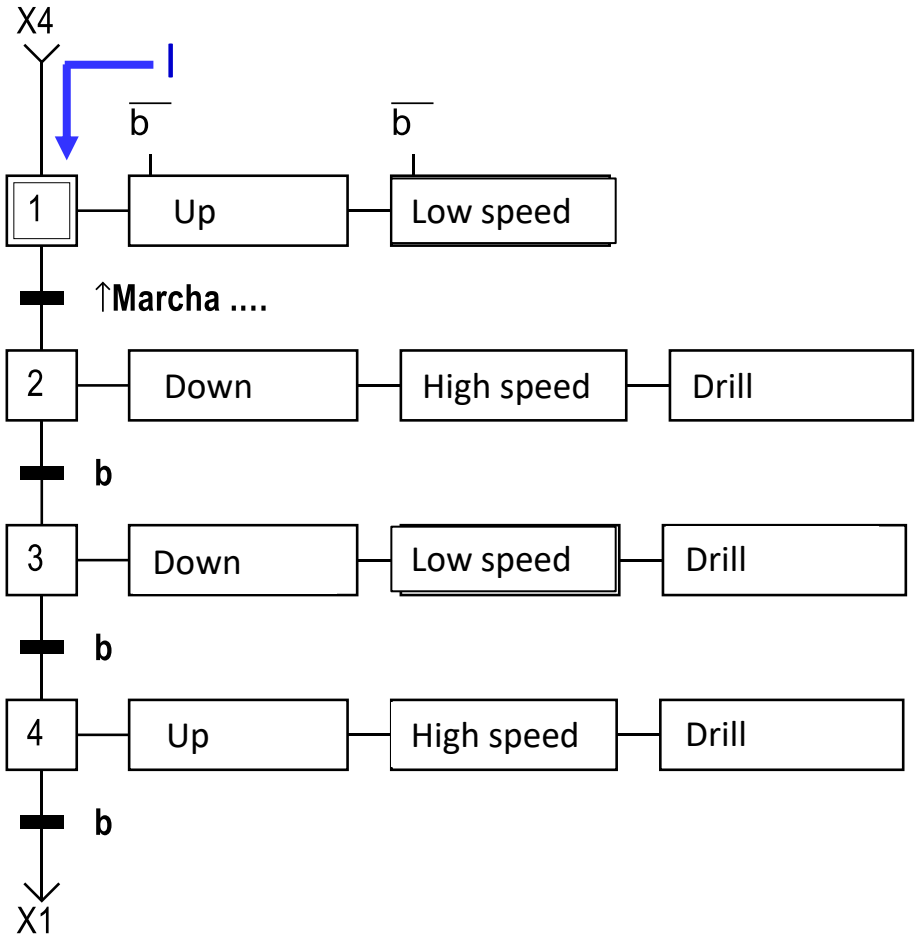
NextGEng

Skill test

Include an **emergency STOP**:

- If PE is pressed the process stops a LED is lighted.
- When PR is pressed the process is prepared to start a new cycle



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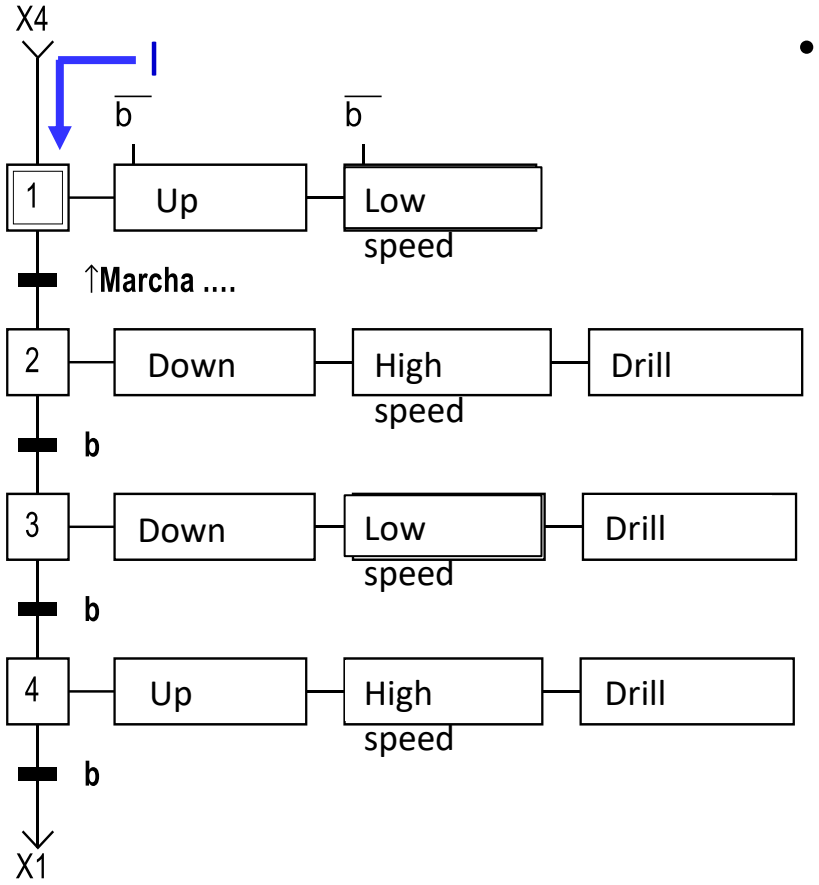
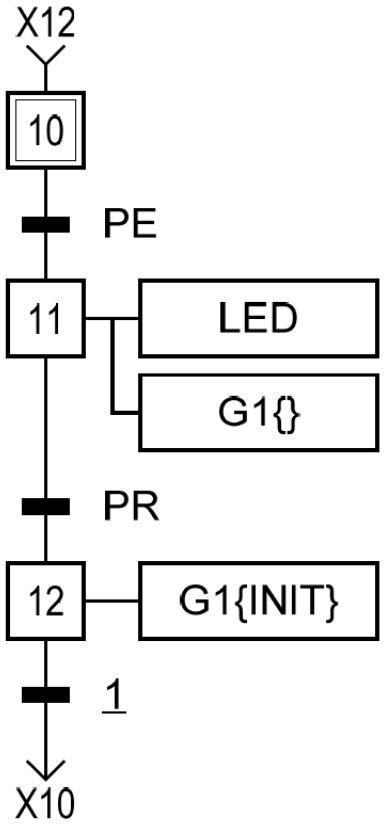
NextGEng

Skill test



Include an **emergency STOP**:

- If PE is pressed the process stops a LED is lighted.
- When PR is pressed the process is prepared to start a new cycle



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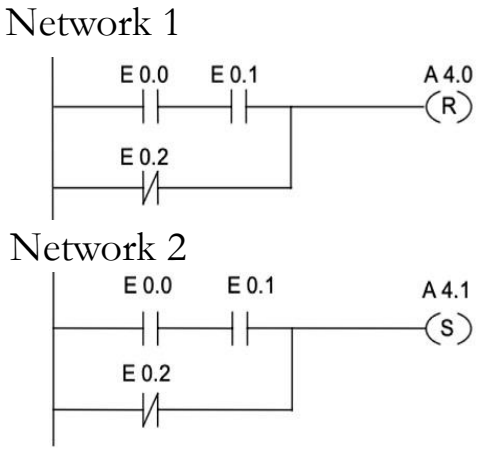
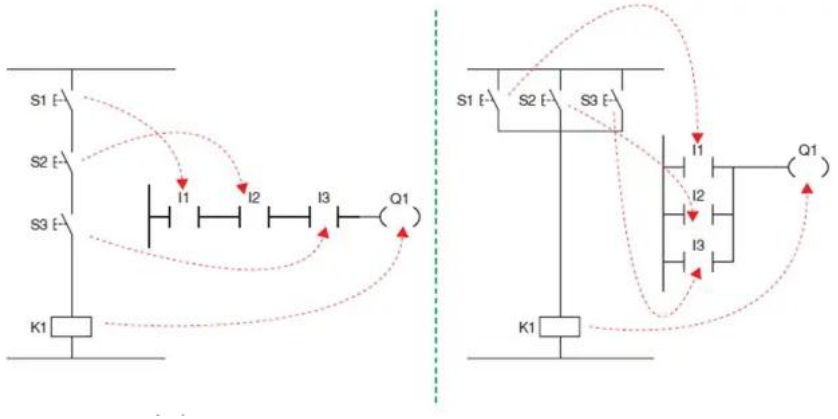
NextGEng

3 **Structured programming using ladder (timers, counters and emergency stop)**





LADDER (LAD o LD)

IEC 61131-3

Ladder Logic Diagram (LD)

Function Block Diagram (FBD)

Instruction List (IL)

Structured Text (ST)

Sequential Function Chart (SFC)

Structured programming using ladder

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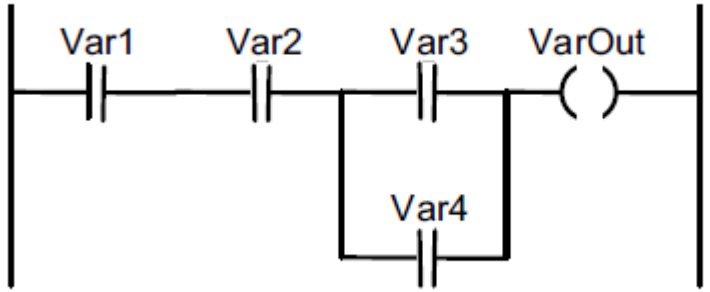
NextGEng

Ladder

The language Ladder Diagram (LD) comes from the field of electromechanical relay systems and describes the power flow through the network of a Program Organization Unit from left to right. This programming language is primarily designed for processing Boolean signals (1 ≡ TRUE or 0 ≡ FALSE).



The evaluation of a network result depends on the graphical layout of the network (including variable names) and its connections. Elements are either connected in series or in parallel.

An **LD** network consists of the following **graphical objects**:

1) Connections,
2) Contacts and coils,
3) Graphical elements to control the execution sequence (jumps),
4) Graphical elements to call a function or FB (standard or user POU),
5) Connectors

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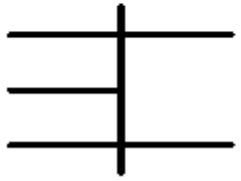
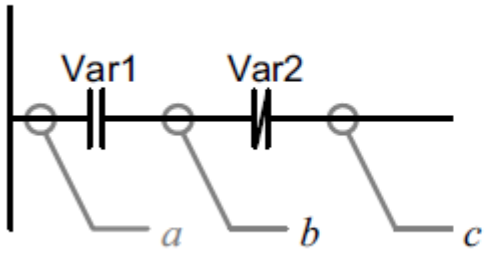
NextGEng

Ladder. Graphical objects

(1) Connections. LD has horizontal and vertical lines to connect elements, and also includes crossing points.

Graphical object	Name	Explanation
	Horizontal connection	The horizontal connection copies the value written on the left-hand side (FALSE or TRUE) to the right-hand side.
	Vertical connection including horizontal lines	A vertical connection evaluates all incoming lines (from left) with OR and copies this value to all connections on the right-hand side.

(2) Contacts and Coils. A **contact** performs a logic operation on the value of an incoming line and the value of the associated variable. The kind of logic operation depends on the type of the contact. The calculated value flows to the right connecting line.



Var1	Var2	Not Var2	value of b	value of c
0	0	1	0	0
1	0	1	1	1
0	1	0	0	0
1	1	0	1	0

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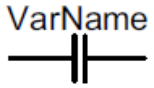
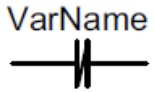
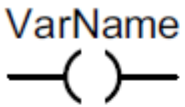
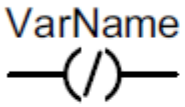
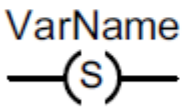
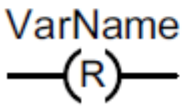
Ladder. Graphical objects

(2) Contacts and Coils

Graphical object	Name	Explanation
	Normally open contact	RightLink := LeftLink AND VarName, (Copy the status of the left link to the right link if the variable evaluates to TRUE, else FALSE).
	Normally closed contact	RightLink := LeftLink AND NOT VarName, (Copy the status of the left link to the right link if the variable evaluates to FALSE, else FALSE).

Coils are elements where values are assigned to variables

Graphical object	Name	Explanation
	Coil	Variable [b] := LeftLink. (Copy the value of the left link to the variable).
	Negated coil	Variable [b] := NOT LeftLink. (Copy the negated value (change FALSE <-> TRUE) of the left link to the variable).
	Set (latch) coil	Variable [b] := TRUE, if LeftLink has the state TRUE, else: do not change the variable.
	Reset (unlatch) coil	Variable [b] := FALSE, if LeftLink has the state TRUE, else: do not change the variable.

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NextGEng

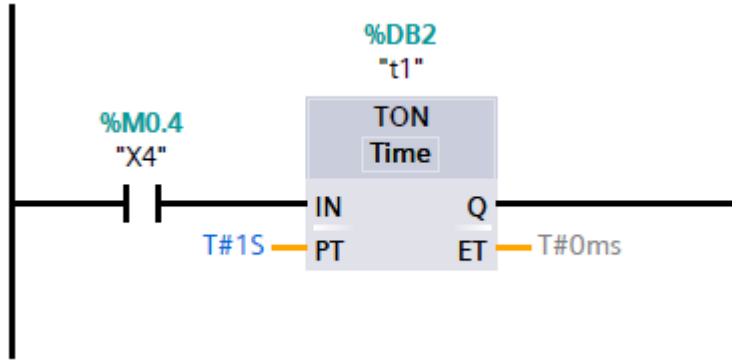
Ladder. Graphical objects

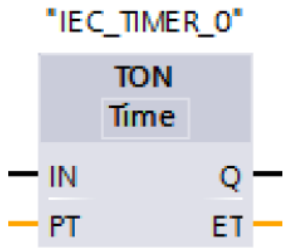
(4) Call of functions and function blocks. LD supports calls to POUs of type Function or FB.

FBs and functions can have several input and output parameters

TIMER

❑ TON. Generate on-delay

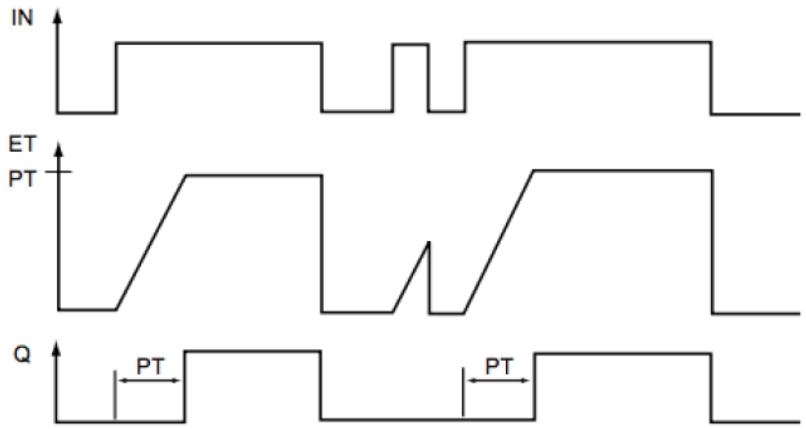




Format PT: T#4s

State: *"NAME".Q*

TON:



Parameter	Description
IN	Start input
PT	Duration of the on-delay. The value of the PT parameter must be positive.
Q	Output that is set when the time PT expires
ET	Current time value

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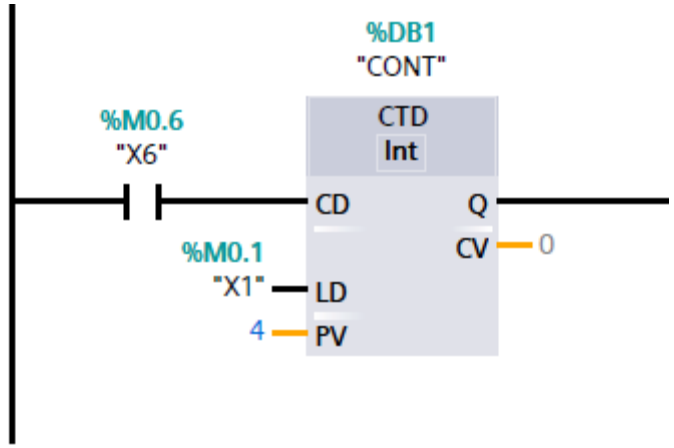
Ladder. Graphical objects

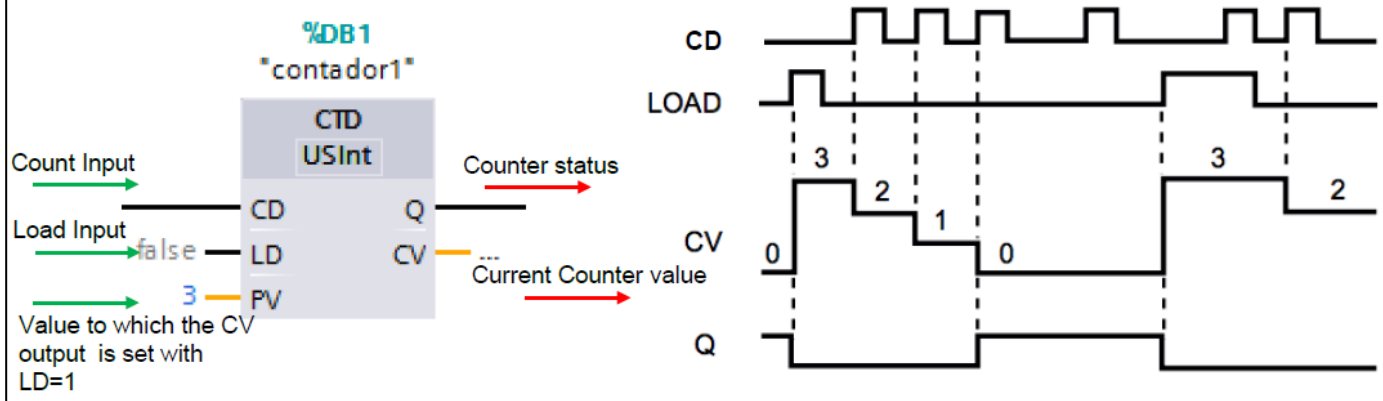
(4) Call of functions and function blocks. LD supports calls to POUs of type Function or FB.

FBs and functions can have several input and output parameters

COUNTER



CTD. Count down



When the load input (**LD**) changes from 0 to 1, the current counter value (**CV**) is set with PV value. Every time **CD** changes from 0 to 1, the counter counts down one unit. The output **Q** will be one if **CV** is 0.

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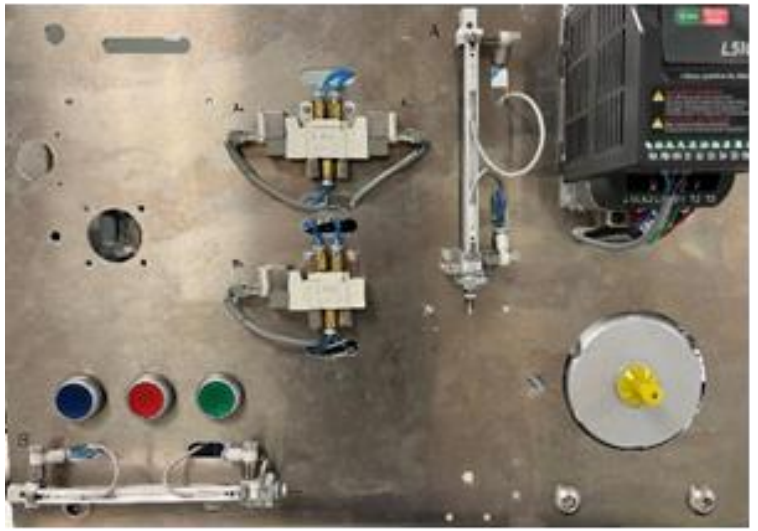
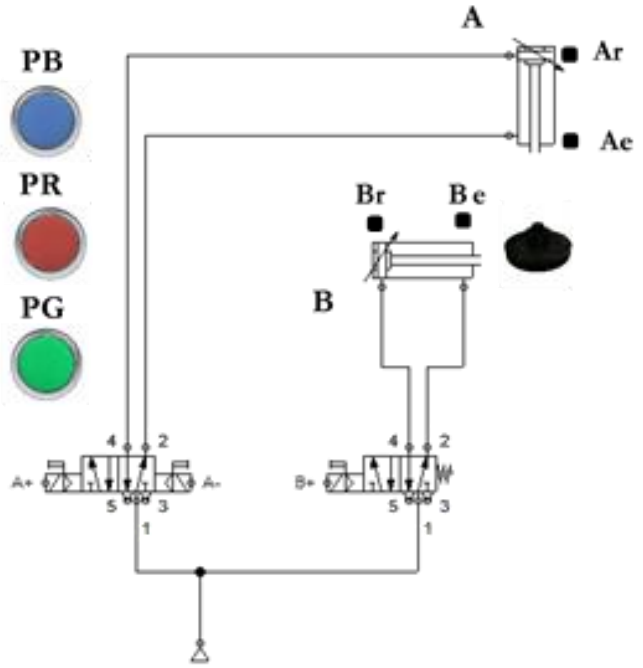
NextGEng

4 **Case study – Pressing a batch of parts**





Case study – Pressing a batch of parts

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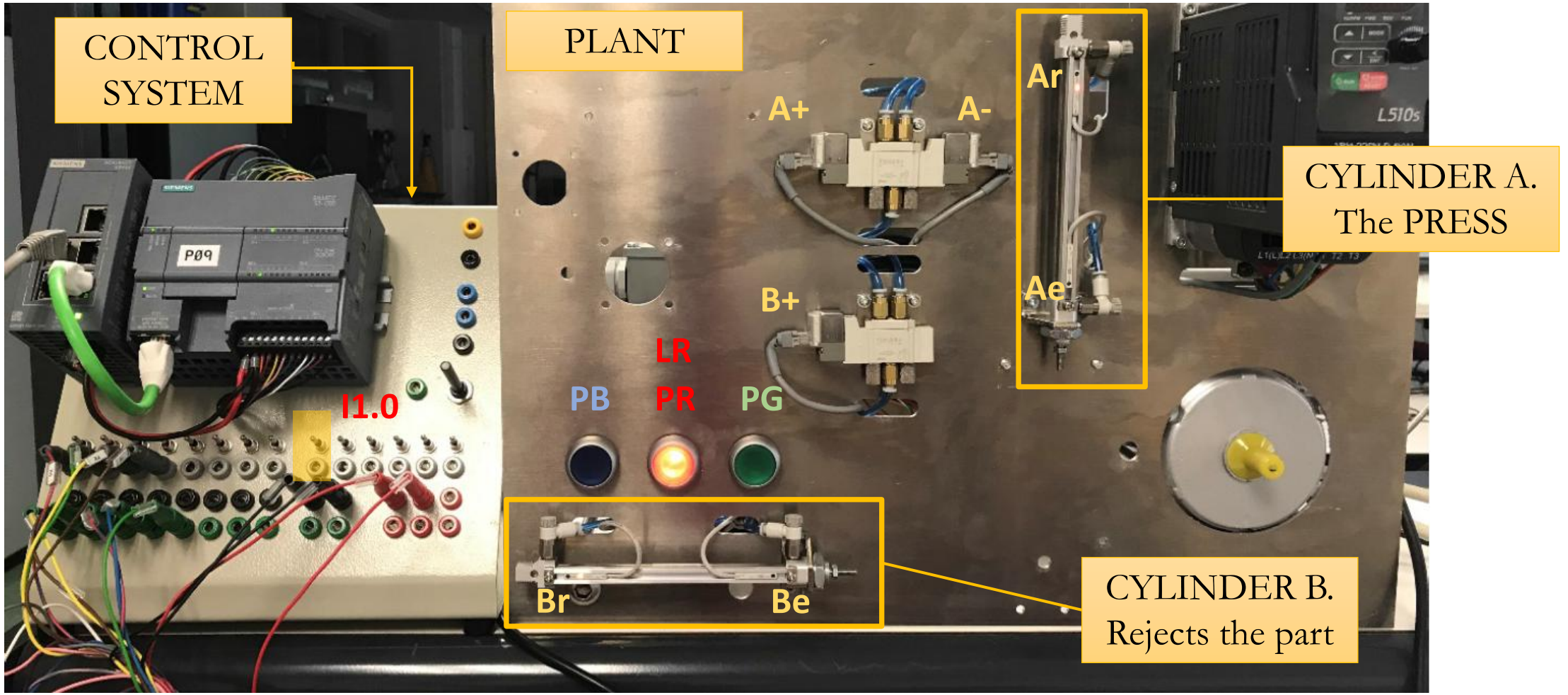
Case study – Pressing a batch of parts

The figure shows the real system to implement the pressing of batch of parts. The batch size can vary depending on the PB pressed. It will be added an emergency stop.



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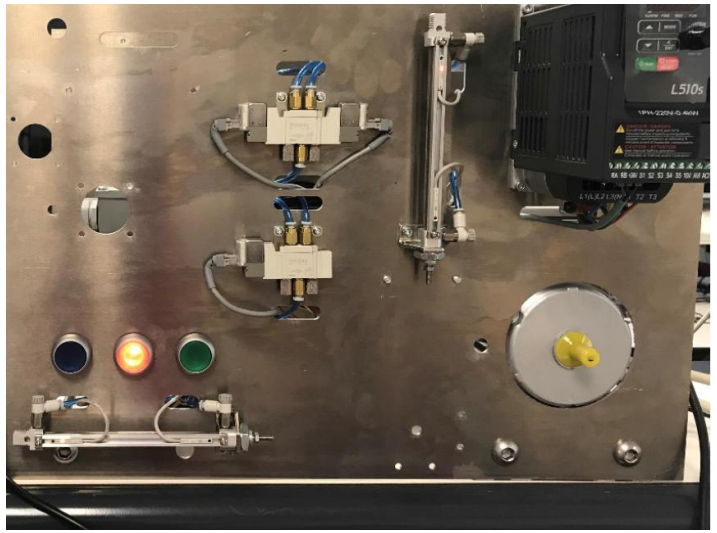
Case study – Pressing a batch of parts



Plant description:

- The **press**: double acting cylinder **A** pre-actuated by a bistable solenoid electrovalve
- The **rejection device**: double acting cylinder **B** pre-actuated by a monostable solenoid electrovalve
- Limit switches: detect the cylinders positions.
- Three push buttons.
- Three LEDs

The **sequence of operation** is as follows:

- **Normal operating cycle**: Pressing **PG** causes cylinder A to do **4** cycles and pressing **PB** causes cylinder A to do **2** cycles . In each cycle A expands, remains expanded for 2 seconds. Then it retracts and remains retracted for 1 second.
- **Emergency stop**: Pressing **PR** stops the normal operating cycle. The red LED is activated (LR), cylinder A retracts if it were expanded and cylinder B expands and retracts. To exit the emergency I1.0 will be activated, LR will be turned off and the operator will be ready to run a new normal operating cycle.

Design considerations:

- Use one CTD and load it with the corresponding value.
- Define initial conditions to assure that both cylinders remain retracted before starting the normal operating cycle.

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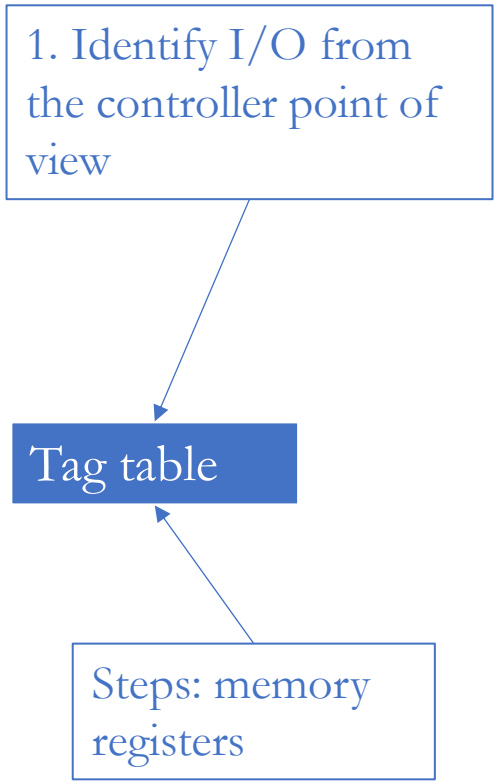
Case study – Pressing a batch of parts

Automatism design: I/O & tag table



Name	Address	Data type	Comment
PG	I 0.0	BOOL	Start push button (4 cycles)
PB	I 0.1	BOOL	Start push button (2 cycles)
PR	I 0.2	BOOL	Emergency stop push button
SW	I 1.0	BOOL	Emergency reset
Ar	I 0.3	BOOL	Limit switch for A retracted
Ae	I 0.4	BOOL	Limit switch for A extended
Br	I 0.5	BOOL	Limit switch for B retracted
Be	I 0.6	BOOL	Limit switch for B extended
A-	Q 0 .0	BOOL	Signal going to the solenoid valve pilot to retract cylinder A
A+	Q 0.1	BOOL	Signal going to the solenoid valve pilot to extract cylinder A
B+	Q 0.2	BOOL	Signal going to the solenoid valve pilot to extract cylinder B
LR	Q 0.3	BOOL	Signal going to the red LED.
X0	M 0.0	BOOL	Variable representing whether step 0 is active or not.
X1	M 0.1	BOOL	Variable representing whether step 1 is active or not.
…	…	…	…

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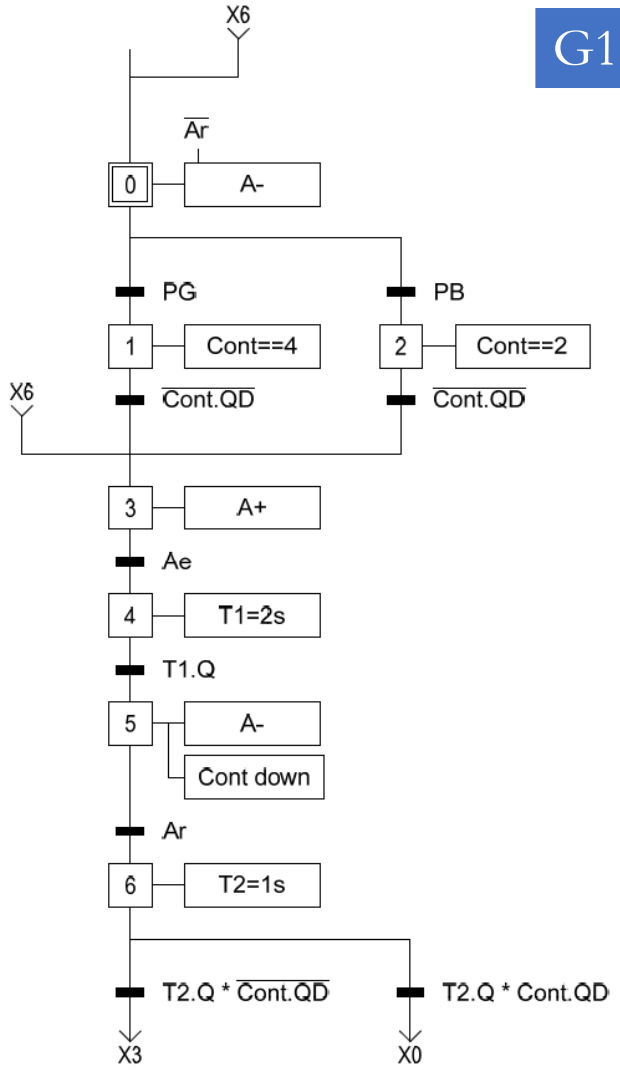
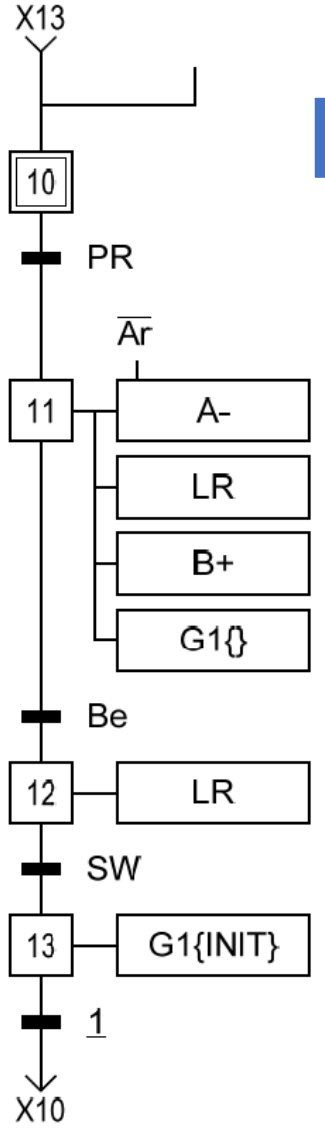
Case study – Pressing a batch of parts

Automatism design: GRAFCET

G1: Normal Operation



G2: Emergency Stop



Reset from X0 to X6

Gives the control to G1

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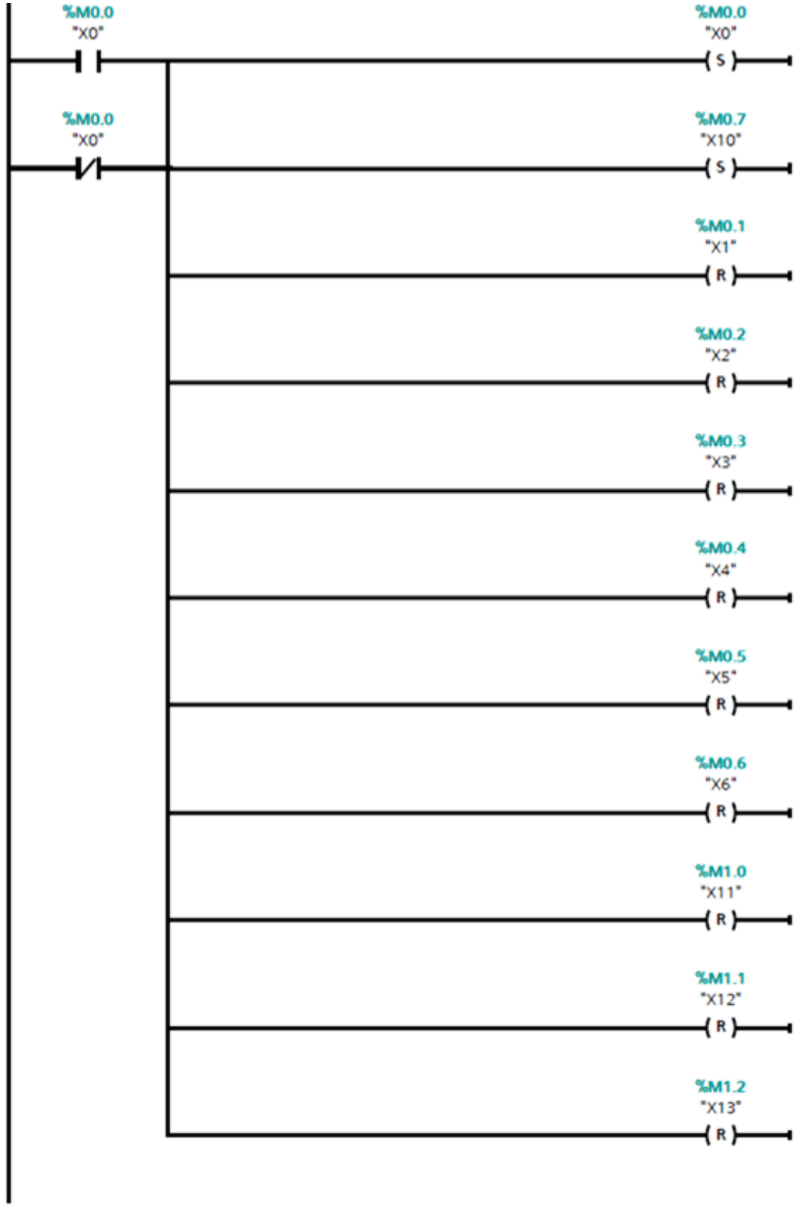
Case study – Pressing a batch of parts

Automatism Programming:

OB100: Start up



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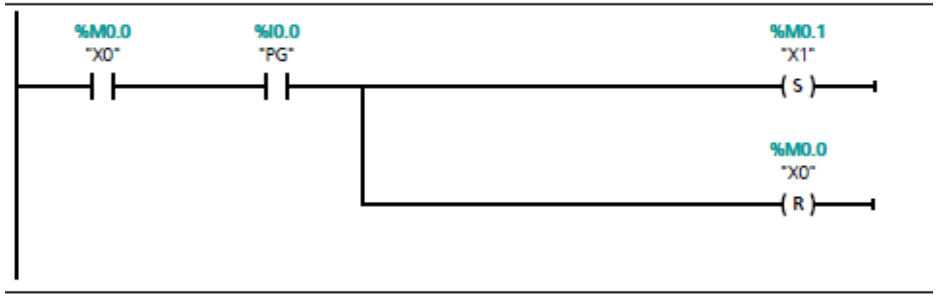
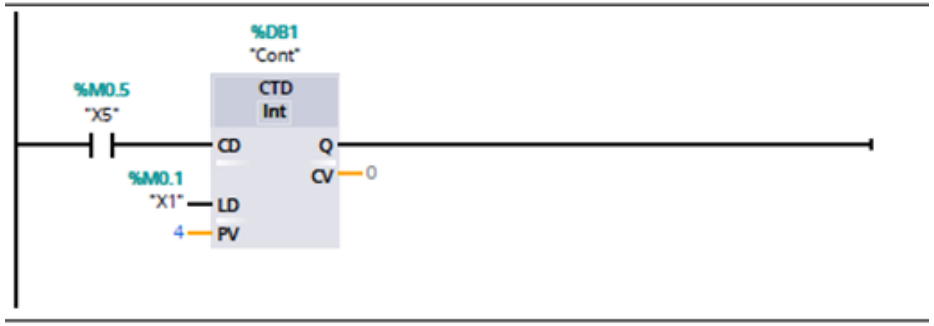
Case study – Pressing a batch of parts

Programming OB1:

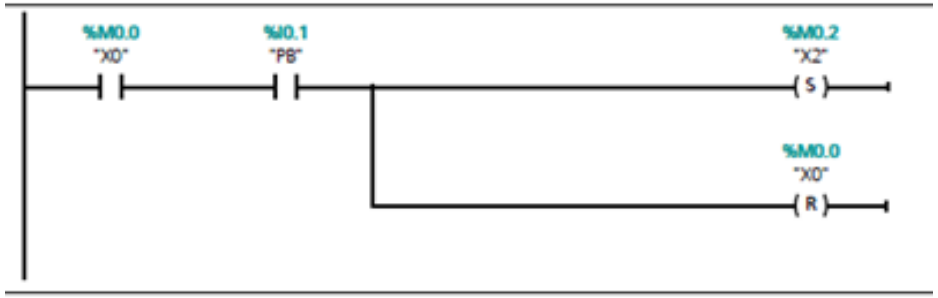
Network 1: Set X1



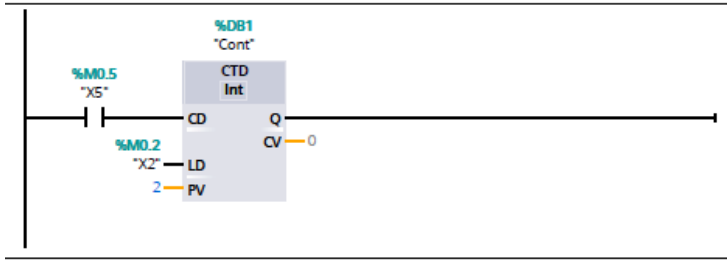
Network 2: Cont==4



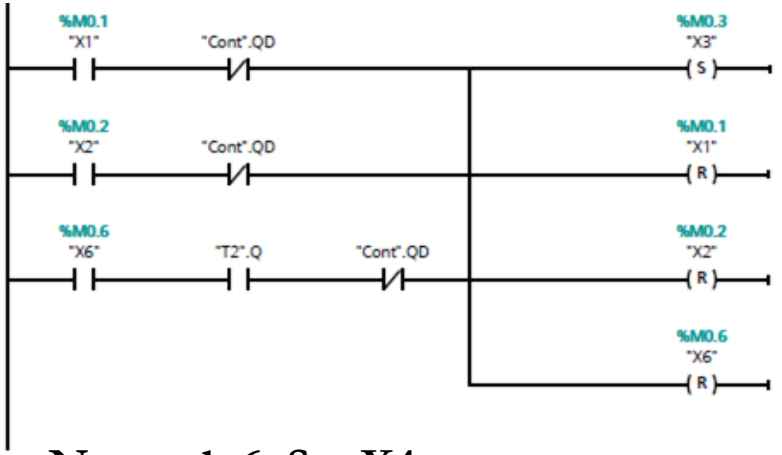
Network 3: Set X2



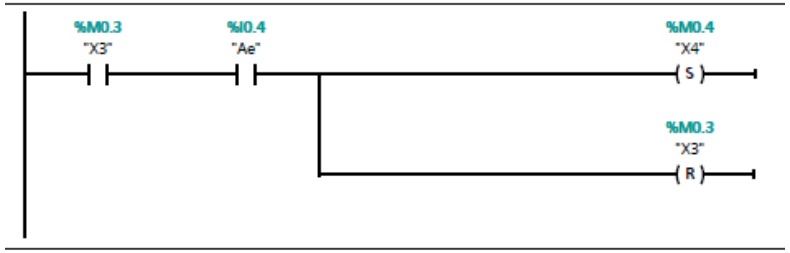
Network 4: Cont==2



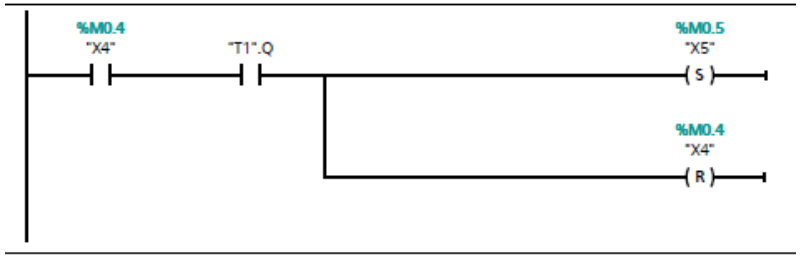
Network 5: Set X3



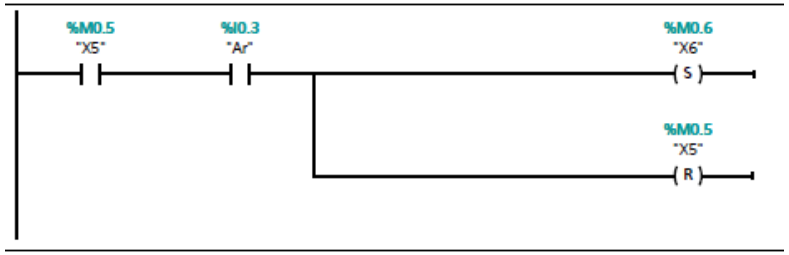
Network 6: Set X4



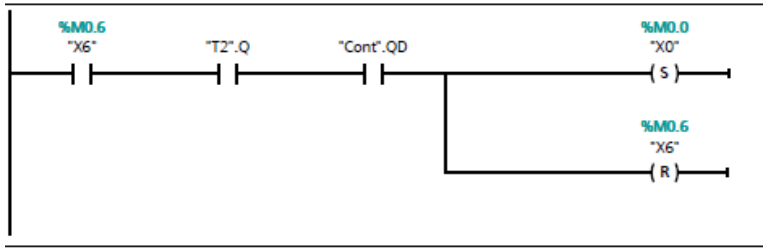
Network 7: Set X5



Network 8: Set X6



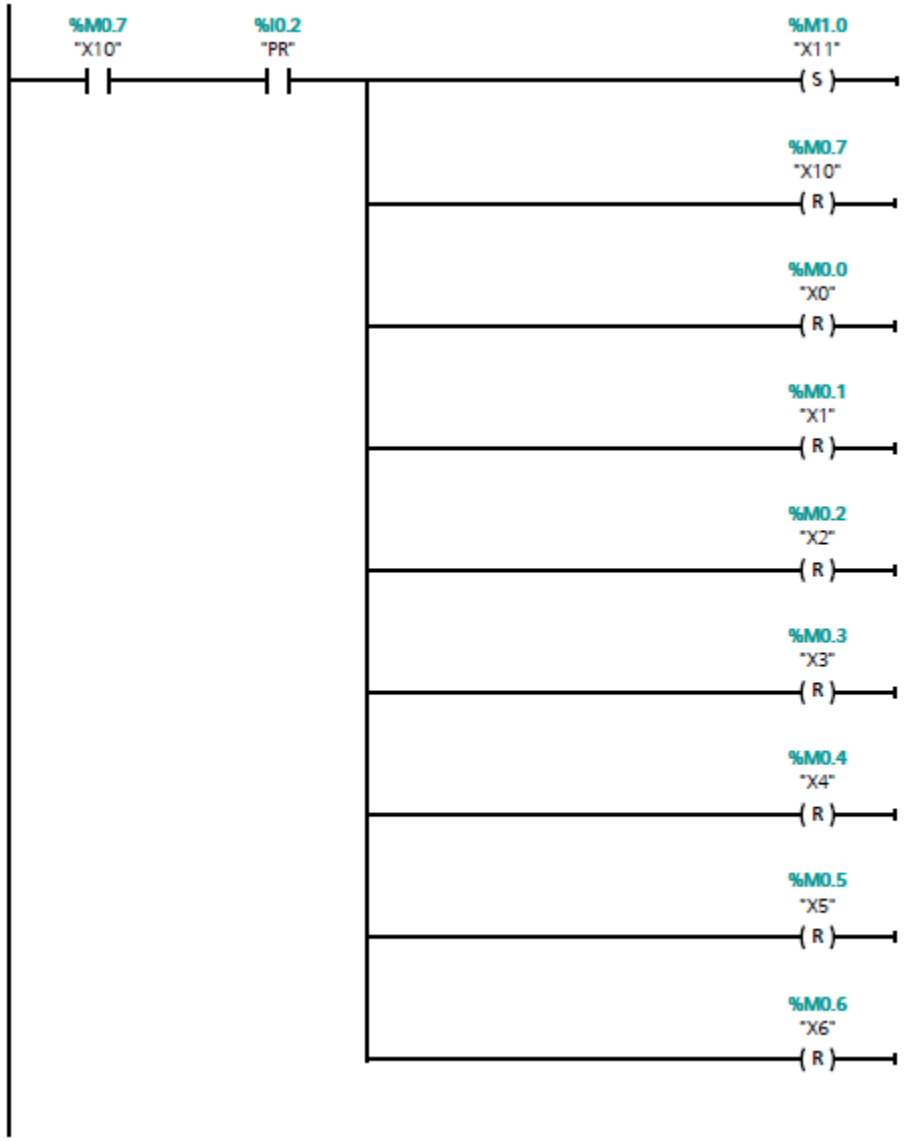
Network 9: Set X0



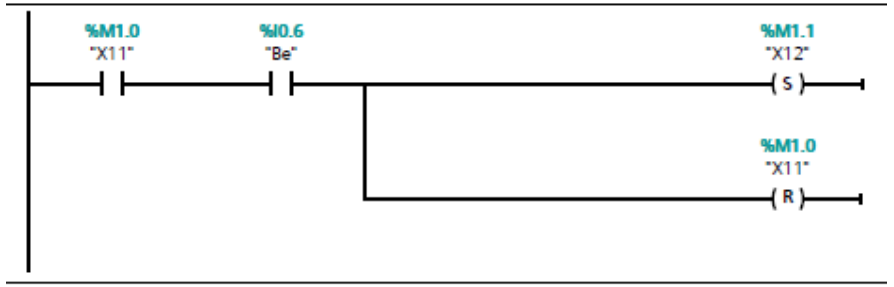
Case study – Pressing a batch of parts

Programming OB1:

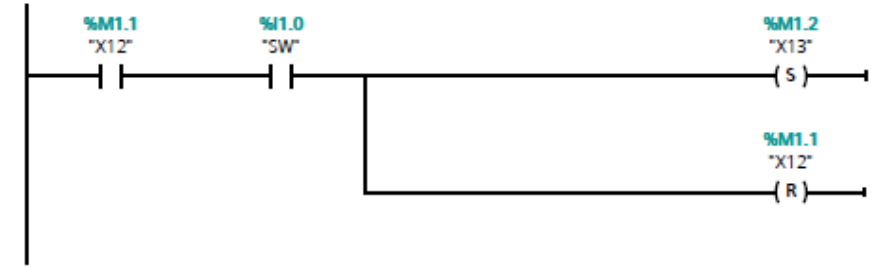
Network 10: Set X11



Network 11: Set X12

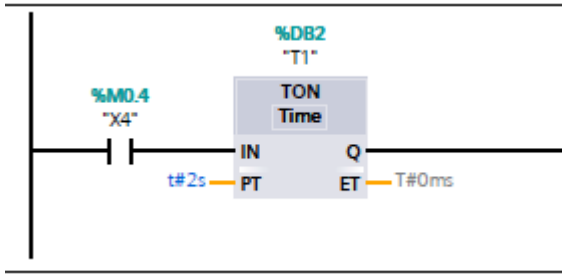


Network 12: Set X13

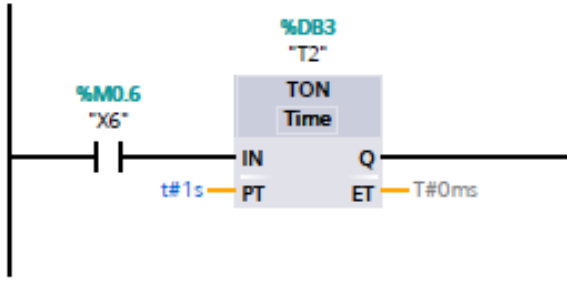


Network 13: Set X10

Network 14: T1



Network 15: T2

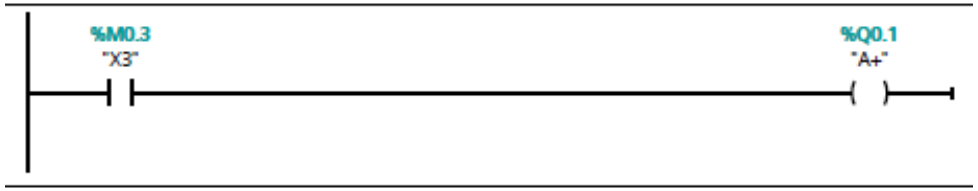


NextGEng

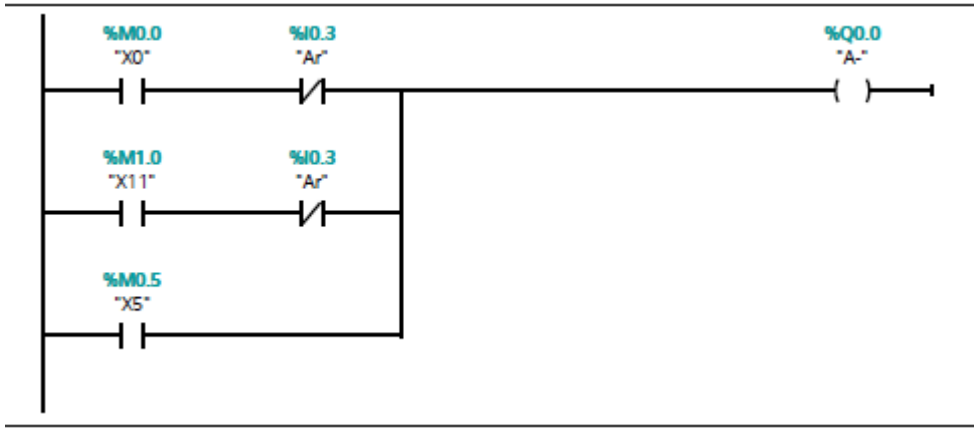
Case study – Pressing a batch of parts

Programming OB1:

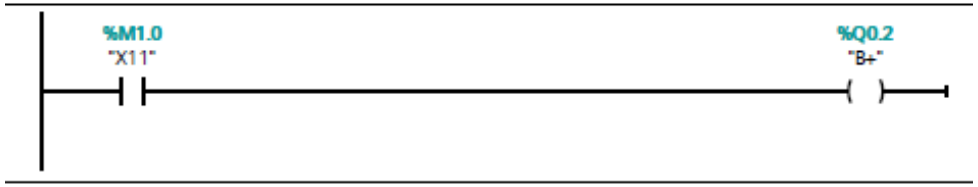
Network 16: A+



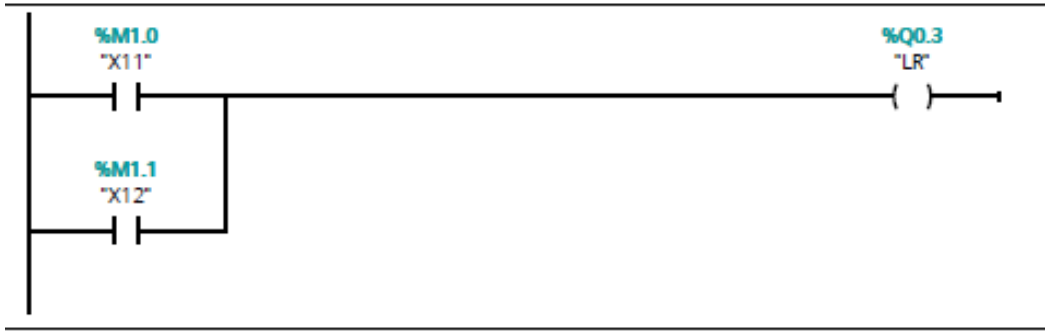
Network 17: A-



Network 18: B+



Network 19: LR



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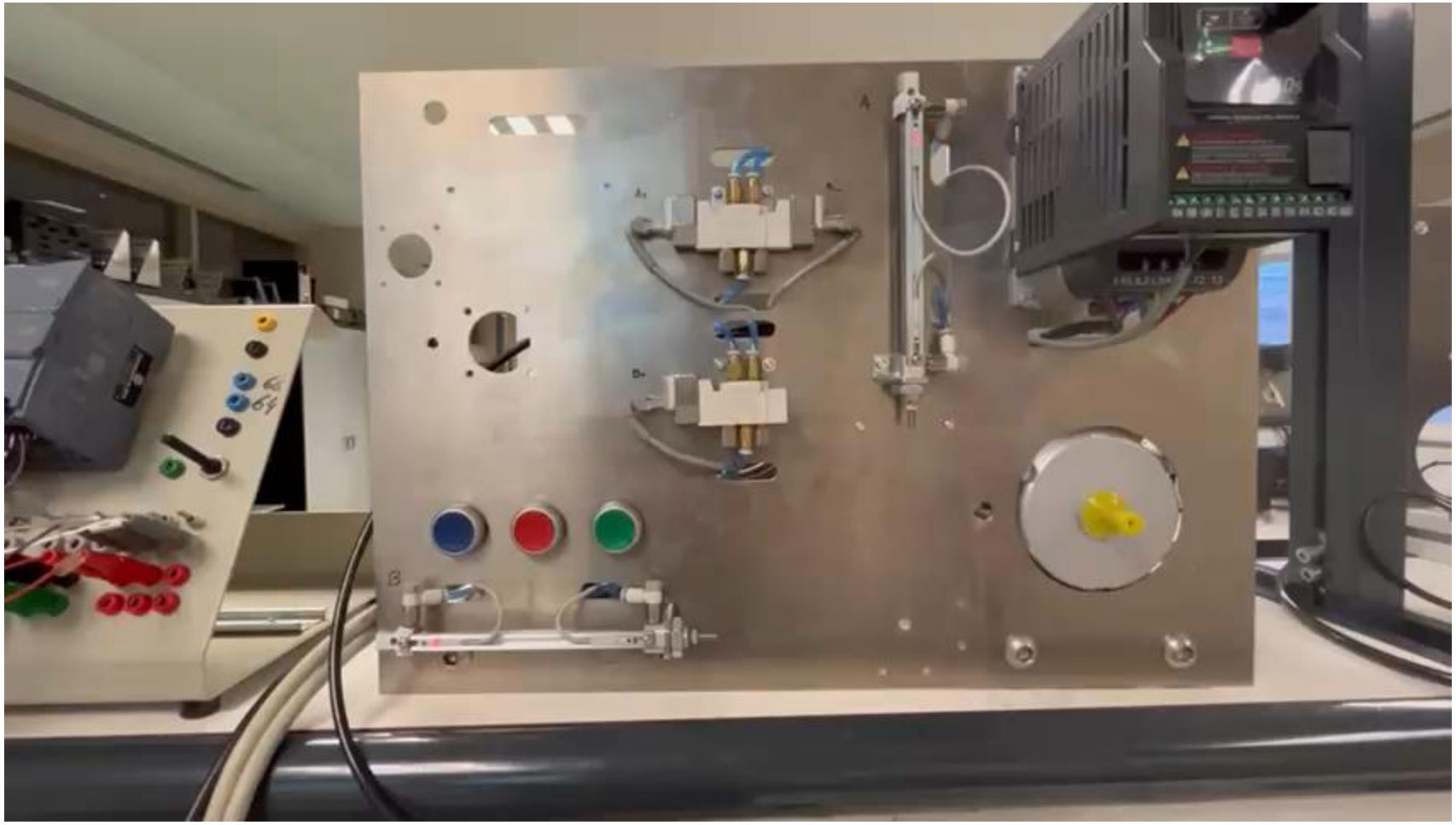
Demo



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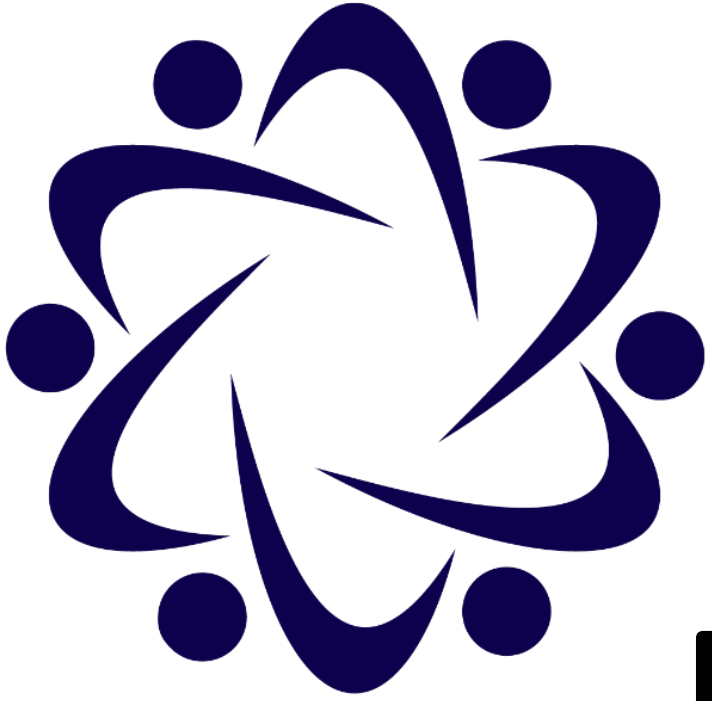
Thank you!

Kiitos!



Gracias!

Mulțumesc!

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- E-mail: dmgila@ujaen.es; satorres@ujaen.es

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C2 – Industrial Automation

M6 – Basics of the PID controllers

University of Jaén

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Module name: Basics of the PID-control

Upon completion of this module, the student will be able to:

1) Experimental modeling of basic linear systems
2) Experimental design of basic controllers

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Content

- Introduction
- Experimental modelling
- The controller in an automatic system
- On-Off controllers
- PID controllers
- Practical exercises using interactive tools

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Introduction

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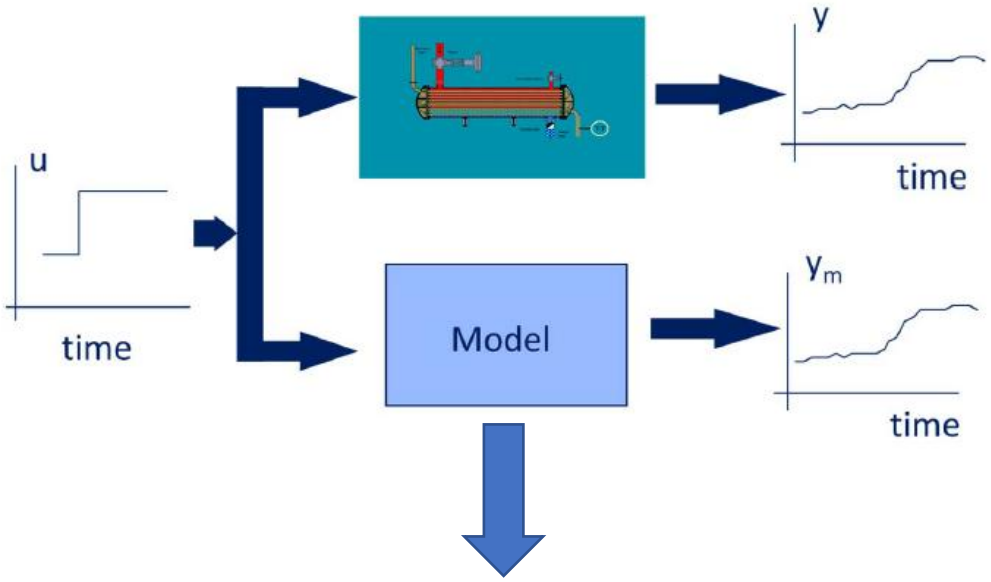
Introduction

Models

They are approximate representations of the real world which include only those aspects relevant to design the control system

What is a mathematical model?

- ✓ Set of equations that describe in a sound way the behaviour of the system we are modelling
- ✓ They are always approximations, not the real system
- ✓ Different models for different types of processes and aims
- ✓ Compromise between ease of use and fidelity in the representation of the reality



Can the models be considered ECOFRIENDLY?

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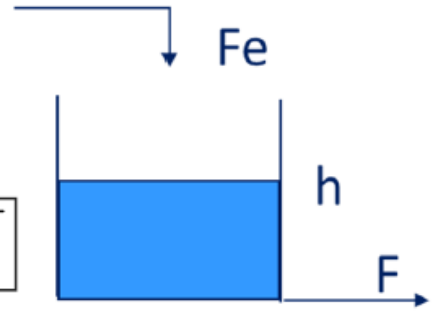
Introduction

❒ Static models:

Relate the values of the process variables at an equilibrium state

- ✓ They describe processes at equilibrium
- ✓ They are described by algebraic equations
- ✓ Typical application: Process design

$$F = F_e \; ; \; F = k\sqrt{h}$$

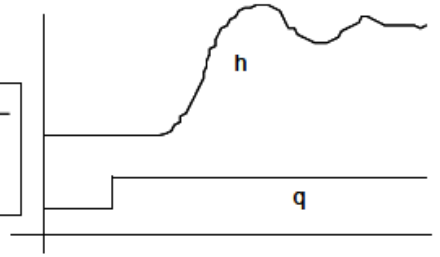


❒ Dynamic models (in continuous time):

Relate the value of the process variables over time

- ✓ They describe the time evolution of the process
- ✓ They are described by differential equations
- ✓ Wide range of applications: control, training, …

$$\frac{dV}{dt} = A\frac{d\,h}{d\,t} = F_e - k\sqrt{h}$$



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Introduction

How to obtain the model of a plant?

- Mathematical modelling

  - ☑ They are obtained from reasoning and the use of laws of nature: conservation of mass, energy or momentum, etc.
  - ☑ They have a wide range of validity
  - ☑ They require a deep knowledge of the process and the applicable laws from chemistry, physics, biology, etc.

- Experimental modelling: “black box”

  - ☑ Using experimentation and data from the process

Experimental Modelling

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Experimental Modelling

Three types of systems are considered:

First order systems:

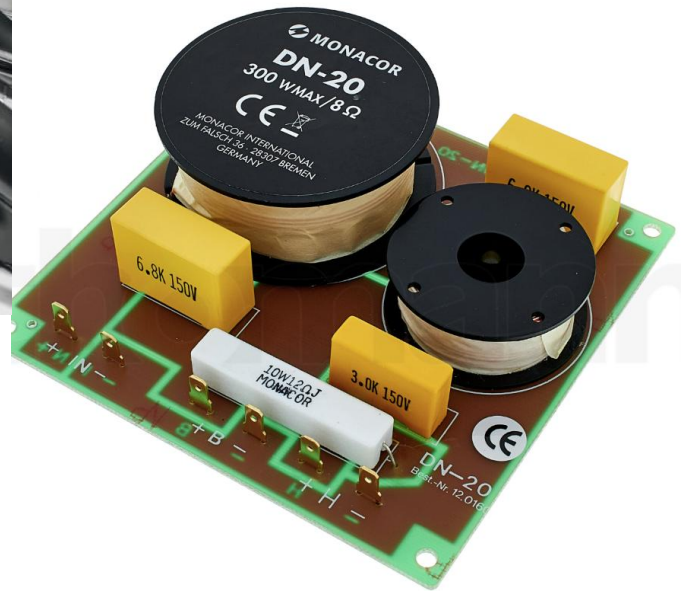
$$G(s) = \frac{Y(S)}{U(S)} = \frac{K}{\tau s + 1}$$

Second order systems:

$$\frac{K\omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2}$$

Higher order systems:

$$\frac{b_m s^m + b_{m-1} s^{m-1} + \ldots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0}$$



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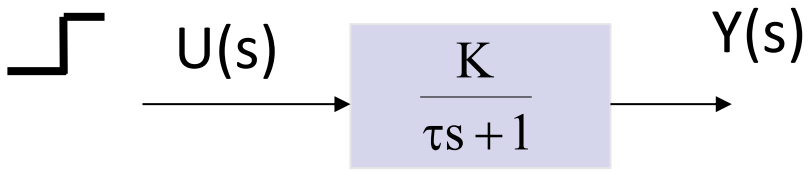
Experimental Modelling

First-order systems :

- ☑ Differential equation: $$\tau \frac{dy(t)}{dt} + y(t) = Ku(t)$$
- ☑ Transfer function: $$G(s) = \frac{Y(S)}{U(S)} = \frac{K}{\tau s + 1}$$



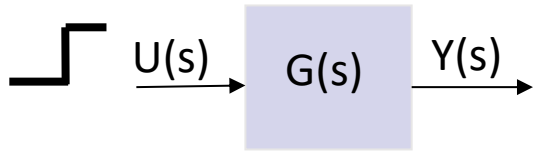
K : gain

τ : time constant

Experimental Modelling

First-order systems :

$$G(s) = \frac{K}{\tau s + 1}$$



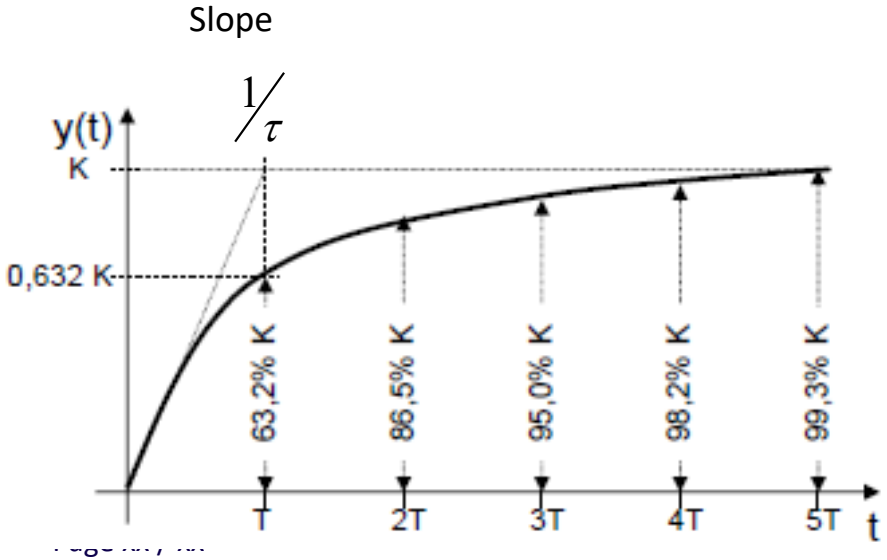
- System response to the step input:

$$Y(s) = G(s) * U(S) = \frac{K}{\tau s + 1} * \frac{u}{s} = \frac{A}{s} + \frac{B}{s + 1/\tau} = Ku\left[\frac{1}{s} - \frac{1}{s + 1/\tau}\right]$$

$$y(t) = Ku\left(1 - e^{-t/\tau}\right) \quad ; t > 0$$

$$en\ t = \tau \ \rightarrow y(\tau) = 0,632 * Ku$$

Static Gain $\longrightarrow K = \frac{\Delta y}{\Delta u}$



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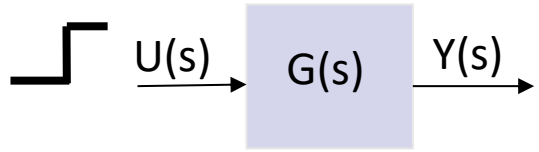
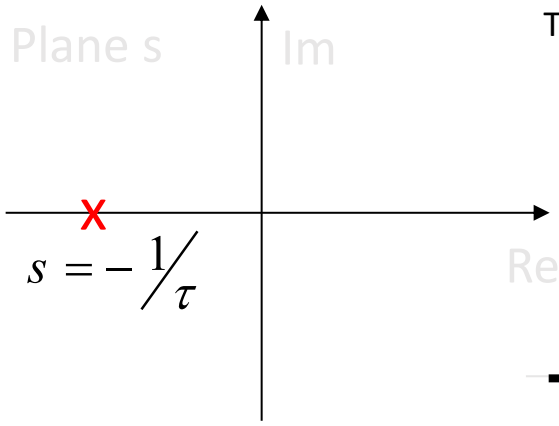
Experimental Modelling

First-order systems : $G(s) = \frac{K}{\tau s + 1}$



- If $\tau > 0$

s domain: pole $s = -1/\tau$

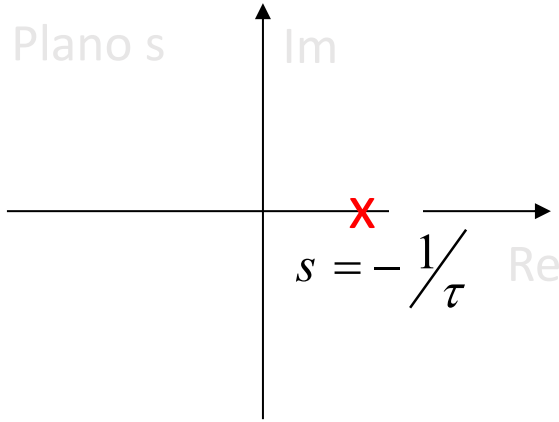


Time domain:

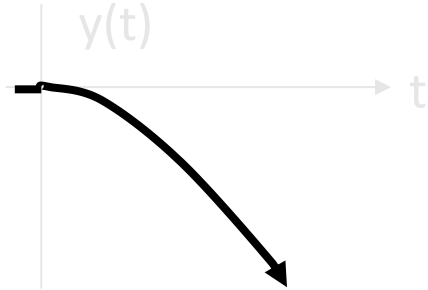
Stable response

- If $\tau < 0$

s domain: pole $s = -1/\tau$



Time domain:



Unstable response

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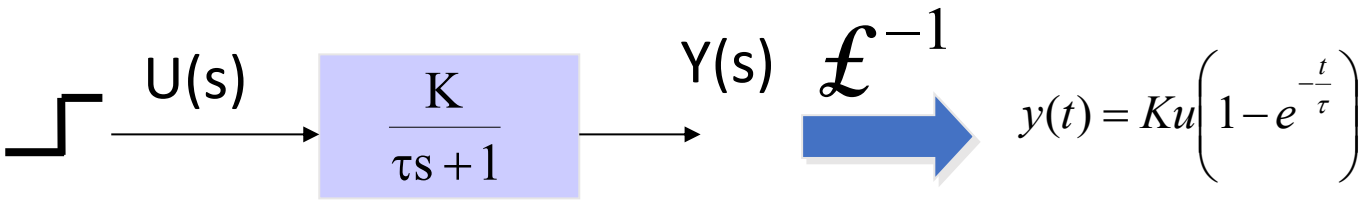
Experimental Modelling

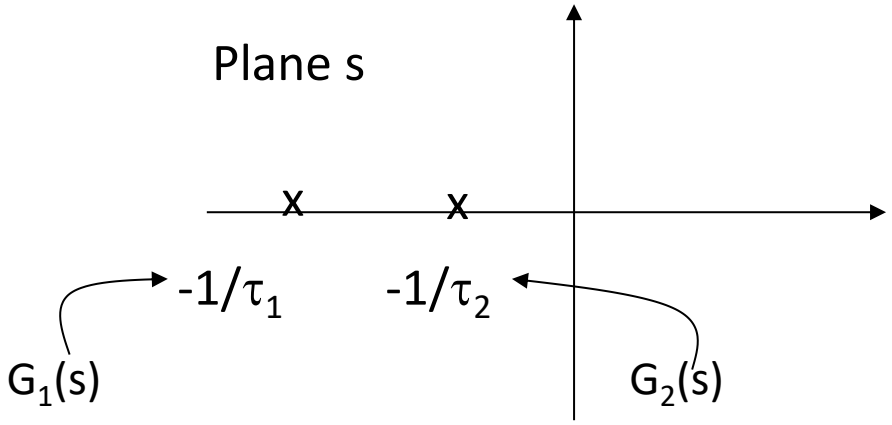
First-order systems : $G(s) = \dfrac{K}{\tau s + 1}$

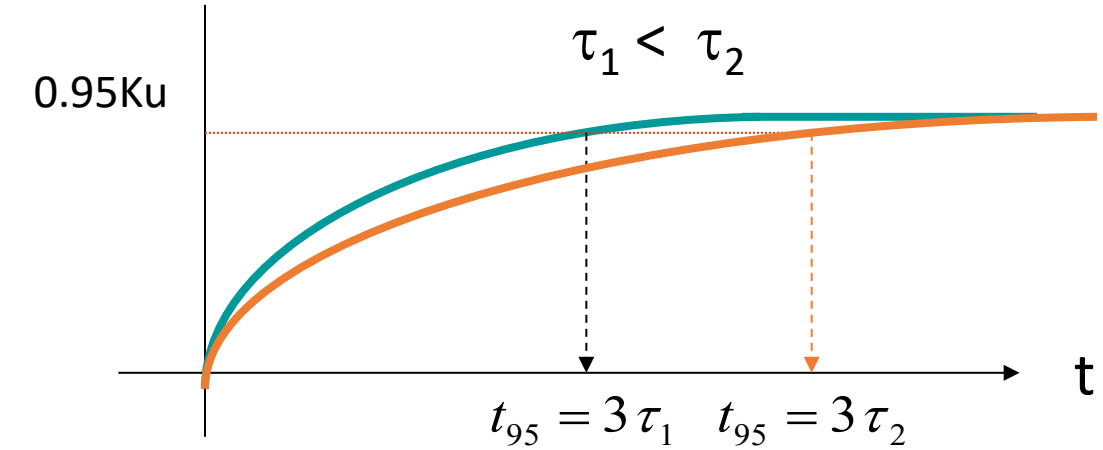
- ☑ System response to the step input:



- ➢ Settling time: t_s
  - ☐ 5% criteria: $y(t_{95}) = 0.95Ku = Ku(1 - e^{-\frac{t_{95}}{\tau}})$ $\quad t_s = 3\tau$
  - ☐ 2% criteria:

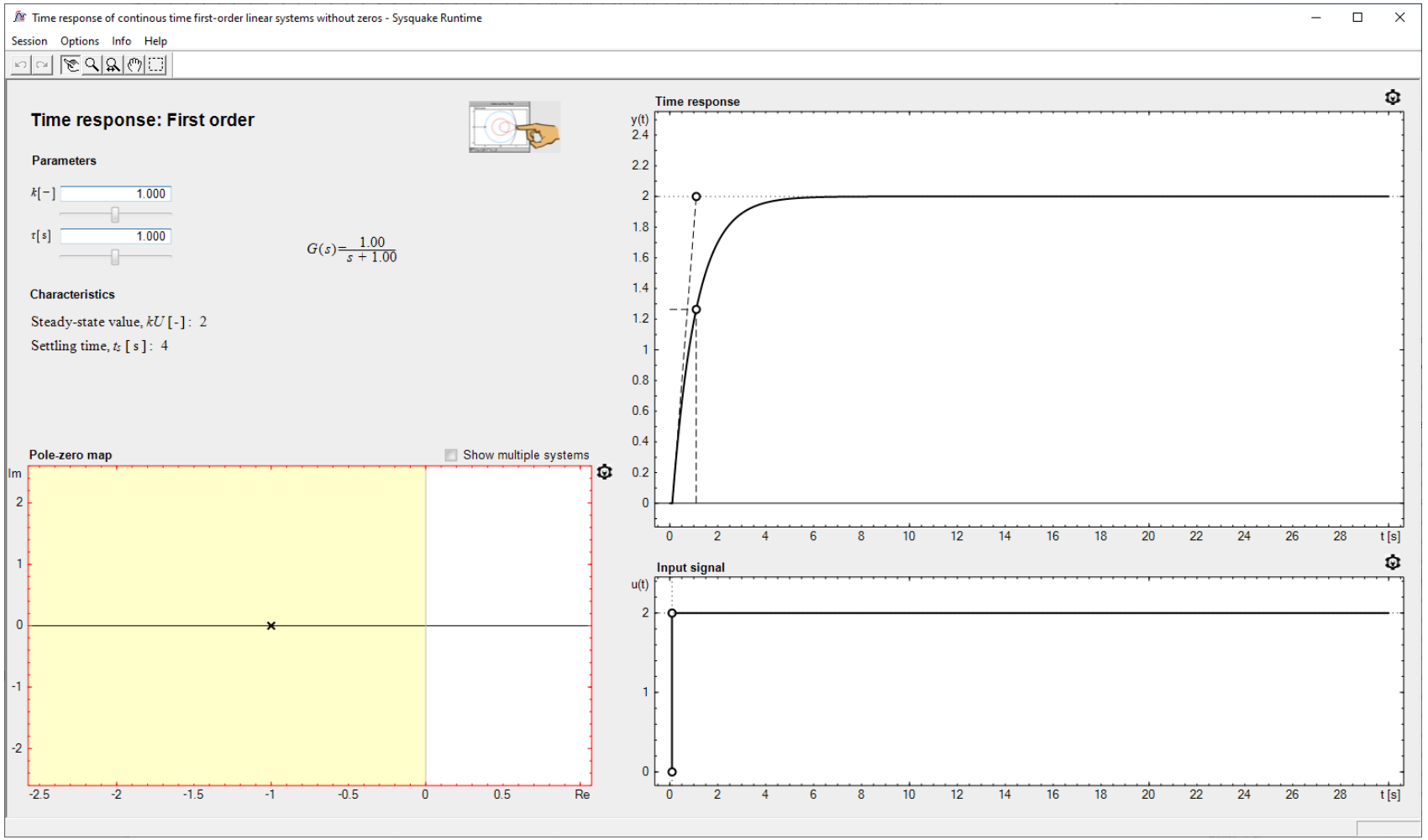
    t_s = 4* tau





Experimental Modelling

First-order systems: Let's experiment with an interactive tool



Experimental Modelling

Second-order systems

K: **Gain** $K = \frac{\Delta y}{\Delta u} = G(0)$

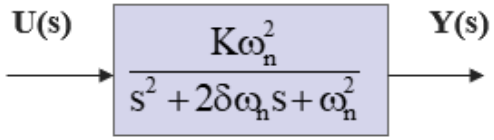
δ: **damping ratio**

ω_n: **undamped natural frequency**

- Differential equation:

$$\frac{d^2 y(t)}{dt^2} + 2\delta\omega_n \frac{dy(t)}{dt} + \omega_n^2 y(t) = K\omega_n^2 u(t)$$

- Transference function:



Standard form of the second-order system

Poles :

$$s^2 + 2\delta\omega_n s + \omega_n^2 = 0$$

$$s = \frac{-2\delta\omega_n \pm \sqrt{4\delta^2\omega_n^2 - 4\omega_n^2}}{2} = -\delta\omega_n \pm \omega_n\sqrt{\delta^2 - 1}$$

$\omega_n > 0$

$\delta=0$	→ Imaginary roots
$0<\delta<1$	→ Complex conjugates
$\delta=1$	→ Double negative real roots
$\delta>1$	→ Negative real roots
$\delta<0$	→ Positive real roots (Unstable system)

$$s = \pm j\,\omega_n$$

$$s = -\delta\,\omega_n \pm j\,\omega_n\sqrt{1-\delta^2}$$

$$s = -\delta\,\omega_n$$

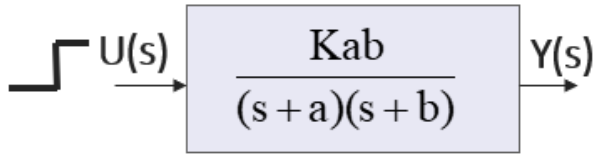
$$s = -\delta\,\omega_n \pm \omega_n\sqrt{\delta^2 - 1}$$

Experimental Modelling

Second-order systems

$\delta > 1$ **Overdamped case**

- System response to the step input u:



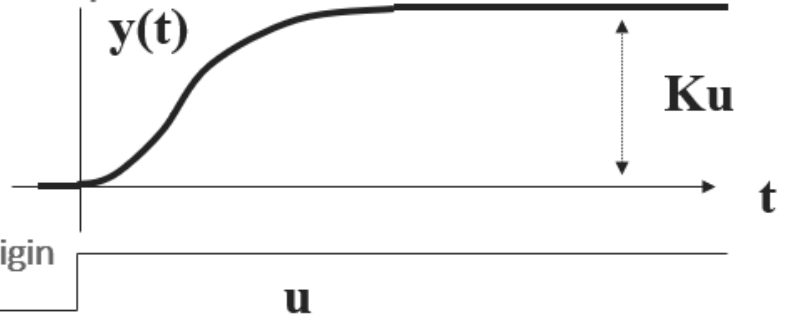
$$y(t) = Ku\left(1 + \frac{-\delta - \sqrt{\delta^2 - 1}}{2\sqrt{\delta^2 - 1}} e^{-at} - \frac{-\delta + \sqrt{\delta^2 - 1}}{2\sqrt{\delta^2 - 1}} e^{-bt}\right)$$

$y(0) = 0 \qquad y(\infty) = Ku$ monotonously increasing function

- Two negative real roots and unequal

$$a = \delta\omega_n - \omega_n\sqrt{\delta^2 - 1}$$

$$b = \delta\omega_n + \omega_n\sqrt{\delta^2 - 1}$$



Time response stable, without delay, with concavity change and overdamped

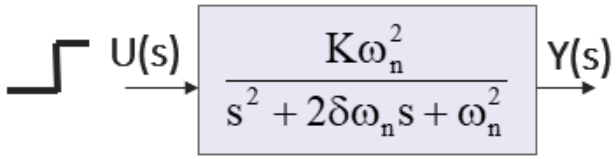
Tangent at the origin is zero

Experimental Modelling

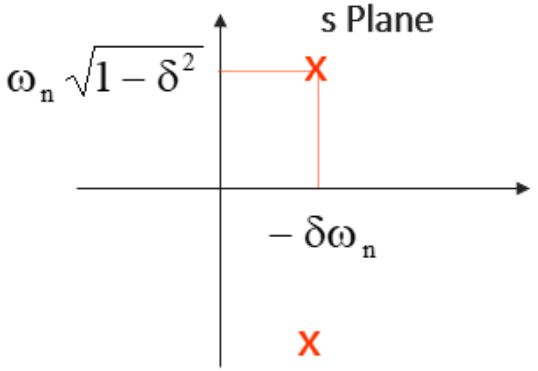
Second-order systems

$\delta < 0$ **Unstable system**

- System response to the step input u:



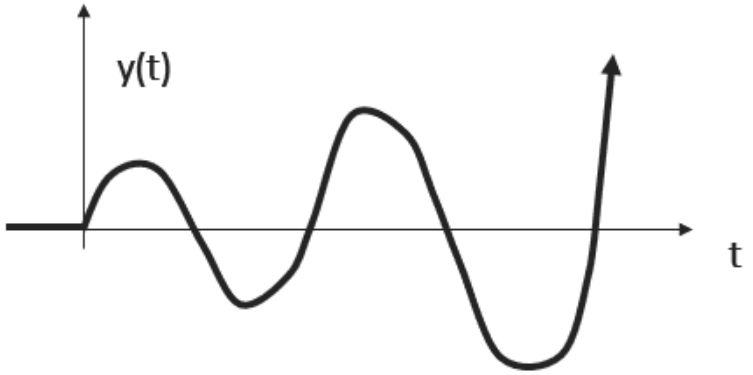
- s Plane



- Time domain

$$y(t) = Ku\left[1 - \frac{1}{\sqrt{1-\delta^2}} e^{-\delta\omega_n t} sen(\omega_n\sqrt{1-\delta^2}\,t + \phi)\right]$$

si $\delta\omega_n < 0$ unstable system



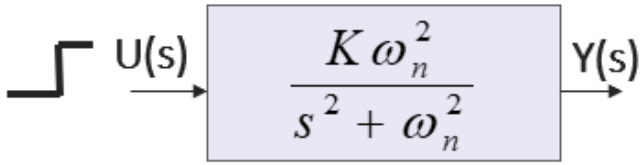
Experimental Modelling

Second-order systems

Critically damped case

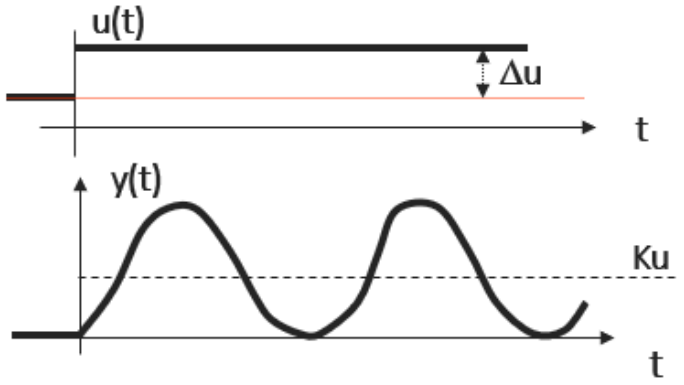
$\delta = 0$

- System response to the step input u:



$$Y(s) = \frac{K\omega_n^2}{s^2+\omega_n^2}\frac{u}{s} \rightarrow y(t) = \mathrm{L}^{-1}\left[Y(s)\right] = Ku\left[1 - sen(\omega_n t + \frac{\pi}{2})\right]$$

- Time domain



$\delta = 0$

The response never damps. Time response in the stability border

Experimental Modelling

Second-order systems

$$0 < \delta < 1$$

Underdamped case

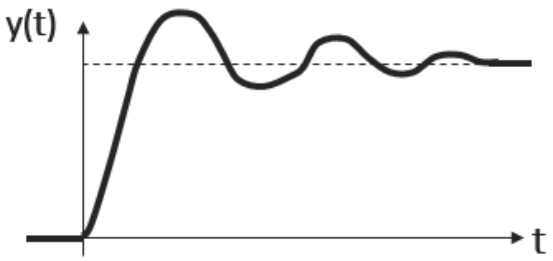
U(s) → $\dfrac{K\omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2}$ → Y(s)

- System response to the step input u:

$$Y(s) = \frac{K\omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2}\frac{u}{s}$$

  - Complex conjugates poles

If $\delta\omega_n > 0$: Time response stable, without delay and underdamped

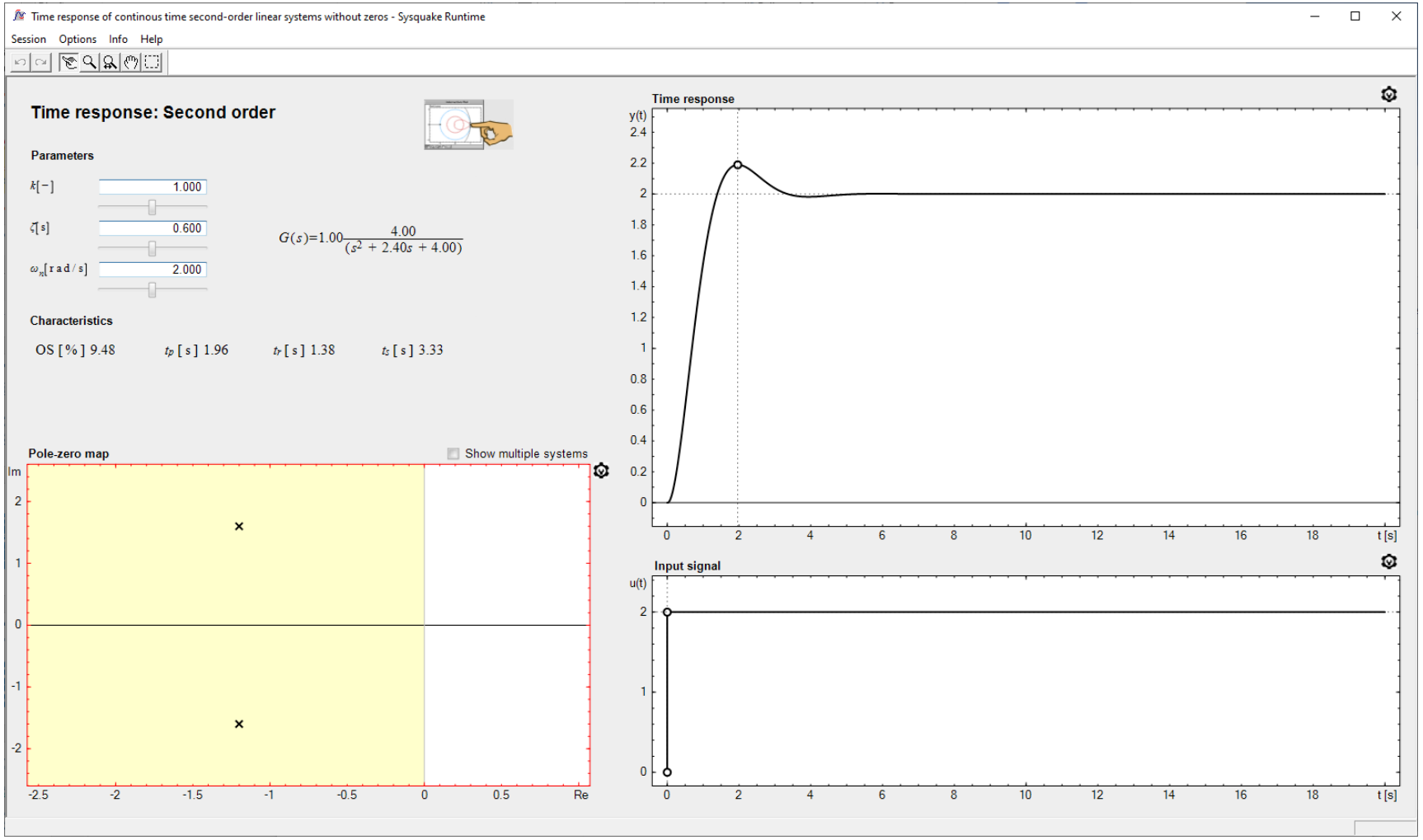


$$y(t) = \mathrm{L}^{-1}[Y(s)] = Ku\left[1 - \frac{1}{\sqrt{1-\delta^2}}e^{-\delta\omega_n t}\,sen(\omega_n\sqrt{1-\delta^2}\,t + \phi)\right]$$

$$\phi = arctg\,\frac{\sqrt{1-\delta^2}}{\delta}$$

Experimental Modelling

Second-order systems: Let's experiment with an interactive tool



The controller in an automatic system

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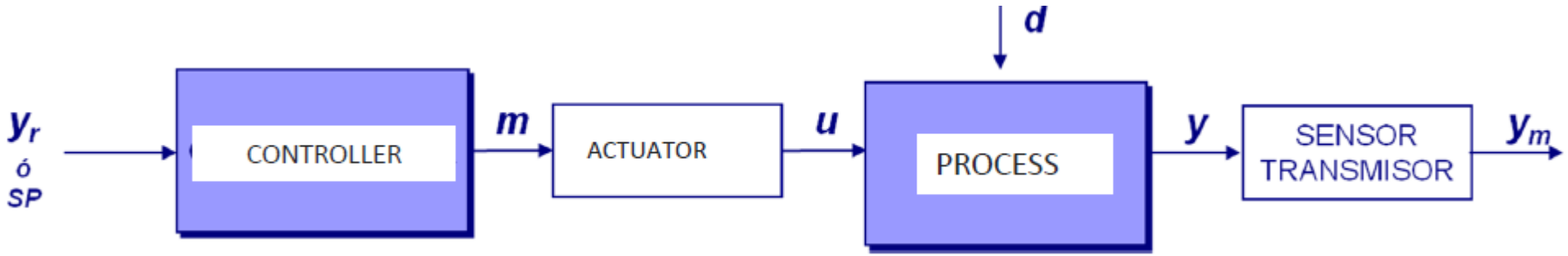
The controller in an automatic system

Previous concepts: Identification of variables in a control system



☑ *Controlled variable (y or y_m)*:

Is the quantity or condition that is measured and controlled

☑ *Reference or setpoint (y_r ó SP-Set Point)*:

The desired value for the controlled variable

☑ *manipulated variable or control signal (m)*:

Is the quantity or condition that it is varied by the controller so as to affect the value

☑ manipulated process *variable (u)*:

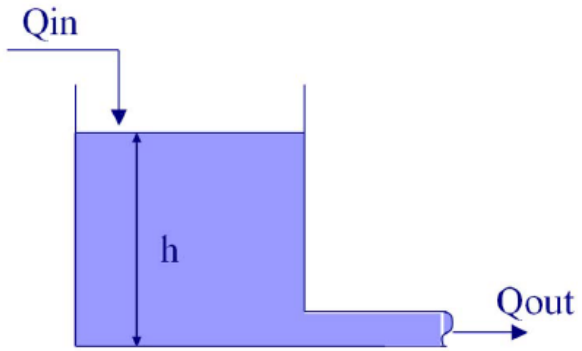
Process variable modified by the actuator

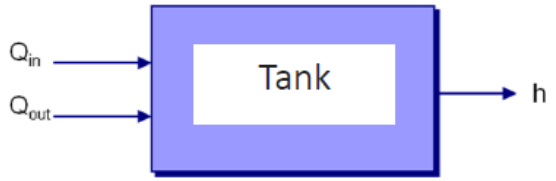
☑ *Disturbances(d)*:

Is a signal that tends to adversely affect the value of the output of a system

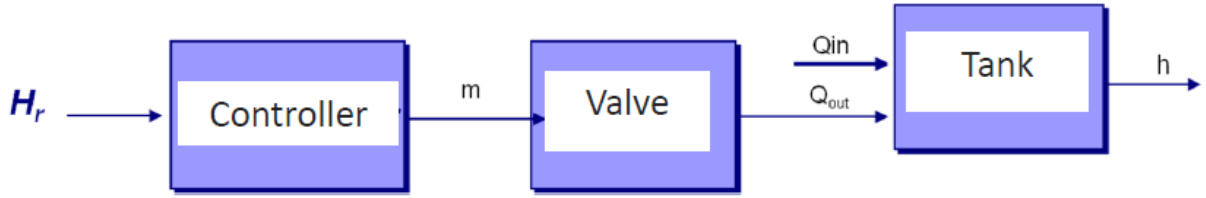
The controller in an automatic system

Previous concepts: Open-loop vs close-loop, the tank system





❑ Open-loop



What happens if Qin varies?

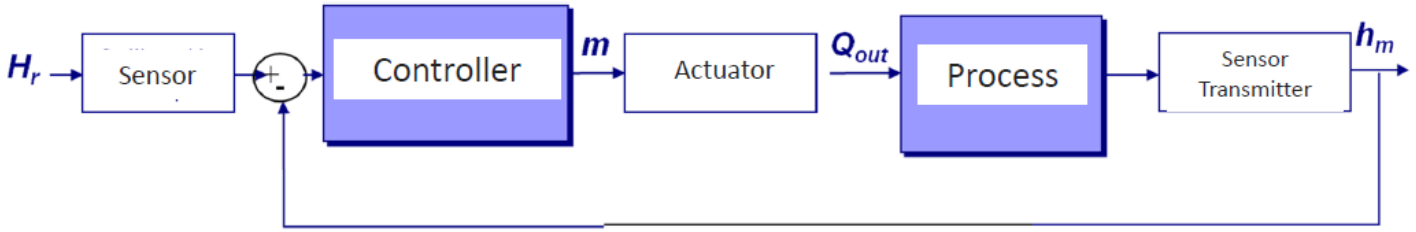
What happens if the output valve blocks?

The controller in an automatic system

Previous concepts: Open-loop vs close-loop, the tank system

❑ Closed-loop:

➲Block diagram of an industrial control system



- ❑ Advantages:
  - ☑ System response relatively insensitive to external disturbances and internal variations in system parameters
  - ☑ It is possible to use relatively inaccurate and inexpensive components to obtain an accurate control of a given plant
- ❑ Disadvantage:
  - ❑ Stability: tends to overcorrect errors and thereby can cause oscillations

On-off controller

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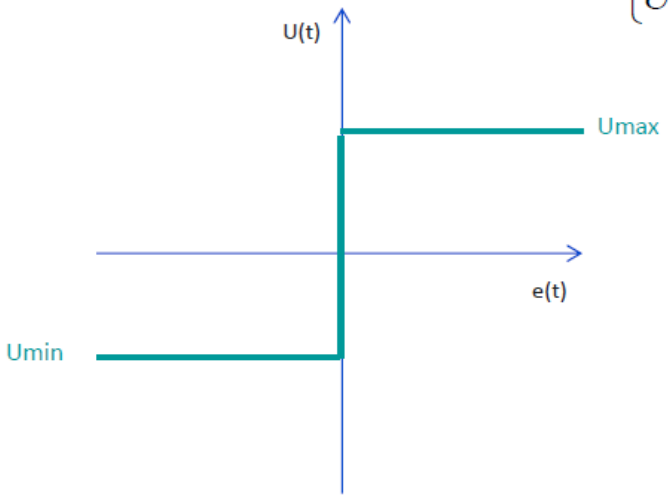
On-off controller

- Controller output has two possible values (On/Off) with no middle state

➲ Off value: $u=U_{min}$

➲ On value: $u=U_{max}$

$$u(t)=\begin{cases} U_{\max} \ si\ e(t)>0 \\ U_{\min} \ si \ e(t)<0 \end{cases}$$



☑ Simple and cheap

☑ Used in residential heating and domestic refrigerators

☑ Limited use in process control due to continuous cycling of controlled variable

➲ The system behavior is oscillatory

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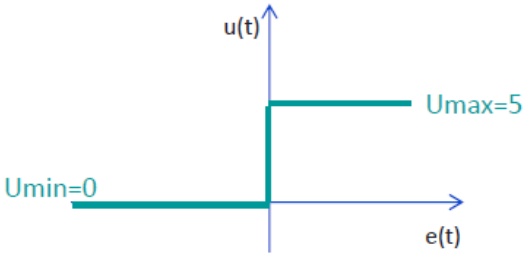
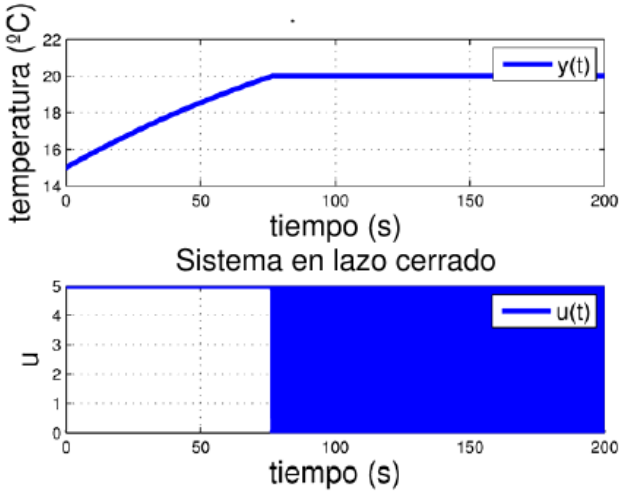
On-off controller

➲ Example: Heating control



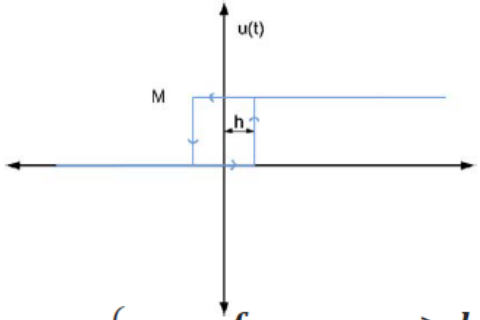
$$u(t) = \begin{cases} U_{max} \; si \; e(t) > 0 \\ U_{min} \; si \; e(t) < 0 \end{cases}$$

It will switch the output only when the temperature crosses the set point

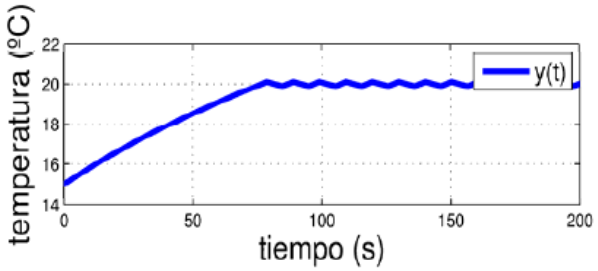


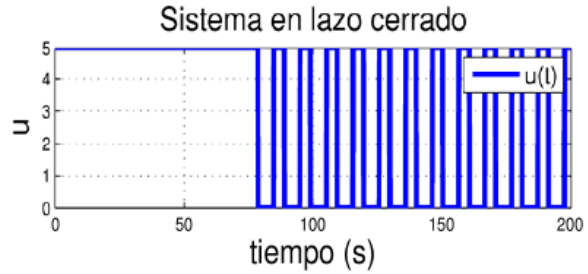
☑ Controller output is always changing 0 and 5 => *IT CAN NOT BE EXECUTED*

➲ Practical case: Dead band



$$u(t) = \begin{cases} u_{max} \; for \; error \; > h \\ u_{min} \; for \; error < -h \end{cases}$$





☑ Continuous cycling of controlled variable

On-off controller

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NextGEng

PID controller

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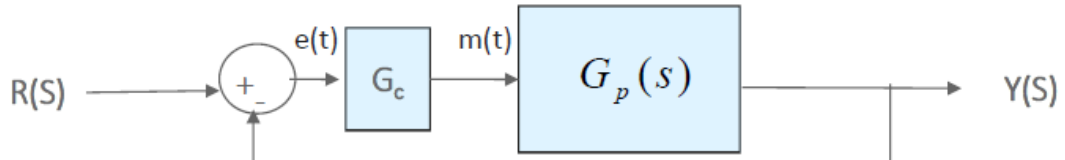
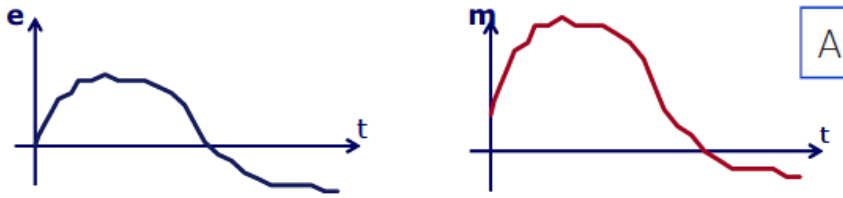
PID controller



❒ Proportional control action: $m(t) = K_c \cdot e(t) + bias$

The Proportional controller is calculated by multiplying the P-Gain (Kc) by the error. The purpose of the proportional, is to have a large immediate reaction on the output to bring the controlled variable close to the set point. As the error becomes less, the influence of the proportional value on the output becomes less.



An error of *x %* creates an action of *m=Kc x %* over the actuator

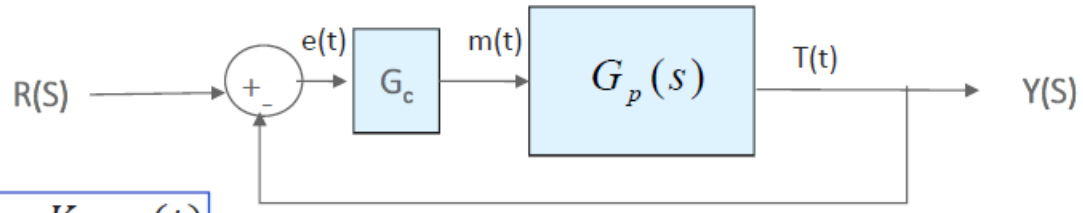
➲ Time domain analysis:

1. Time response decreases when Kc increases
2. Kc increases → oscillations in the time response
3. Kc > Ku → unstable system

Limit value:	. Stability (R-H criteria) => Kc = K_{last}
	. Physical limit => actuator saturation

➲ In the proportional control of a plant whose transfer function does not possesses an integrator in the TF, there is a steady-state error in the response to a step input. Integral control action eliminates the error.

PID controller



❒ Example: Heating control

$$m(t) = K_c \cdot e(t)$$

Initial conditions:
Room temperature= 15ºC

$$G_p(s) = \frac{2.5}{150 \cdot s + 1}$$

➲ The temperature set-point is 20 ºC:

$$G_{ol}(s) = K_c \cdot G_p(s)$$

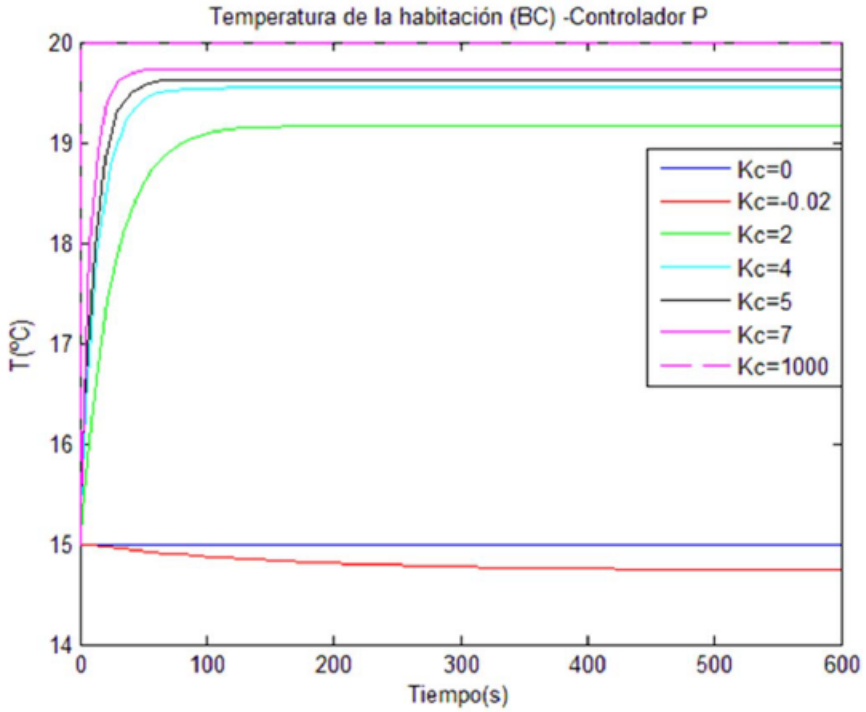
$$G_{cl}(s) = \frac{G_{ol}(s)}{1+G_{ol}(s)} = \frac{N_{ol}(s)}{D_{ol}(s)+N_{ol}(s)}$$

Unitary feedback

$$G_{CL}(s) = \frac{2.5 \cdot K_c}{150 \cdot s + 1 + 2.5 \cdot K_c}$$

R-H stability criteria:

$$Kc > \frac{-1}{2.5}$$

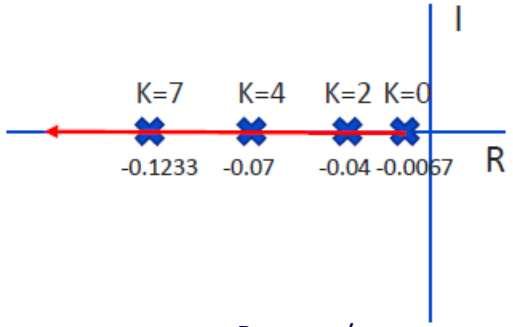


Pole in the closed-loop

$$s = -\frac{1}{150} - \frac{2.5}{150} \cdot K_c$$

Plant Pole

$$s = -\frac{1}{150}$$



Steady-state error in the response to a step input

. Physical limit => actuator saturation

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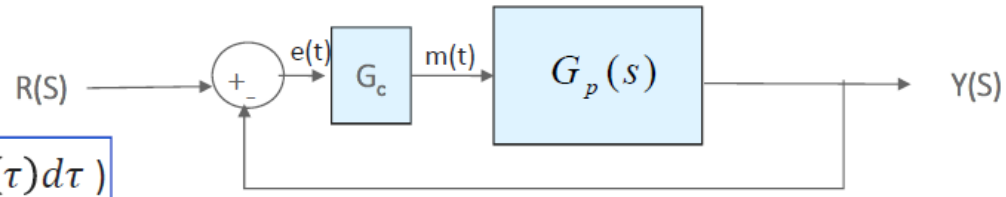
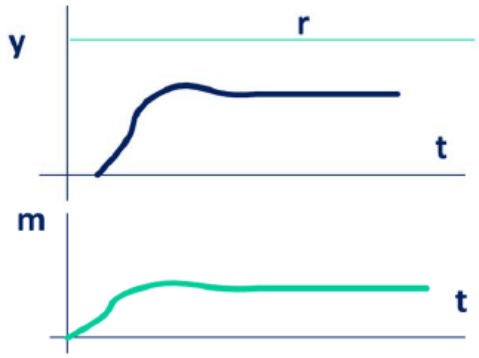
PID controller



❒ Integral control action: $m(t) = \frac{K_c}{T_i} \cdot \int_0^t e(\tau)d\tau$)

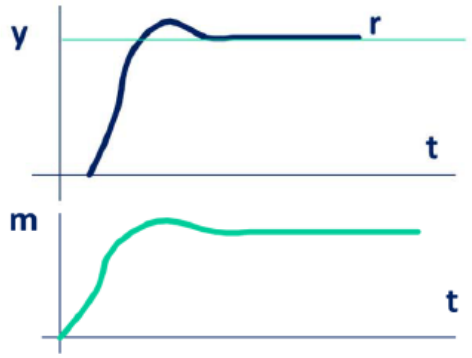
- ➲ The control signal (m(t)) at any instant is the area under the actuating-error-signal curve up to that instant
- ➲ While removing steady-state error may lead to oscillatory response
- ➲ Integral control action is normally used with the proportional control action

❒ P controller



A P controller does not get steady-state zero error

❒ PI controller



The integral term changes continuously the control signal until the error is zero

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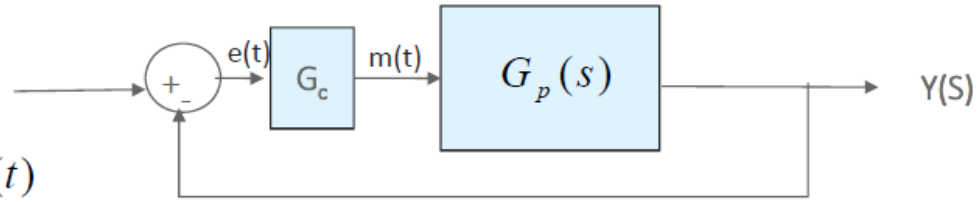
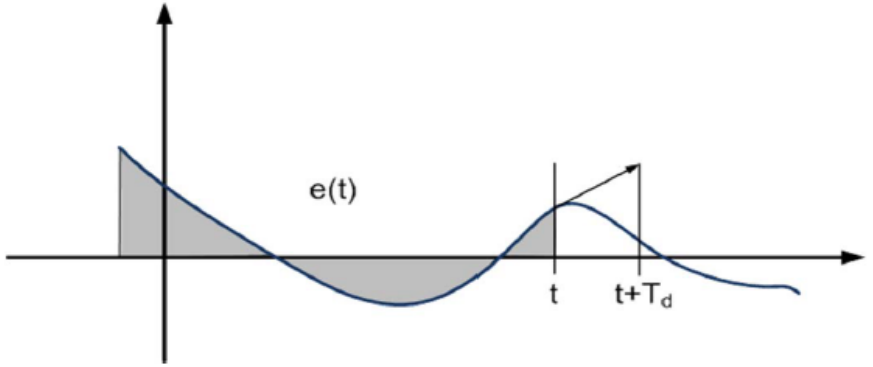
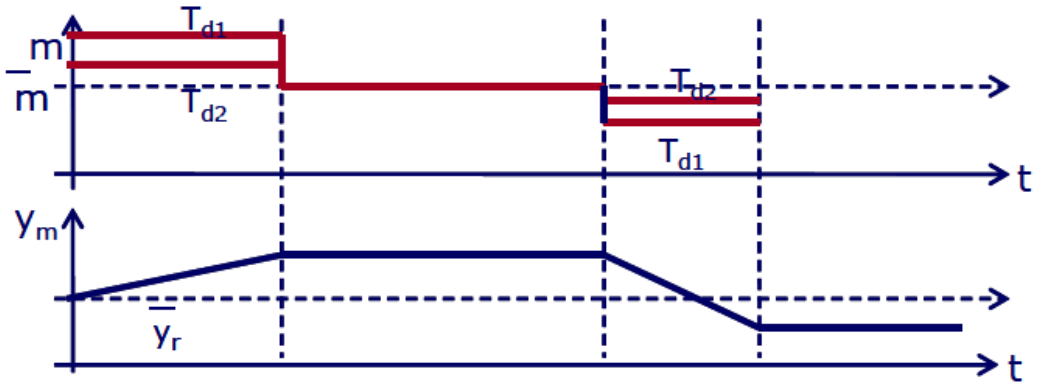
PID controller



- Derivative control action: $m(t) = K_c T_d \frac{de(t)}{dt}$
  - Anticipative action
  - Will smooth sharp changes in the control signal due to fast changes in the error
  - It has no influence in the steady-state





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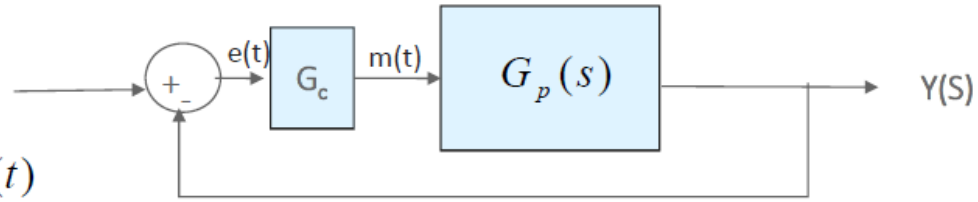
PID controller



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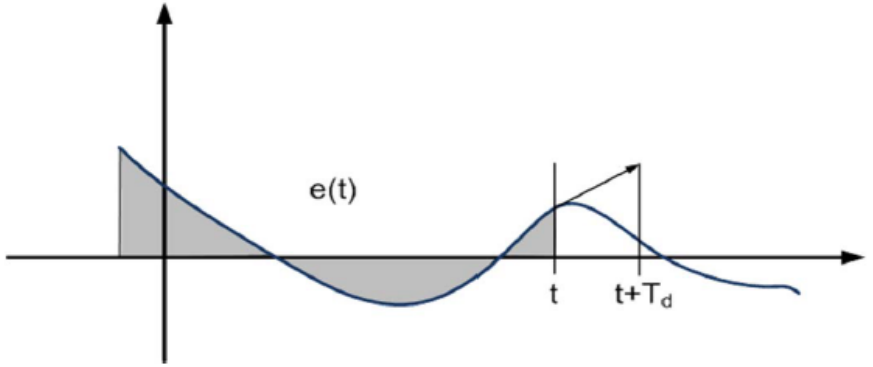

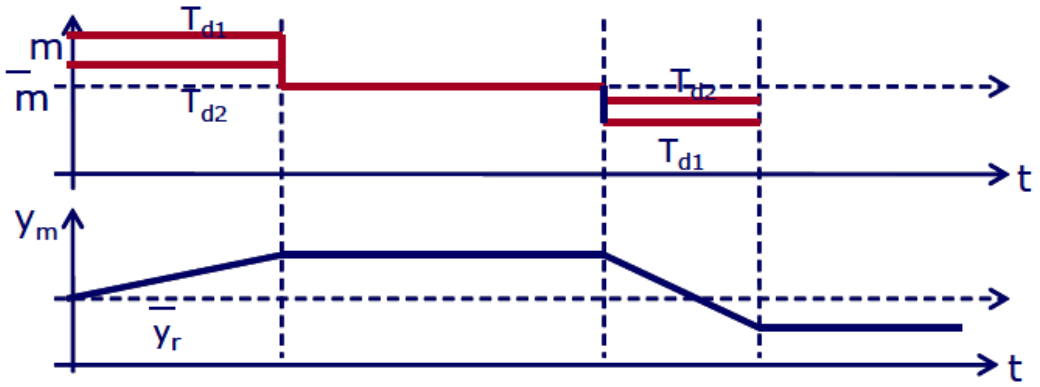

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NextGEng

Practical exercises using interactive tools

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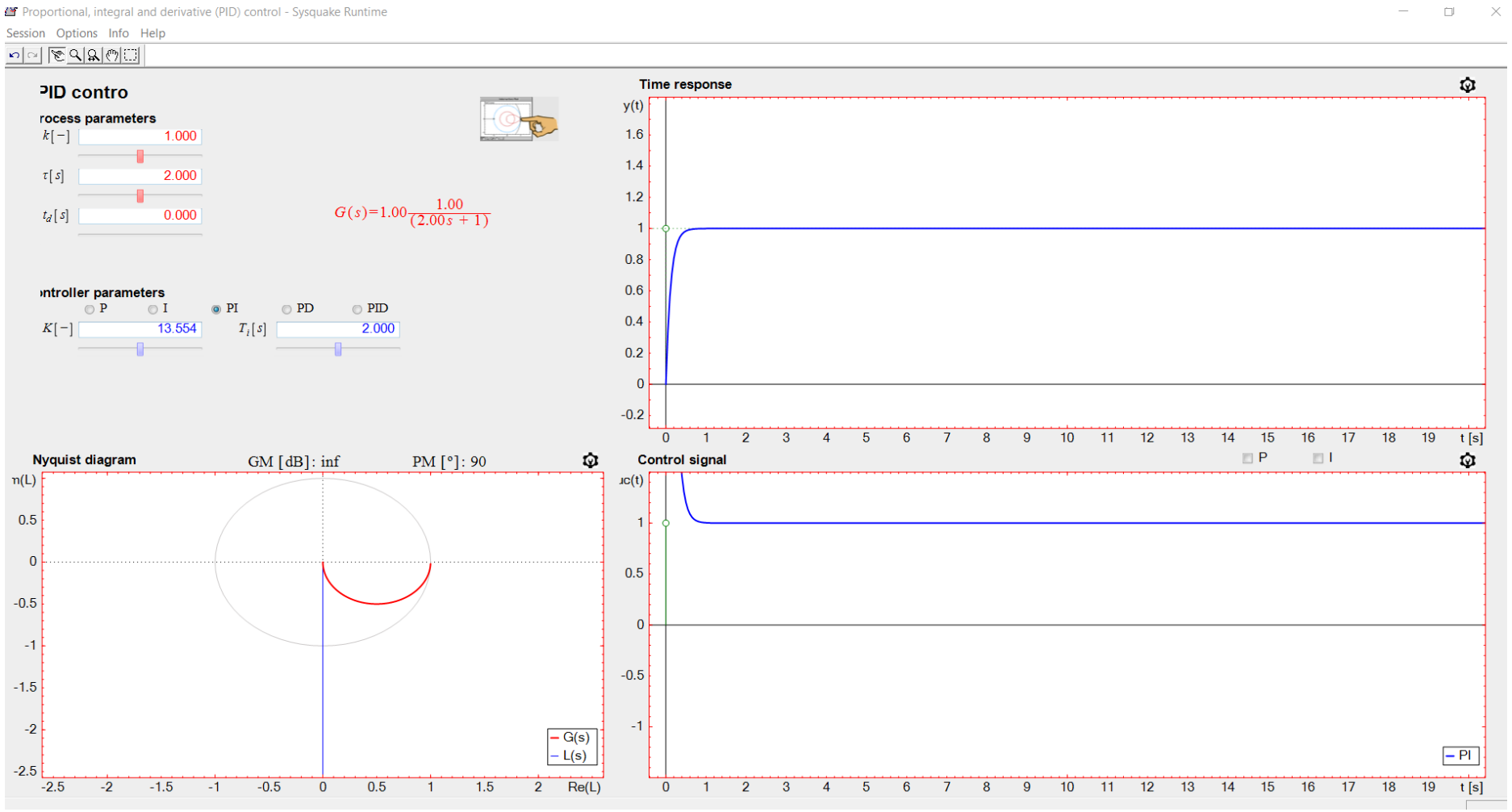
The students will be organized into teams, each team will receive a manual and will try to solve the problem posed in the manual using the interactive tool.



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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Integracion Sensorial y Robotica

Jamk University of Applied Sciences

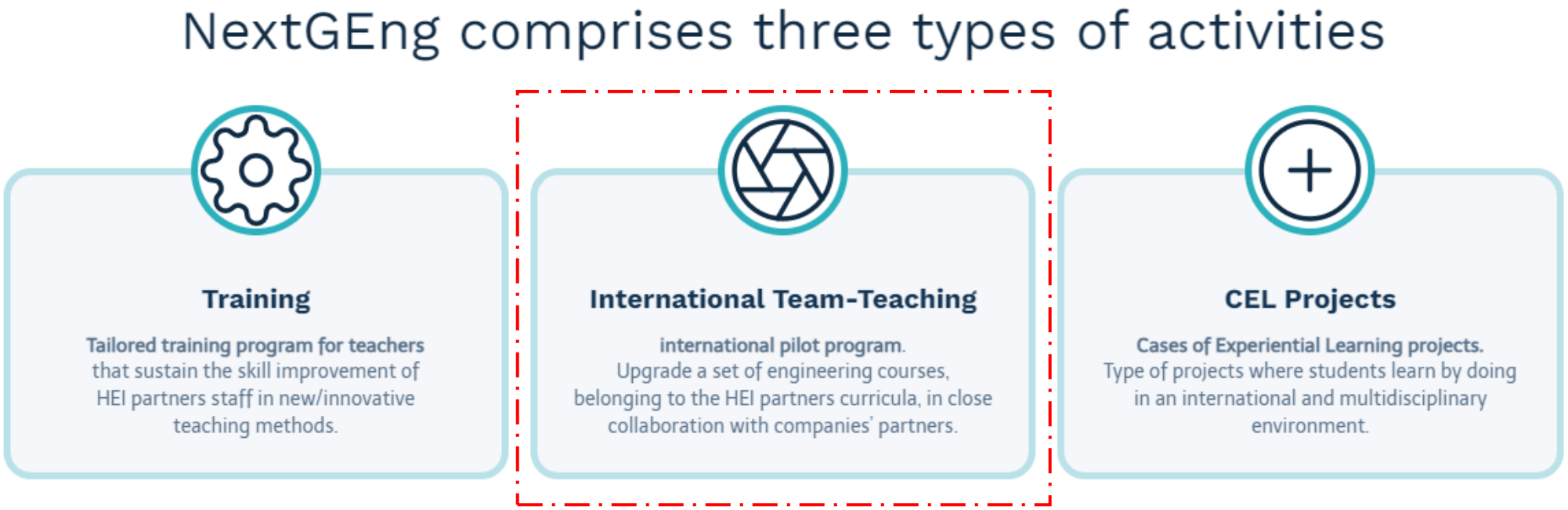
Valmet Technologies Oyj

University of Jaén

Rober Bosch SRL

About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



About guest speaker

- **Diego Martínez** works as a professor at the University of Jaén (Spain), within the department of electronic and automatic engineering. He researches in the automatic robotics and computer vision group and his research topic is related to the integration of sensors within the olive oil production process.

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C3 – Design Projects

M1 - Applying ergonomics in companies – sustainability impact of ergonomics projects

Technical University of Cluj-Napoca

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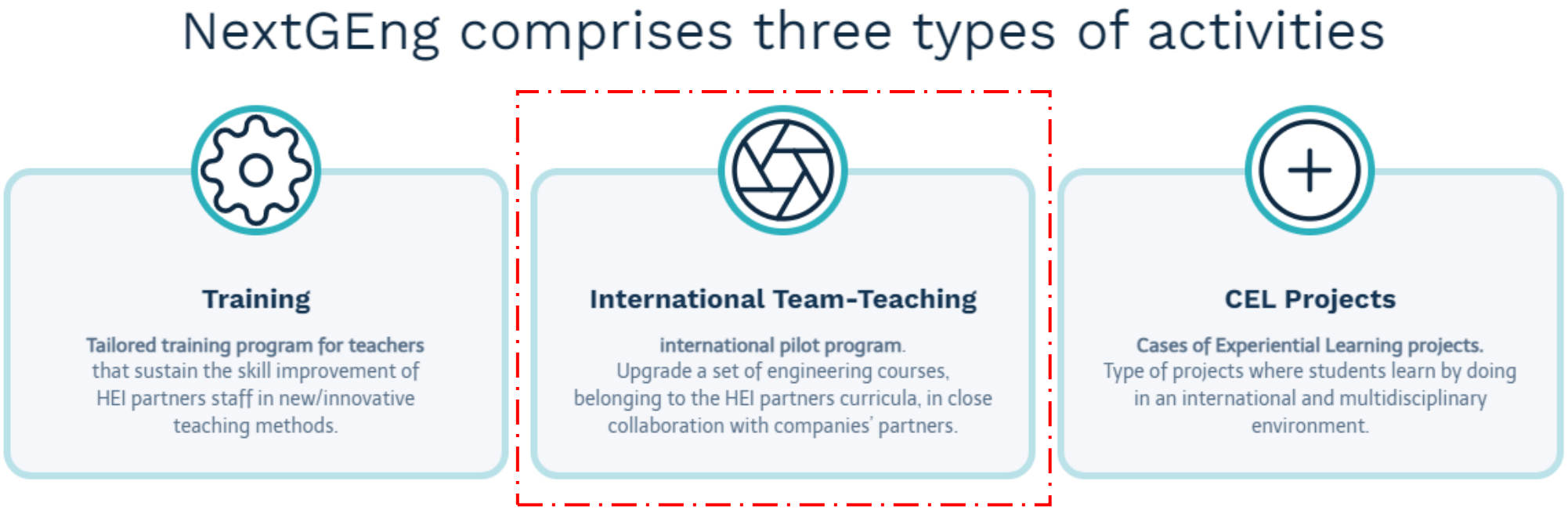

Applying ergonomics in companies – sustainability impact of ergonomics projects

Altwork Moving Desk, *Ergostyle Ergonomic Solutions Specialists*
https://www.youtube.com/watch?v=SBgoGL8_57w

Ergonomic workstation
http://www.haid-kg.de

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NextGEng

Applying ergonomics in companies – sustainability impact of ergonomics projects

Upon completion of this module, the student will be able to:

1) Understand the need for sustainable Engineering projects
2) Think about Engineering projects from a new perspective (Ergonomics perspective)
3) Learn how to increase sustainability impact of Engineering projects using Ergonomics
4) Use RULA, REBA and ERGO-checklist for ergonomic evaluation

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Content

- Introduction
- Should Engineering projects be also Ergonomics projects?
- Applying Ergonomics in companies
  - for products design and analysis
  - for workplace redesign – using methods for ergonomic evaluation
  - for improving organizational performance (economic and social performance)
- Sustainability impact of ergonomics projects
- Conclusions

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Introduction

Introduction

What does the word ERGONOMICS bring to your mind?

Adapted from: *ISO bulletin, 2003*

Main topics:

- Human interaction with technology and environment
- Tasks and work design
- Human performance and comfort
- Human-centered design
- Wellbeing-centered design
- IEA – International Ergonomics Association
- HFES – Human Factors and Ergonomics Society

Adapted from: *https://align1solutions.com/wp-content/uploads/2018/02/Ergonomics-01.jpg*

Introduction

What means ERGONOMICS / Human Factors?

The scientific discipline:

- concerned with *understanding of interactions* among humans and other elements of a system (technology and environment)

The profession:

- that applies theory, principles, data, and methods to *design* in order *to optimize human well-being* and *overall system performance*.

https://iea.cc/about/what-is-ergonomics/

Should Engineering projects be also Ergonomics projects?

Sustainability

”Sustainable Development Goals 2030”

- 2030 Agenda – Sustainable Development Goal 9 (SDG 9): *the sustainable industrial development*, the creation of **a resilient infrastructure and innovation**
- the foundation of the sustainable economic growth is represented by **a sustainable and inclusive industrial development**

Industrial development – new ideas and technologies – new workplaces

Contributes to:

- the efficient use of resources
- increase of work productivity
- workforce wellbeing
- investing in people by developing new abilities for technology use

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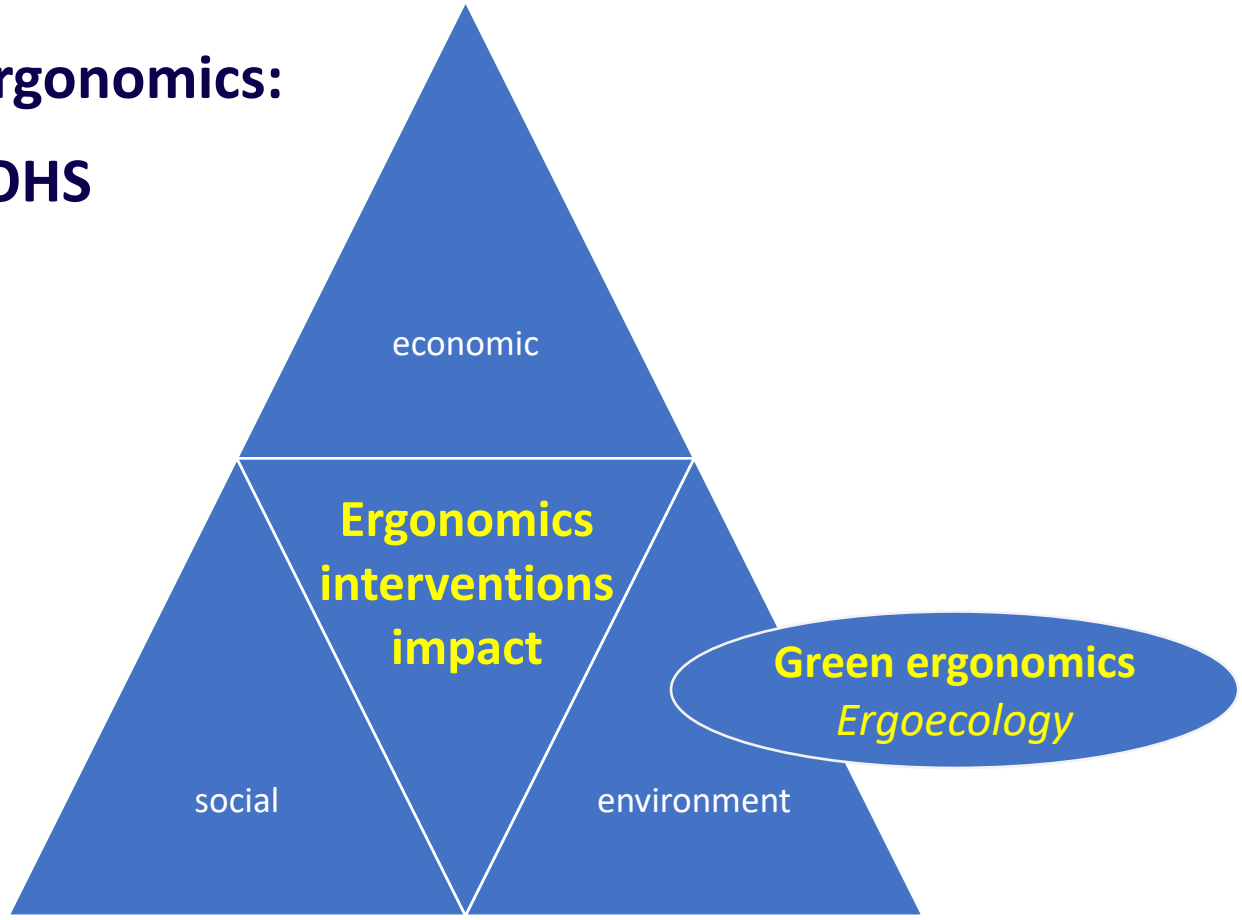
The common goal of Sustainability and Ergonomics:

- **increasing employees' wellbeing and OHS (occupational health and safety)**

"There is a need for a better understanding of how they (ergonomics and sustainability) interrelate and can support decision-making".
Bolis et al. (2020)



Bolis I. et al., "The centrality of workers to sustainability based on values: Exploring ergonomics to introduce new rationalities into decision-making processes", *Applied Ergonomics,* vol. 88 (103148), pp. 1-11.

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Should Engineering projects be also Ergonomics projects?

What do you think are the fundamental rules necessary for engineering projects to be sustainable?

Main topics:

- Long-term financial impact (implementation and maintenance)
- Eco-friendly impact (”smart” use of resources)
- Social impact (human wellbeing)

Should Engineering projects be also Ergonomics projects?

Arguments

- Ergonomics means Human Centered design – optimizing interactions between Humans and other system elements (Technology and Environment)
- Engineering solutions must be human centered to be sustainable
- Economic, Environment and Social impact of Ergonomics projects
- Each Engineering project should have an Ergonomics approach!

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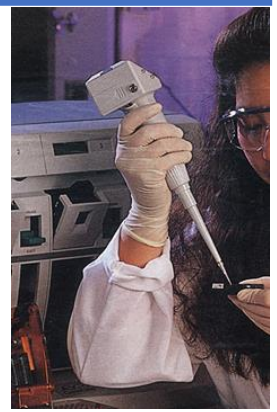
Applying Ergonomics in companies

Applying Ergonomics for products design and analysis

Example – product concept design

Using *Ergonomic Work Analysis (EWA)* for product design



BEFORE

AFTER

Adapted from: Ovation, *BioNatural Pipette*, presentation CD, 2000

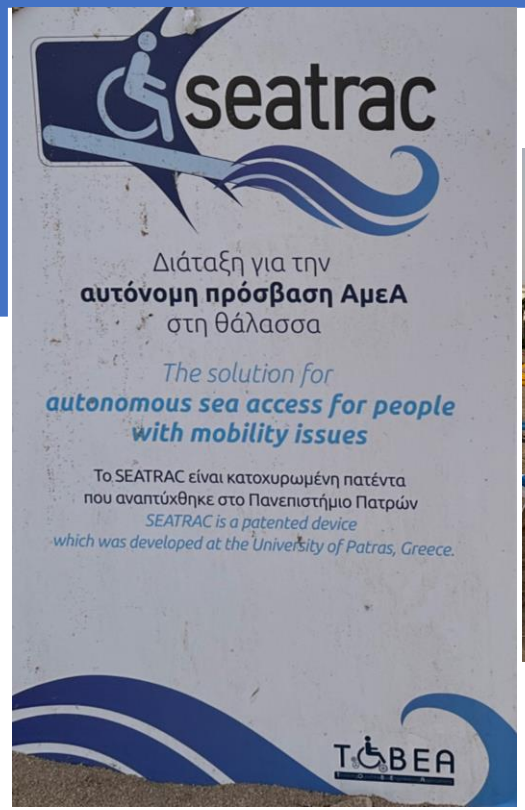
OVATION

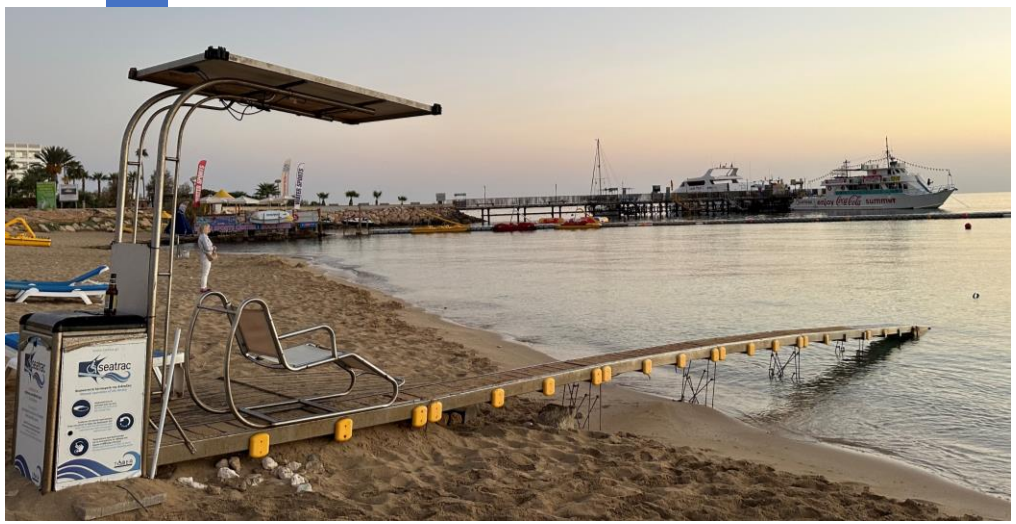
- pipetting ergonomic work analysis (EWA):
  - injuries attributed to pipetting
  - causes of musculoskeletal disorder (MSD): muscles repeatedly put under stress, awkward posture, repetitive movements, forces applied, contact stress
  - EWA conclusion: a new design needed
- changes included:
  - a new look, different from a traditional pipette
  - reinventing the concept of liquid transfer

Adapted from: Ovation, *BioNatural Pipette*, presentation CD, 2000

Example – product concept design

SEATRAC – Autonomous sea access for people with mobility issues – Protaras beach (Cyprus)





Example – product design assessment

Using surface electromyography (sEMG) sensors and statistical analysis (SPSS) for assessing the design of anti-vibration gloves

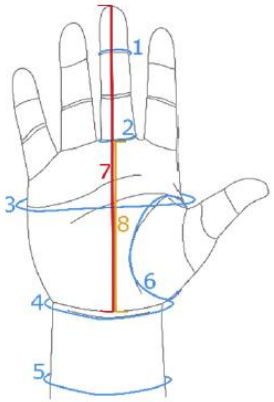
Adapted from: Yu A, Sukigara S., ” Evaluation of the design and materials of anti-vibration gloves: Impact on hand dexterity and forearm muscle activity”, *Applied Ergonomics*, 2022

Co-funded by the European Union

Kyoto Institute of Technology, Japan

Anti-vibration gloves materials and design analysis:

- anthropometric measurements (hand dimension) of participants were used
- muscle activity during different tasks was analyzed: gripping, key pinching, woodblock transporting, screw inserting and screw driving
- conclusions:
  - the gloves could affect hand performance when carrying out different tasks
  - the perception on ease of hand movement for the different gloves depends on the glove properties (circumferential dimensions, thickness and the compression properties of both the palm and dorsal sides of the gloves).



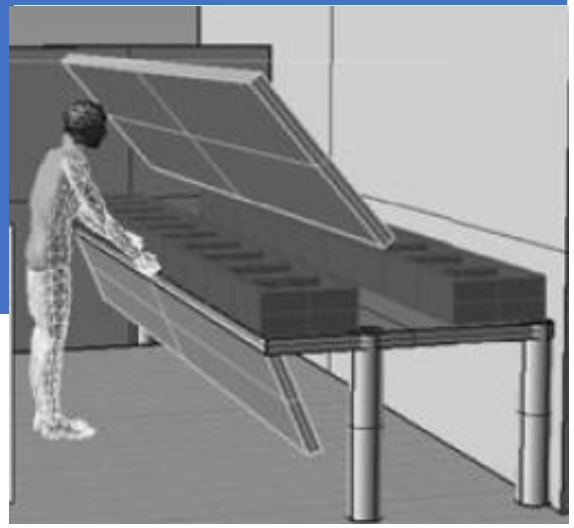
Adapted from: Yu A, Sukigara S., ” Evaluation of the design and materials of anti-vibration gloves: Impact on hand dexterity and forearm muscle activity”, *Applied Ergonomics*, 2022

Applying Ergonomics for workplace redesign

Example – workplace & workstation (re)design

Using Digital Human Modeling for workplace design assessment →

- a new workstation design
- workplace redesign
- occupational risks reduction



Adapted from: Alvarez-Casado E. et al., ” Using Ergonomic Digital Human Modeling in Evaluation of Workplace Design and Prevention of Work-Related Musculoskeletal Disorders Aboard Small Fishing Vessels”, *Human Factors and Ergonomics in Manufacturing & Service Industries*, 2011

Co-funded by the European Union

Example – workstation redesign

Using RULA method for workplace redesign

Adapted from: McAtamney L., Corlett N., ”Rapid Upper Limb Assessment (RULA)”, in Stanton N. et al., Handbook of Human Factors and Ergonomics *Methods*, CRC Press, 2005.

Co-funded by the European Union

Methods for ergonomic evaluation

Rapid Upper Limb Assessment (RULA) – aims to "rapidly" evaluate the exposure to ergonomic risk factors associated with upper extremity MSD (musculoskeletal disorders) of individual workers.

RULA Employee Assessment Worksheet

Task Name: Date:

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position:

Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

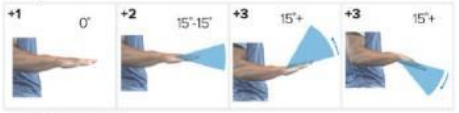
Upper Arm Score

Step 2: Locate Lower Arm Position:

Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:



Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

Wrist Twist Score

Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

Posture Score A

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>1 minute),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain Wrist and Arm Score. Find row in **Table C**.

Wrist & Arm Score

Scores

Table A		Wrist Score							
		1		2		3		4	
Upper Arm	Lower Arm	Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
		1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C		Neck, Trunk, Leg Score						
		1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

RULA Score

B. Neck, Trunk and Leg Analysis

Step 9: Locate Neck Position:

Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:

Trunk Score

Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

Leg Score

Neck Posture Score	Table B: Trunk Posture Score											
	1		2		3		4		5		6	
	Legs		Legs		Legs		Legs		Legs		Legs	
	1	2	1	2	1	2	1	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	8	8	
5	7	7	7	7	8	8	8	8	8	8	8	
6	8	8	8	8	8	8	9	9	9	9	9	

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above, locate score in Table B

Posture B Score

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>1 minute),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score

Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain Neck, Trunk and Leg Score. Find Column in **Table C**.

Neck, Trunk, Leg Score

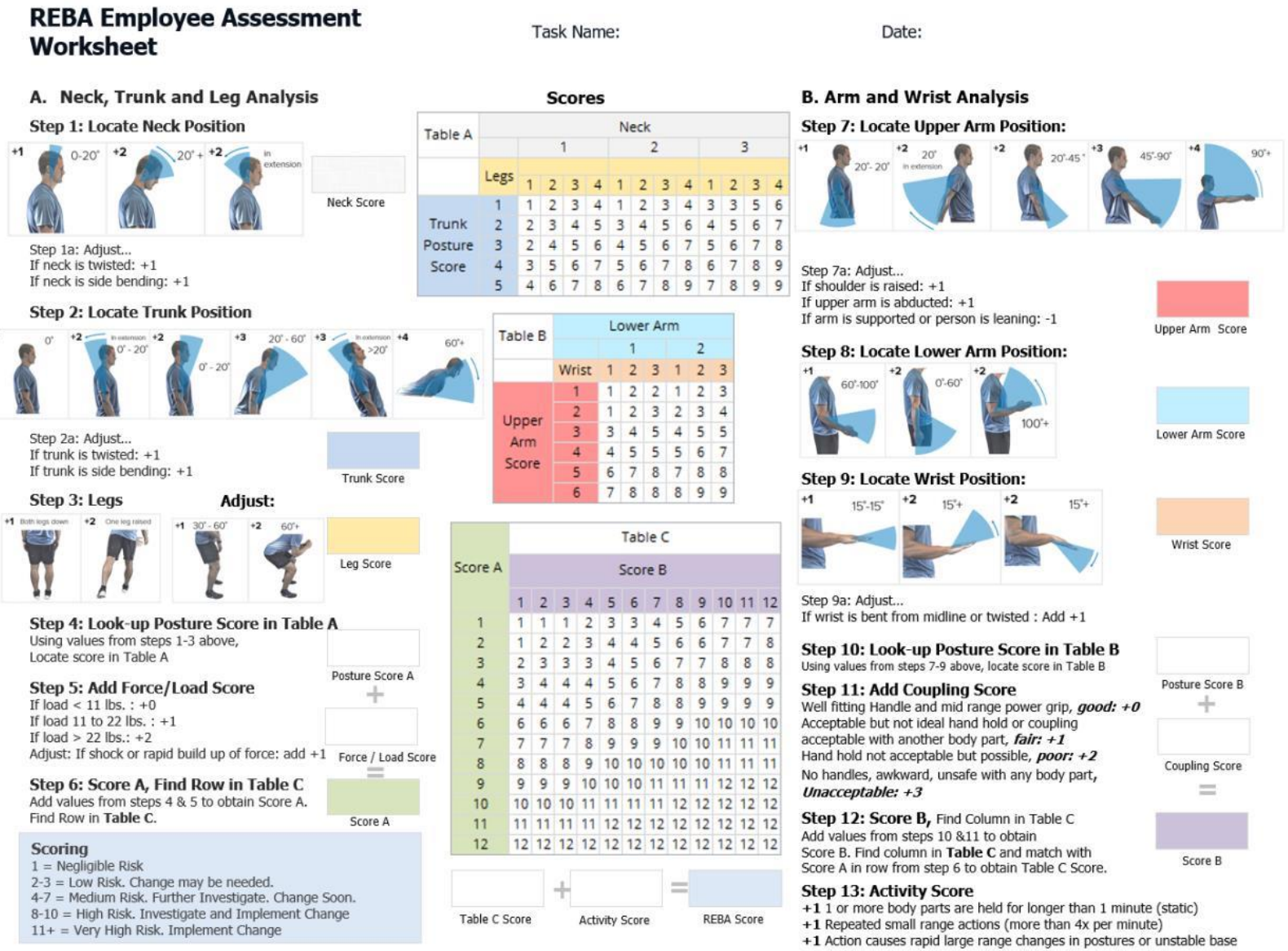
based on RULA: a survey method for the investigation of work-related upper limb disorders, McAtamney & Corlett, Applied Ergonomics 1993, 24(2), 91-99

https://www.ergo.human.cornell.edu/cutools.html

Co-funded by the European Union

NextGEng

Rapid Entire Body Assessment (REBA) – aims to "rapidly" evaluate the risk of MSD (musculoskeletal disorders) associated with certain job tasks.



REBA Employee Assessment Worksheet

Task Name: Date:

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 0-20° +2 20°+ +2 in extension

Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 0° +2 0°-20° extension +2 0°-20° +3 20°-60° +3 >20° extension +4 60°+

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score

Step 3: Legs

Adjust:

+1 Both legs down +2 One leg raised +1 30°-60° +2 60°+

Leg Score

Step 4: Look-up Posture Score in Table A

Using values from steps 1-3 above, Locate score in Table A

Posture Score A

Step 5: Add Force/Load Score

If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score

Step 6: Score A, Find Row in Table C

Add values from steps 4 & 5 to obtain Score A. Find Row in **Table C**.

Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A

Legs	Neck 1				Neck 2				Neck 3			
Trunk Posture Score	1	2	3	4	1	2	3	4	1	2	3	4
1	1	2	3	4	1	2	3	4	3	3	5	6
2	2	3	4	5	3	4	5	6	4	5	6	7
3	2	4	5	6	4	5	6	7	5	6	7	8
4	3	5	6	7	5	6	7	8	6	7	8	9
5	4	6	7	8	6	7	8	9	7	8	9	9

Table B

Upper Arm Score	Lower Arm Wrist 1	1	2	3	Lower Arm 2	2	3
1	1	2	2	1	2	3
2	1	2	3	2	3	4
3	3	4	5	4	5	5
4	4	5	5	5	6	7
5	6	7	8	7	8	8
6	7	8	8	8	9	9

Table C

Score A \ Score B	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score + Activity Score = REBA Score

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 20°-20° +2 20° in extension +2 20°-45° +3 45°-90° +4 90°+

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 8: Locate Lower Arm Position:

+1 60°-100° +2 0°-60° +2 100°+

Lower Arm Score

Step 9: Locate Wrist Position:

+1 15°-15° +2 15°+ +2 15°+

Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B

Using values from steps 7-9 above, locate score in Table B

Posture Score B

Step 11: Add Coupling Score

Well fitting Handle and mid range power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score

Step 12: Score B, Find Column in Table C

Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B

Step 13: Activity Score

+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Original Worksheet Developed by Dr. Alan Hedge. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205

https://www.ergo.human.cornell.edu/cutools.html

Co-funded by the European Union

NextGEng

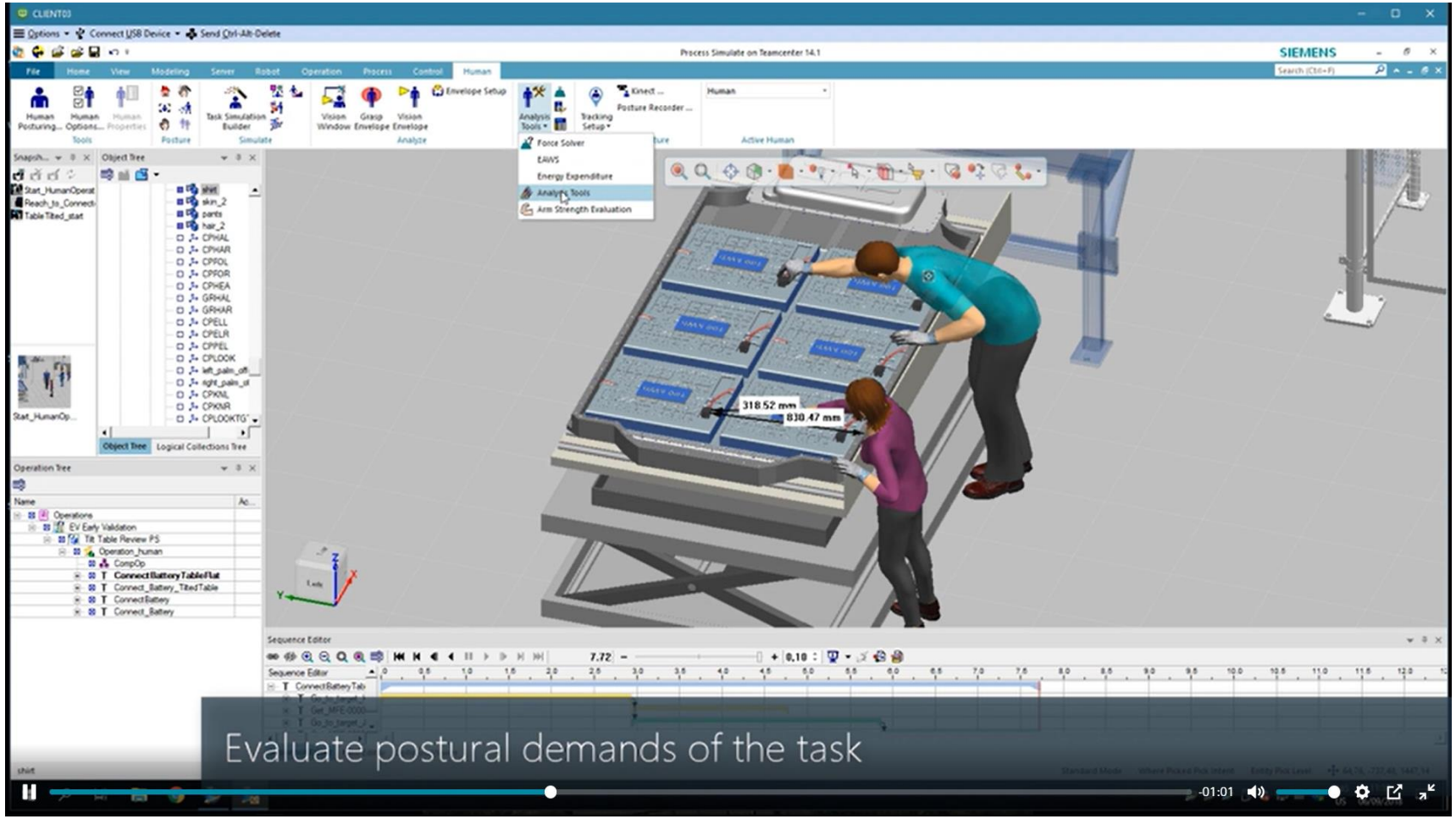
Example – ergonomic evaluation software

ErgoPlus Industrial:

- based on RULA method
- determine body position
- upper and lower arm & wrist analysis
- muscle use & force analysis
- neck, trunk, and leg analysis

https://ergo-plus.com/software/

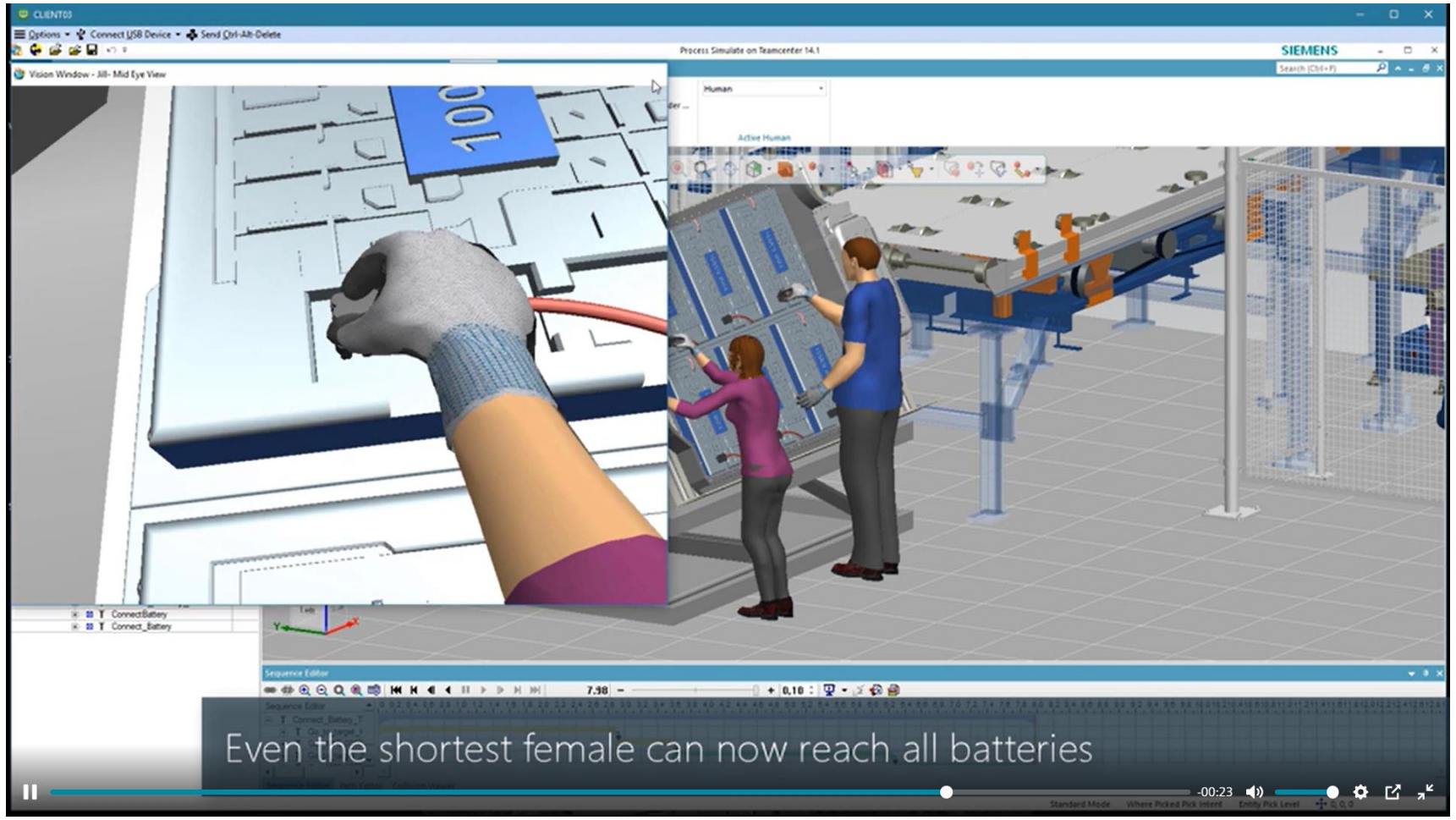
Example – based-ergonomic design software



https://trials.sw.siemens.com/en-US/trials/tecnomatix-process-simulate-human

Software for ergonomic design

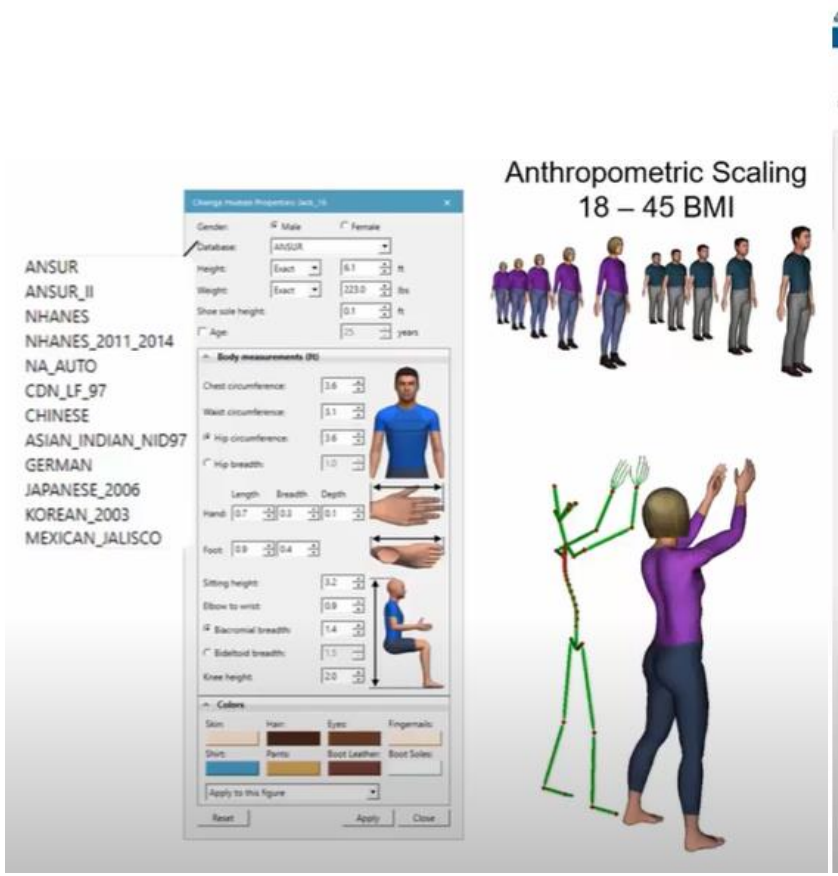
- simulate human tasks
- perform an ergonomic evaluation of a task sequence
- validate and optimize assembly sequences

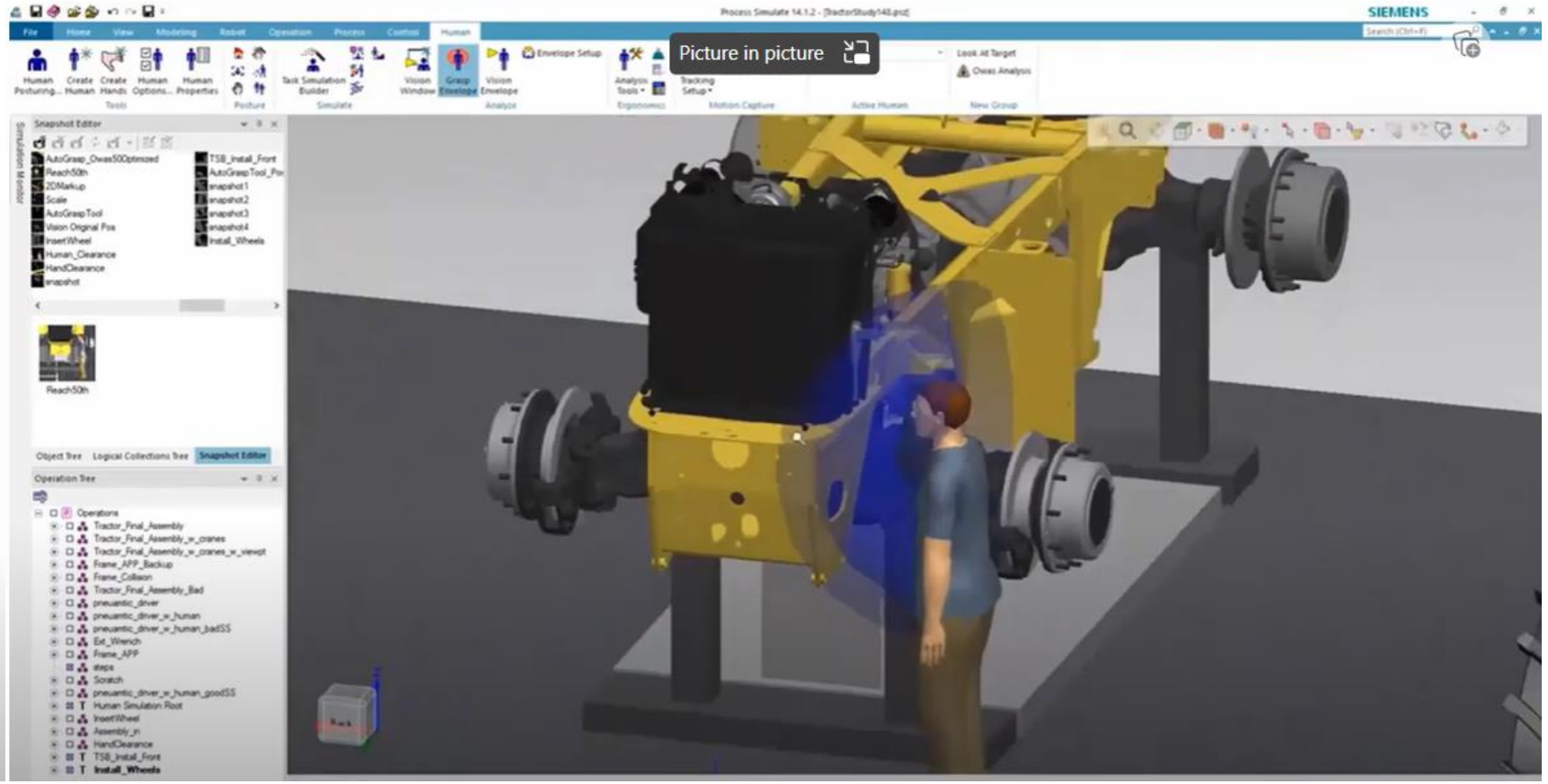


https://trials.sw.siemens.com/en-US/trials/tecnomatix-process-simulate-human

Co-funded by the European Union

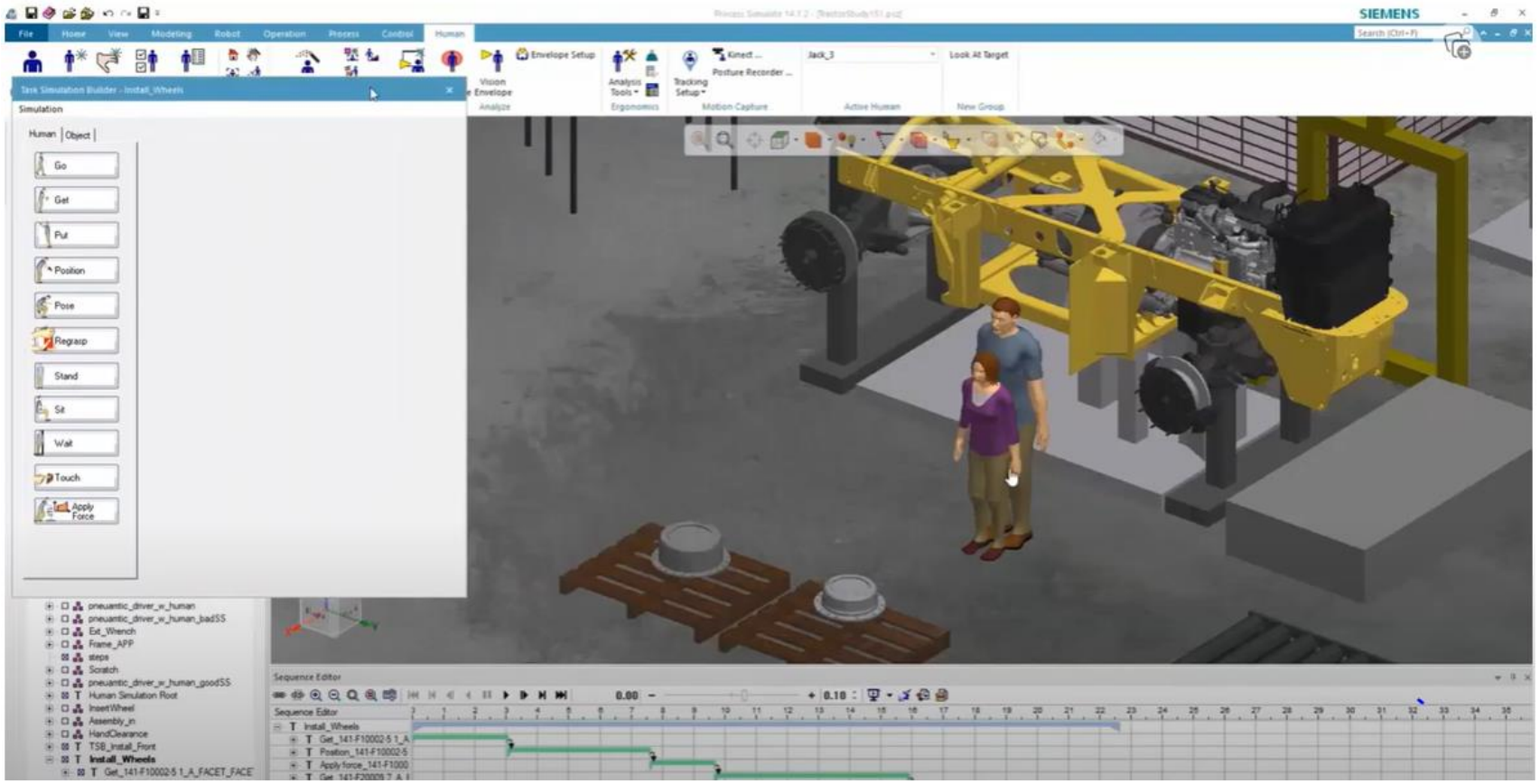
- simulate human tasks and reach distances





Bringing the Human into Your Process Planning with Siemens Tecnomatix Process Simulate Human
Banar K., *The Power of Virtual Human Modeling*, https://www.youtube.com/watch?v=YbF-XPSesB8 starting with min. 5:55

- simulate human tasks and reach distances



Bringing the Human into Your Process Planning with Siemens Tecnomatix Process Simulate Human
Banar K., *The Power of Virtual Human Modeling*, https://www.youtube.com/watch?v=YbF-XPSesB8 starting with min. 5:55

Example – ergonomic assessment checklist: ERGO-checklist for NextGEng students use

Co-funded by the European Union

NextGEng

International Cooperation Framework for Next Generation Engineering Students

TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ERGO CHECKLIST

ERGO checklist: a method for the investigation of workspace design
developed within NextGEng project for students use

Only mark the BLUE boxes (YES or NO) in the Ergo CHECKLIST worksheet.

Fill in the details in the WHITE box below.

Project name:	**Ergonomic evaluation and (re)design of an assembly manufacturing workplace**
Assessment type:	**1 - ergonomic evaluation of an existing solution**
Activity/ Task name:	xxx
Assessor:	xxx
Date:	dd/mm/yyyy

Assessment type:
0 - design phase
1 - ergonomic evaluation of an existing solution
2 - redesigned phase (after improvements)

ERGO CHECKLIST

Workstation (re)design objectives:

(1) comfort and wellbeing

(2) work efficiency

(3) sustainability - workstation easy adaptability (for mixed working population, male and female)

A. COMFORT AND WELLBEING Workplace dimensions and body posture assessment		YES	NO	Arguments/ Explanations/ Remarks
A1.	The workplace design allows alternative posture (sitting / standing)			
A2.	The operator position (sitting / standing) is chosen correctly and according to the task.			
A3.	The REBA score is less than or equal to 3.			
A4.	The awkward body posture is avoided.			
A5.	The workstation design allows adjustment of the working level height (between the necessary levels and according to the task).			
A6.	The workstation design alows comfortable reach distances (arms and wrists working areas are good).			
A7.	The workstation design alows operator visibility (head and eye working areas are good).			

B. WORK EFFICIENCY Task efficiency assessment		YES	NO	Arguments/ Explanations/ Remarks
B1.	The activities are carried out in the maximum working area for the arms.			
B2.	The operating level, tools, materials, etc. are arranged so that the most common movements are carried out in the normal working area.			
B3.	The instruments and materials frequently used by the operator are placed in the normal working area for the arms.			
B4.	The instruments and materials required are arranged in the order in which they are used, so that the operator movements are continuous.			
B5.	Tools are prepositioned - for increasing work efficiency and be easily manipulated by the user.			
B6.	The operator arms movements are in different directions or symmetrical - for increasing work efficiency and accuracy.			
B7.	The torso twisting action and lifting heavy or bulky objects above shoulders is not needed during work.			

C. SUSTAINABILITY Social and eco-friendlly design assessment		YES	NO	Arguments/ Explanations/ Remarks
C1.	The workstation design alows the 5th percentile female and the 95th percentile male to adopt a good body posture.			
C2.	The workstation design is user-centered.			
C3.	The workplace design solution takes into account workplace usability and user experience.			
C4.	The project of workplace design has Economic and Financial Feasibility			
C5.	The maintainance costs for the workplace are low.			
C6.	The workstation design is eco-friendly.			
C7.	Workplace waste is recyclable			

ERGO CHECKLIST REPORT

Project name:	**Ergonomic evaluation and (re)design of an assembly manufacturing workplace**
Assessment type:	**0 - design phase**
Activity/ Task name:	**xxx**
Assessor:	**xxx**
Date:	**dd/mm/yyyy**

Workplace design criteria	Number of CHECKS	
	YES	NO
A. COMFORT AND WELLBEING	0	0
B. WORK EFFICIENCY	0	0
C. SUSTAINABILITY	0	0

Applying Ergonomics for improving organizational performance

Example – social impact

Adjusting equipment to improve ergonomics and attract male and female employees

- improving gender diversity in connection with firm strategy to *create an inclusive and diverse work environment*

BEFORE ergonomics intervention: a totally masculine workplace where a woman would be unable to operate

Adapted from: Alcoa, *2020 Sustainability Report,* p. 61
https://www.alcoa.com/sustainability/en/pdf/2020-Sustainability-Report.pdf

Co-funded by the European Union

ALCOA
Poços de Caldas casthouse in Brazil (2019)

- changes included:
  - *reducing the weight* of the oven-opening sledgehammer *from 5 kilograms to 4 kilograms*
  - *reducing the weight* of the alloy hopper *from 7 kilograms to 5 kilograms*
- women started to work in the hot top – paired with male coworkers

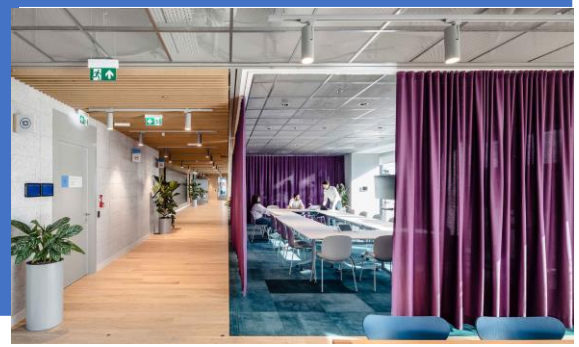
Adapted from: Alcoa, *2020 Sustainability Report,* p. 61
https://www.alcoa.com/sustainability/en/pdf/2020-Sustainability-Report.pdf

Example – social and green impact

Combining biophilic design with ergonomics and aesthetics.

- improving employees wellbeing

Using sustainable 3R's principle (Reduce, Reuse and Recycle) for workplace design



Adapted from: *https://www.flokk.com/global/projects/orsted-warsaw*

Ørsted new office in Warsaw

- designed to reflect the company values, using *sustainable 3R's principle* (Reduce, Reuse and Recycle) for workplace design
- the design combines *biophilic* design with *ergonomics* and *aesthetics*.
- the workspace solution:
  - *height adjustable chairs able to fit both high and low desks*
- provides basic components of employee well-being:
  - *physical and mental comfort*
  - *contact with nature.*

Co-funded by the European Union

Example – using new technologies for MSD prevention

Ergonomics measures to prevent MSD (musculoskeletal disorders)

wearable robot for assisting workers → improving work processes

Hyundai Motor

- since 2020 has tested 10 *wearable devices* at 36 processes with 104 people working
- the results highlighted *the need for an ergonomics related measures*: “the need to reflect physical diversity and lower the operational difficulty and weight of equipment”.
- CEX - a “chair-type wearable robot” and VEX - a “wearable robot in the form of a suit, equipped with a multi-link muscle compensation device” were used for *assisting workers to maintain a good sitting posture and in arm lifting processes.*

Adapted from: *Hyundai, Road to Sustainability: 2022 Sustainability Report*, pp. 38-39
https://www.hyundai.com/worldwide/en/company/sustainability

Co-funded by the European Union

Example – using based-ergonomic software for MSD prevention

Ergonomics measures to prevent MSD (musculoskeletal disorders)

MSD management → integrated in OHS management

Hyundai Motor

- "Management of MSD" is a component of H-SAT (Hyundai Safety Assessment Tool), a tool developed for OHS management level assessment.
- The tool evaluation items are continuously revised to reflect the new regulations regarding safety and new trends in international obligations.
- Safety KPIs are used, and safety leadership and accident prevention efforts are enhanced.

Adapted from: *Hyundai, Road to Sustainability: 2022 Sustainability Report*, pp. 38-39
https://www.hyundai.com/worldwide/en/company/sustainability

Co-funded by the European Union

Example – using based-ergonomic software for MSD prevention

Ergonomics measures to prevent MSD (musculoskeletal disorders)

BMW

- the use of a *Digital Workplace Stress Management system* "to assess ergonomic aspects of workplaces on a fully automated basis".
- The company range for risk assessment "was expanded to include *a mobile workplace analysis in view of the increased scale of working from home*".

Hankook

- the company has established a *MSD prevention and response system* based on work analyses and identifying improvements using RULA (Rapid Upper Limb Assessment) and NLE (NIOSH Lifting Equation) ergonomic posture evaluation tools.

Adapted from: *The future is electric, digital and circular: BMW Group Report 2021 & Sustainable Mobility: Hankook driving emotion. ESG Report 2021/22*

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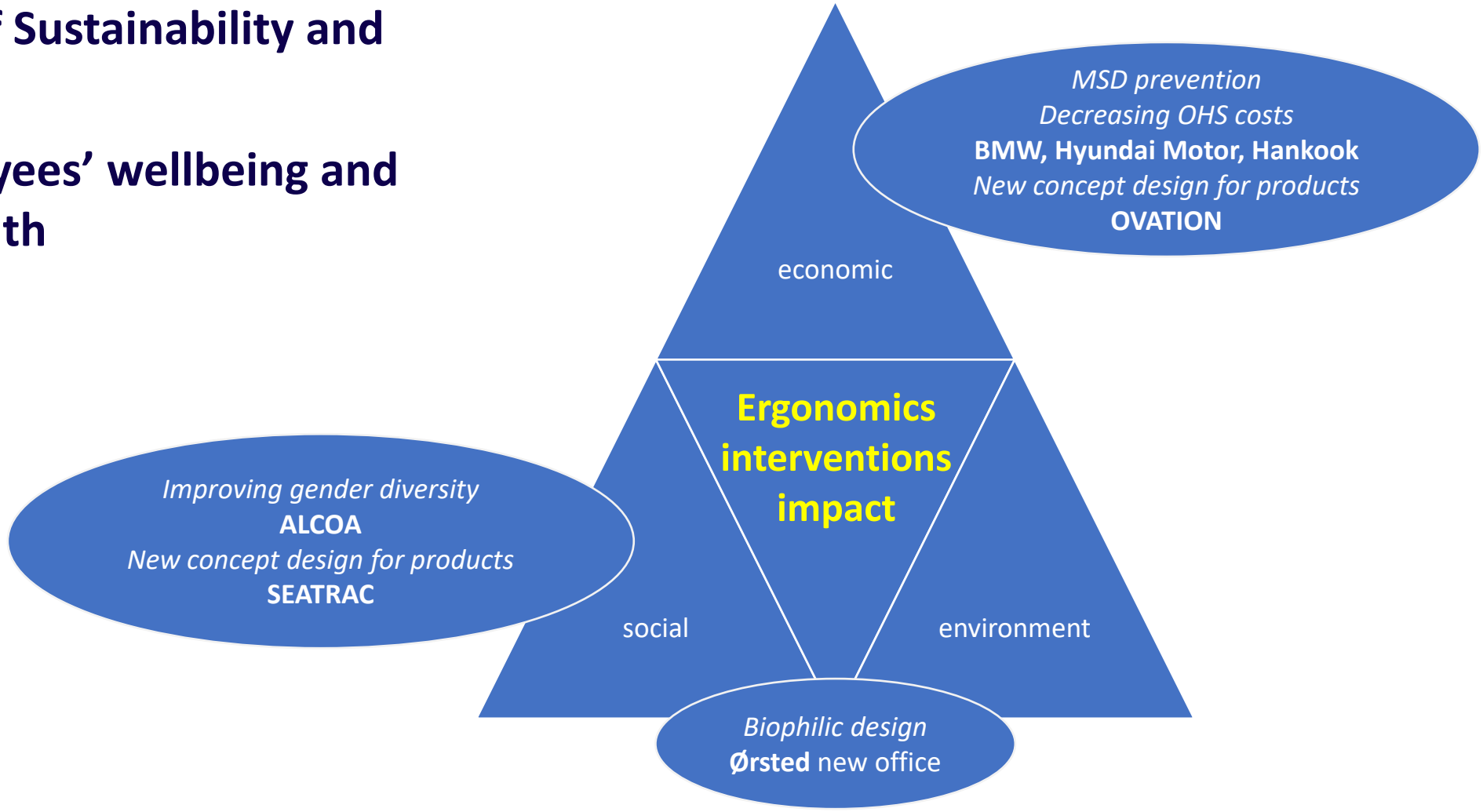
Sustainability impact of ergonomics projects

The common goal of Sustainability and Ergonomics:

- **increasing employees' wellbeing and occupational health**

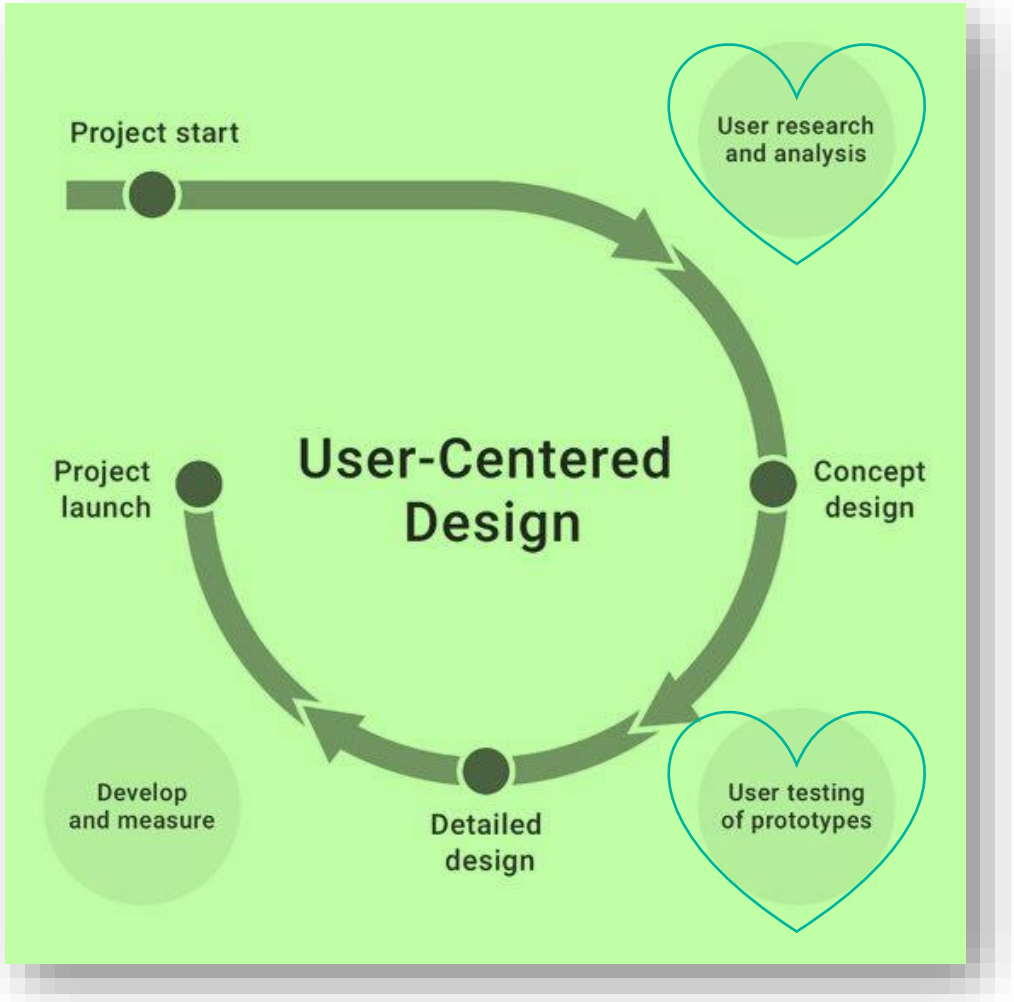


Conclusion

Conclusion: engineering projects and the need for Ergonomics

Topics to be consider during design phase:

- Human-centered design
- Spaces and facilities dimensions
- Obstacles, limits, barriers
- Accessibility, visibility, adaptability of spaces
- Handling objects, forces, reaches and manipulations
- Unfit facilities



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C3 – Design Projects

M2 - Ergonomic principles and criteria for design

Technical University of Cluj-Napoca

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Integracion Sensorial y Robotica

Jamk University of Applied Sciences

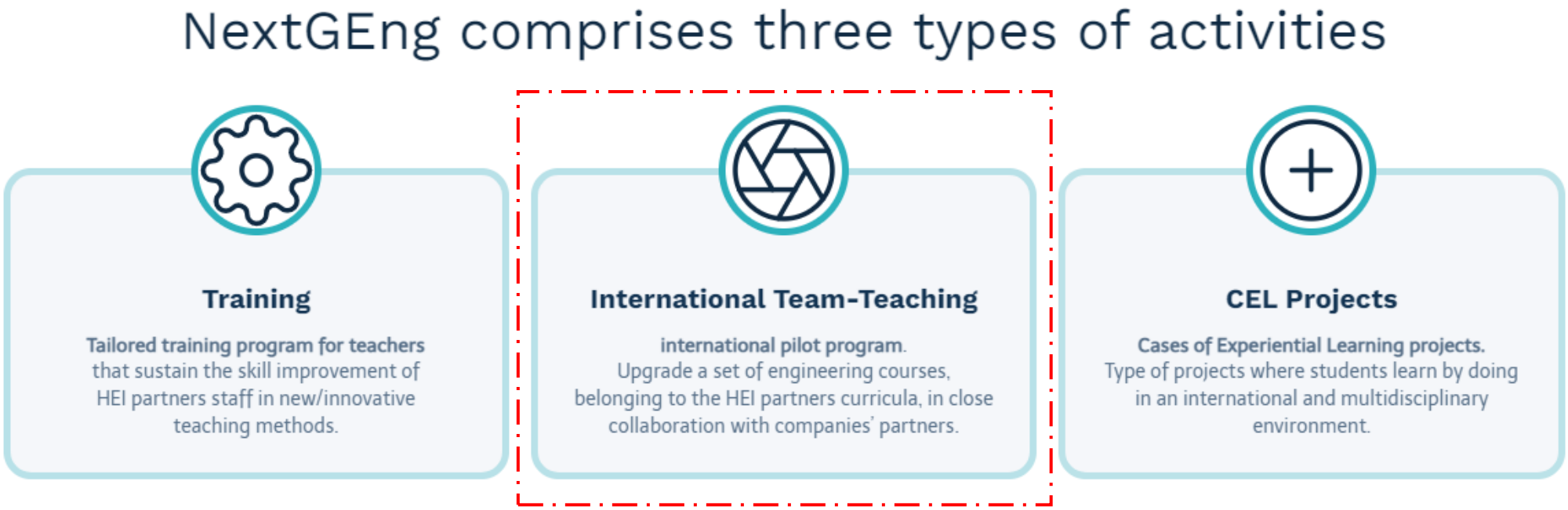
Valmet Technologies Oyj

University of Jaén

Robert Bosch SRL

About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



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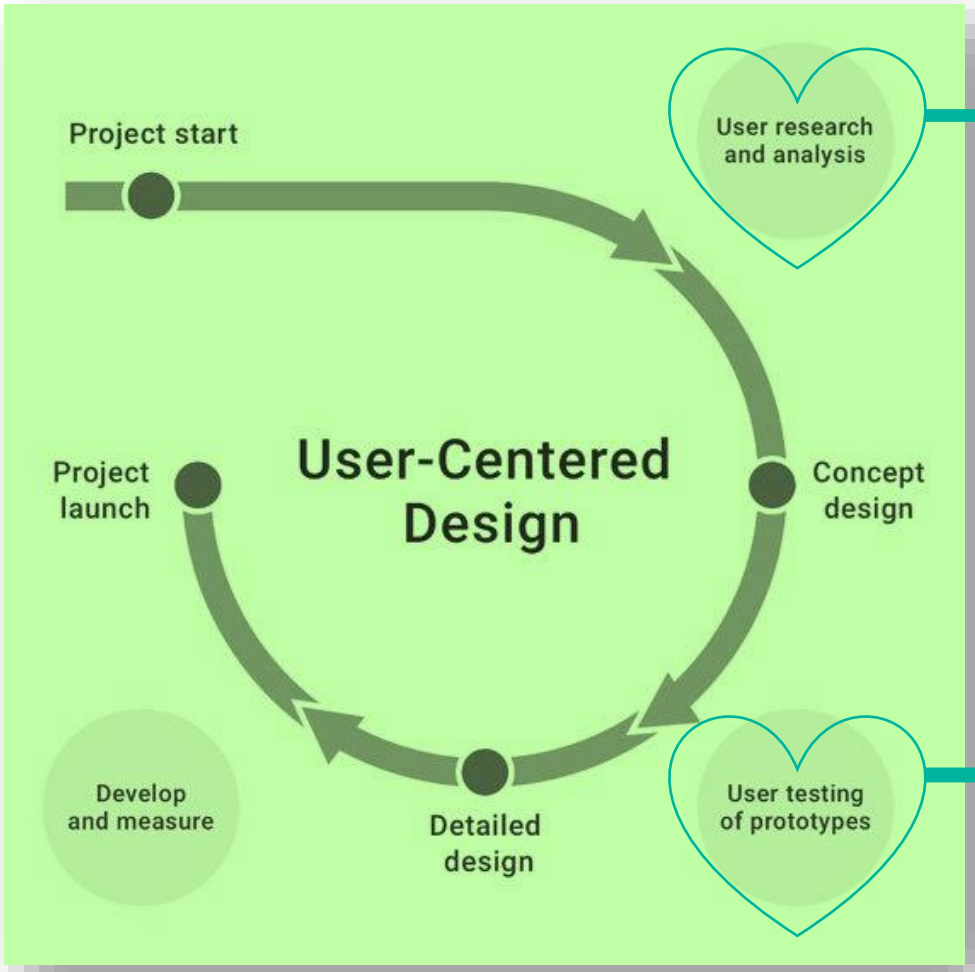
Ergonomic principles and criteria for design



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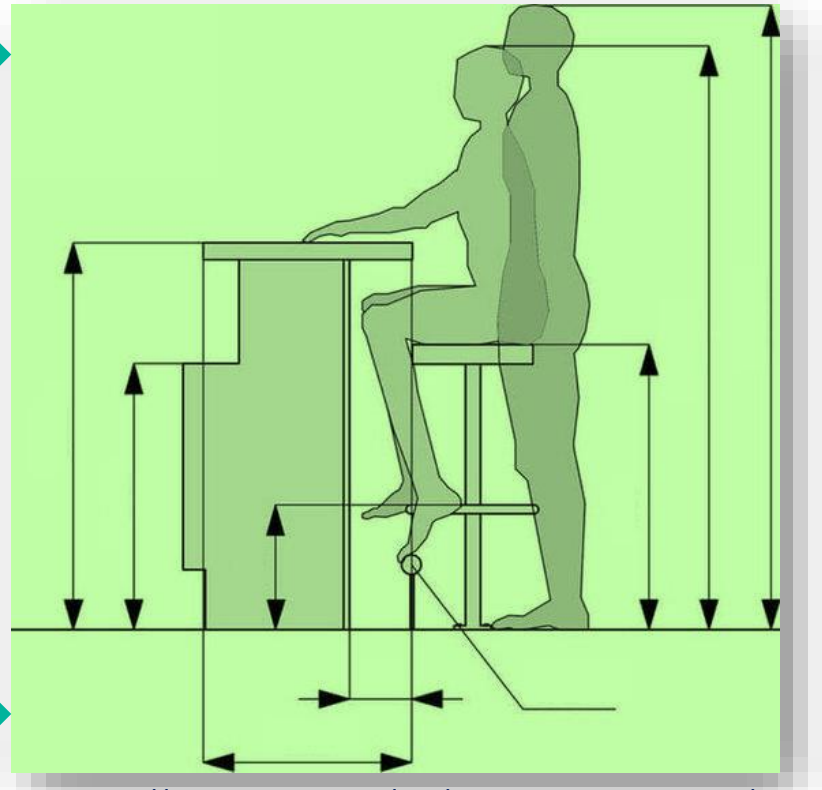

https://ro.pinterest.com/pin/868561478118744250/

Ergonomic principles and criteria for design

Upon completion of this module, the student will be able to:

1) Think about Engineering project from a new perspective (Ergonomics perspective)
2) Identify complementary aspects of engineering design related to Ergonomics
3) Apply the ergonomics principles and criteria for workplace, workspace and products design
4) Use anthropometric data in workspace and products design
5) Apply workspace and products design procedure

Content

- Introduction
- Engineering projects and the need for human-centered design
- Ergonomics principles and criteria for workplace design
- Ergonomics principles for products design
- Using anthropometric data in design
- Workplace design procedure
- Criteria for selecting the best design solution
- Conclusion

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Introduction

Introduction

What is the first word that comes to your mind when you say DESIGN?

What is the first word that comes to your mind when you say ENGINEERING?

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Engineering projects and the need for human-centered design

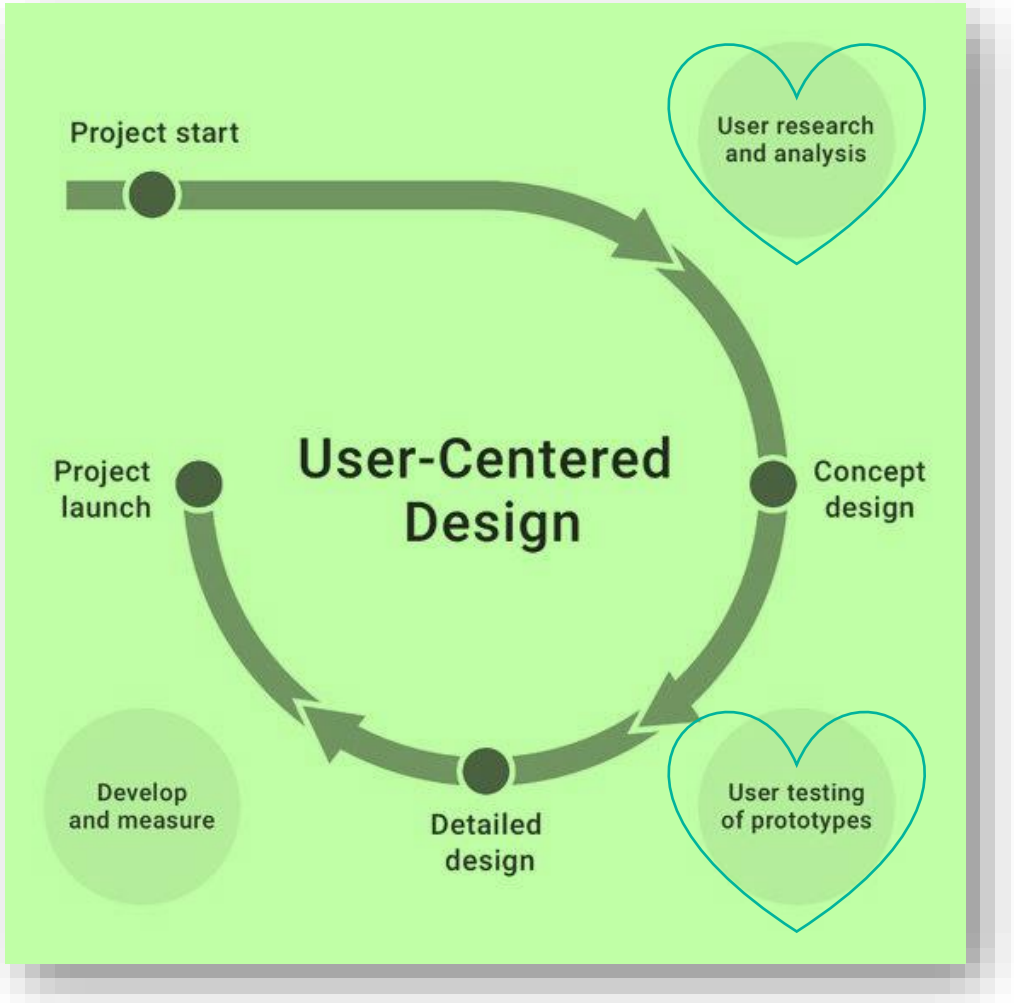
Engineering projects and the need for human-centered design

What places/ services/ devices etc. in the project you work on it:

- are available for humans?
- are not accessible for some people (children, physically disabled people, tallest or shortest people, etc.)?

Main topics:

- Obstacle, limits, architectural barriers
- Accessibility, visibility, adjustability of spaces
- Handling objects, forces, reaches and manipulations
- Unfit facilities



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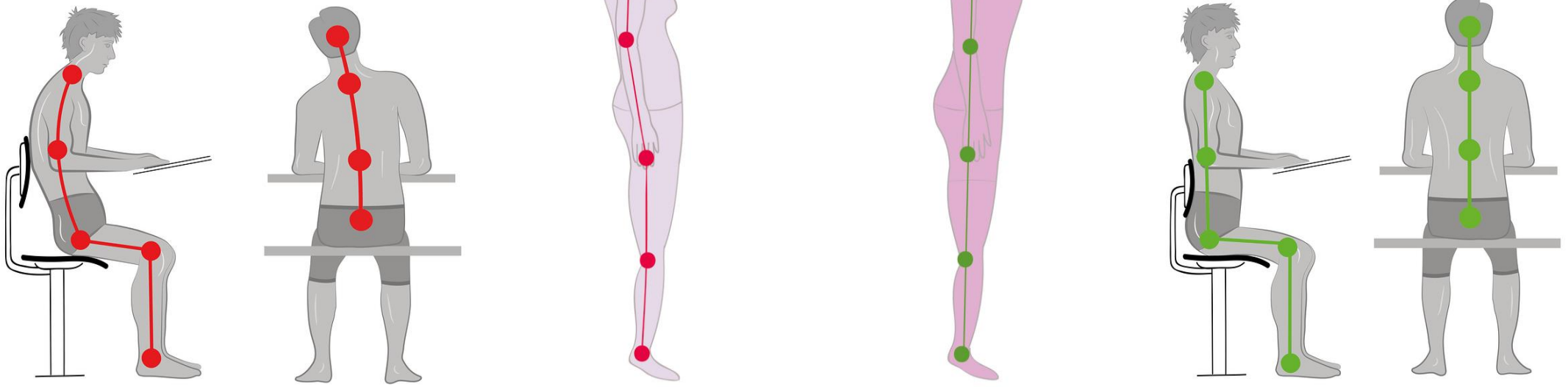
Ergonomics principles for design

Look at the people on the left side. What their posture suggest?

Main topics:

- Posture type
- Workstation design problems
- Design solutions



https://www.istockphoto.com/

Ergonomics principles and criteria for workplace design

Ergonomics criteria for workplace design

Primary criteria for workplace design

- Comfort = adjustability / allow a good working posture
- Work efficiency = enhance the efficiency of operations and tasks
- Safety and health = minimize MSD, OHS risks, and fatigue
- Aesthetics = workplace aspect and colors
- Speed of work (time)
- Accuracy = compromise between ”speed of work” and ”lack of errors”
- Ease of maintenance
- User good mood = user emotions
- Ethics
- Economic = an economical design
- Well-being

“What is the point in spending vast sums of money to create the healthiest and safest factory in the country if the only people who work in it are liquidators?”

Simpson G., apud. Lehto De Mark, Buck J, *Introduction to Human Factors and Ergonomics for Engineers*, CRC Press, 2007

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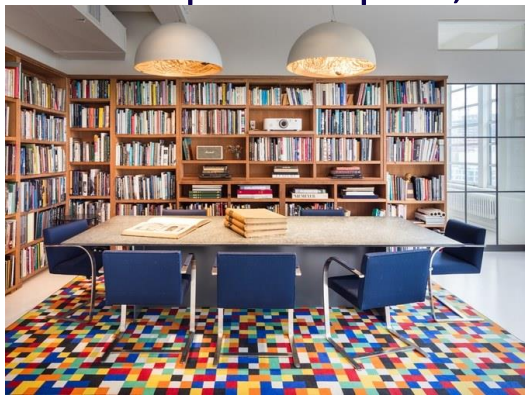
Ergonomics criteria for workplace design

Comfort = adjustability

Safety and health = reduced MSD and OHS risks

Aesthetics & **good mood** = workplace aspect, emotions and colors



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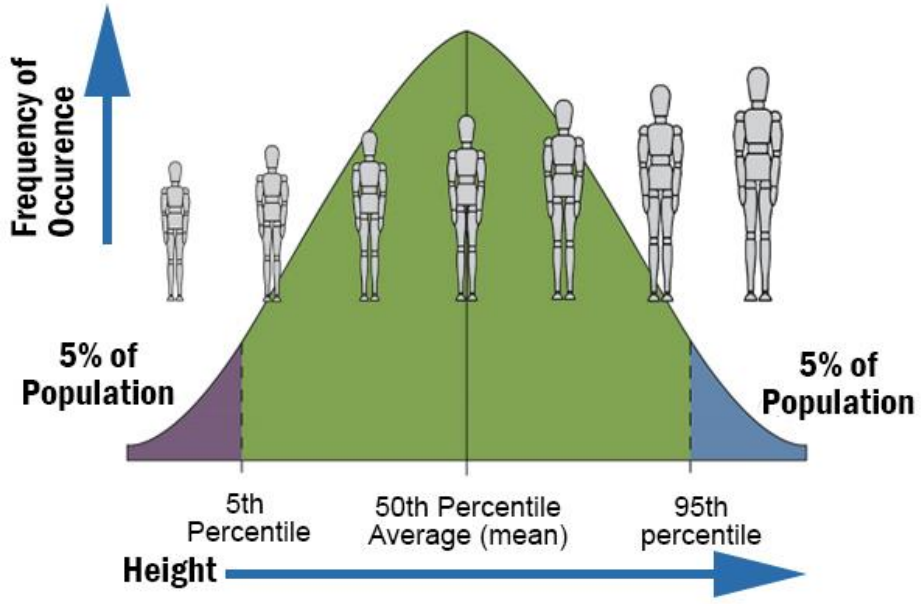
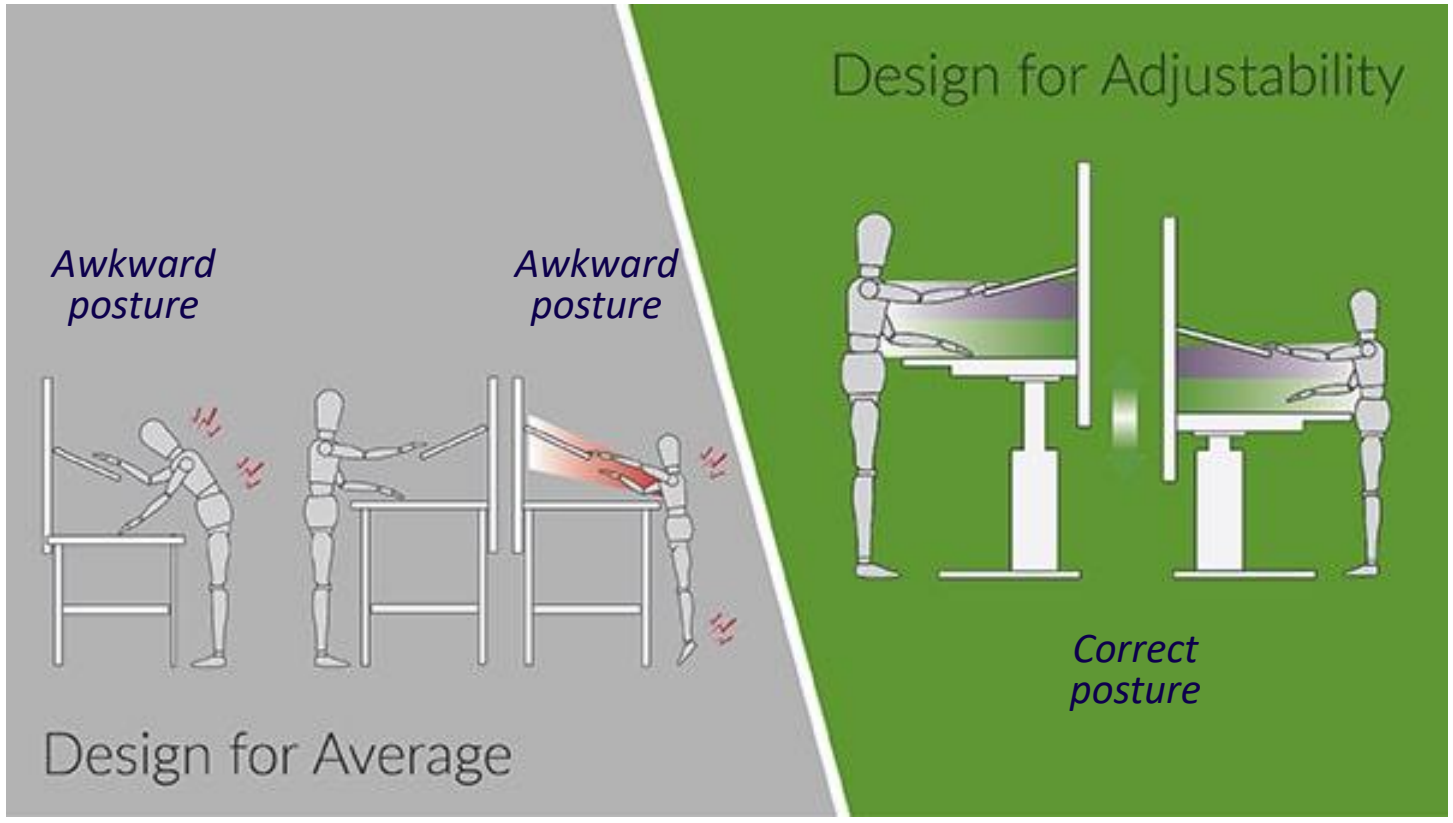
Ergonomics criteria for design

Secondary criteria

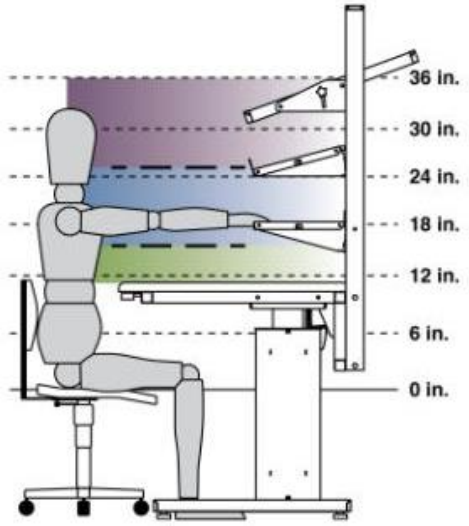
- Adjustability / Adjustable design
- Design for average
- Design for the extreme



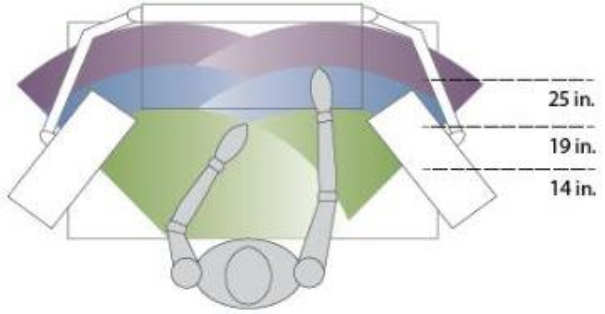


https://www.bostontec.com/designing-an-industrial-workbench-for-adjustability/

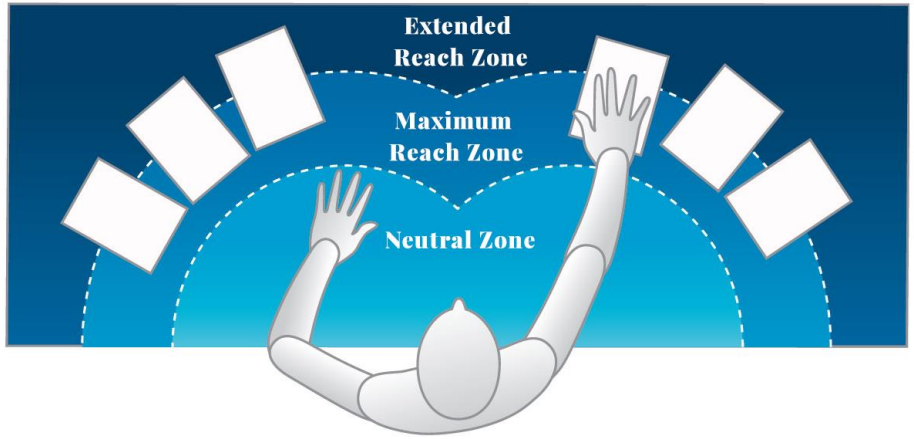
Working area for the arms



Zone 1: High-use items
Zone 2: Medium-use items
Zone 3: Low-use items
Zone 4: Storage only

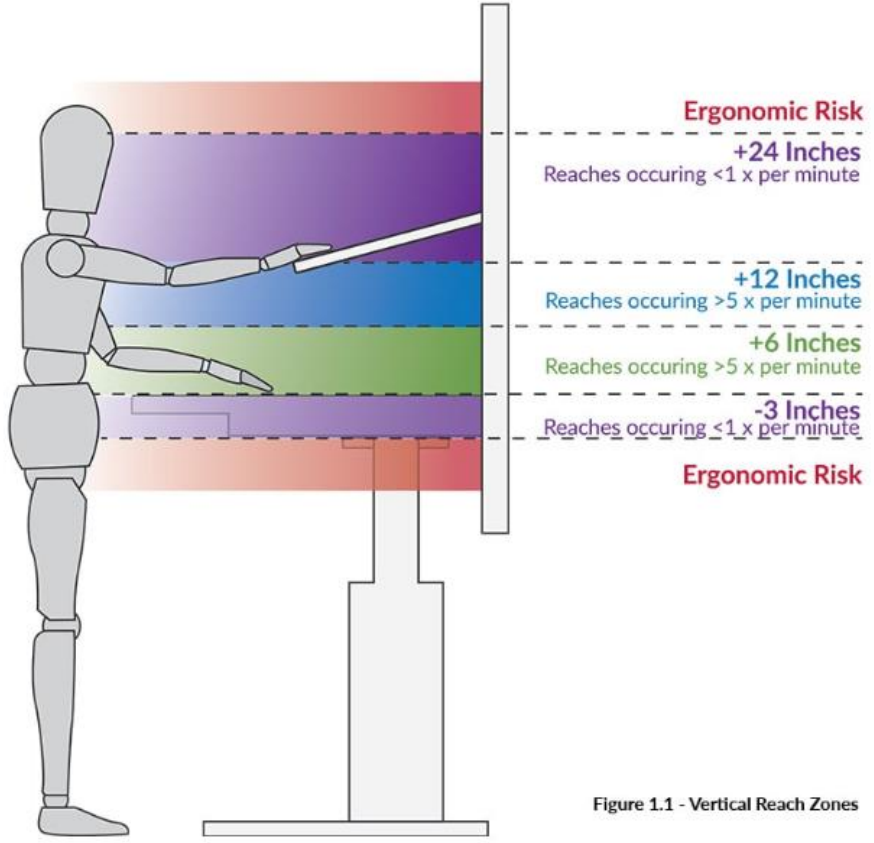


https://www.bostontec.com/designing-an-industrial-workbench-for-adjustability/



https://www.work-fit.com/blog/how-reach-zones-help-manufacturing-employees-lead-safer-lives

Working area for the arms



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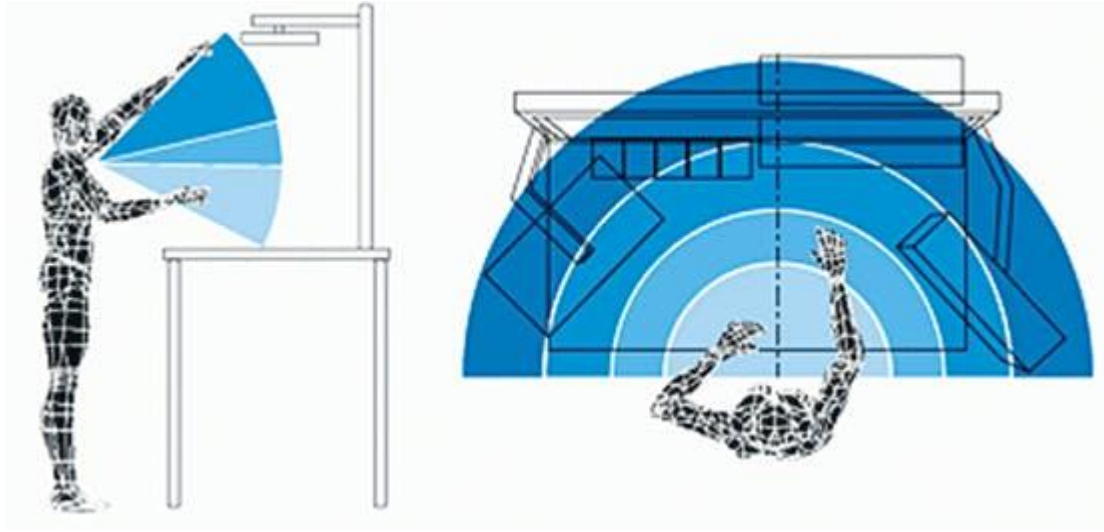

https://www.ehstoday.com/health/article/21915827/four-simple-ergonomic-steps-to-a-more-productive-workplace

Ergonomics principles for workplace design

Design principles for work efficiency:

- All activities should be carried out in *the maximum working area for the arms*.
- Tools, materials, and operating levels should be arranged so that the most common movements are carried out in *the normal working area*.
- The instruments and materials frequently used by the operator should be placed in *the normal working area for the arms.*
- All instruments and materials required by the task must be arranged in the order in which they will be used, so that the trajectory of movements made by the operator is continuous.
- Tools should be prepositioned to increase work efficiency and be easily manipulated by the user.
- The arm movements should be in different directions or symmetrical to increase work efficiency and accuracy.
- Torso twisting action and lifting heavy or bulky objects above shoulders should be prevented. Twisting is especially dangerous when performed in conjunction with lifting.

Tayayari F., Smith J.L., *Occupational Ergonomics. Principles and applications*, Chapman&Hall, 1997, pp.128-135

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Ergonomics principles for workplace design

Design principles for comfort:

- It is recommended that the workplace design allows *alternative body posture,* because prolonged sitting or standing will cause discomfort and OHS problems.
- Consider workplace design recommendations for seated/ standing/ sit-stand workstations
- Awkward posture may cause spine curvature (weaken the abdominal muscle and disturbing the internal organs functions / breathing and digestion), static load on the muscle involved

- The workplace must be designed for the *user population.* All dimensions should be determined using relevant *anthropometric data*.
- The workplace must provide sufficient visibility and clearance for the user.
- The head, arms, shoulders, knees, and legs mobility zones are calculated considering *the highest user (95th percentile)* for whom the workplace is designed.

Anthropometry

Tayayari F., Smith J.L., *Occupational Ergonomics. Principles and applications*, Chapman&Hall, 1997, pp.128-135

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Ergonomics principles for products design

Ergonomics principles for products design

User NEEDS

Utility is the only true measure of the quality of a design!

Efficiency in use

- Work efficiency
- Ease of maintenance
- Minimal effort for use

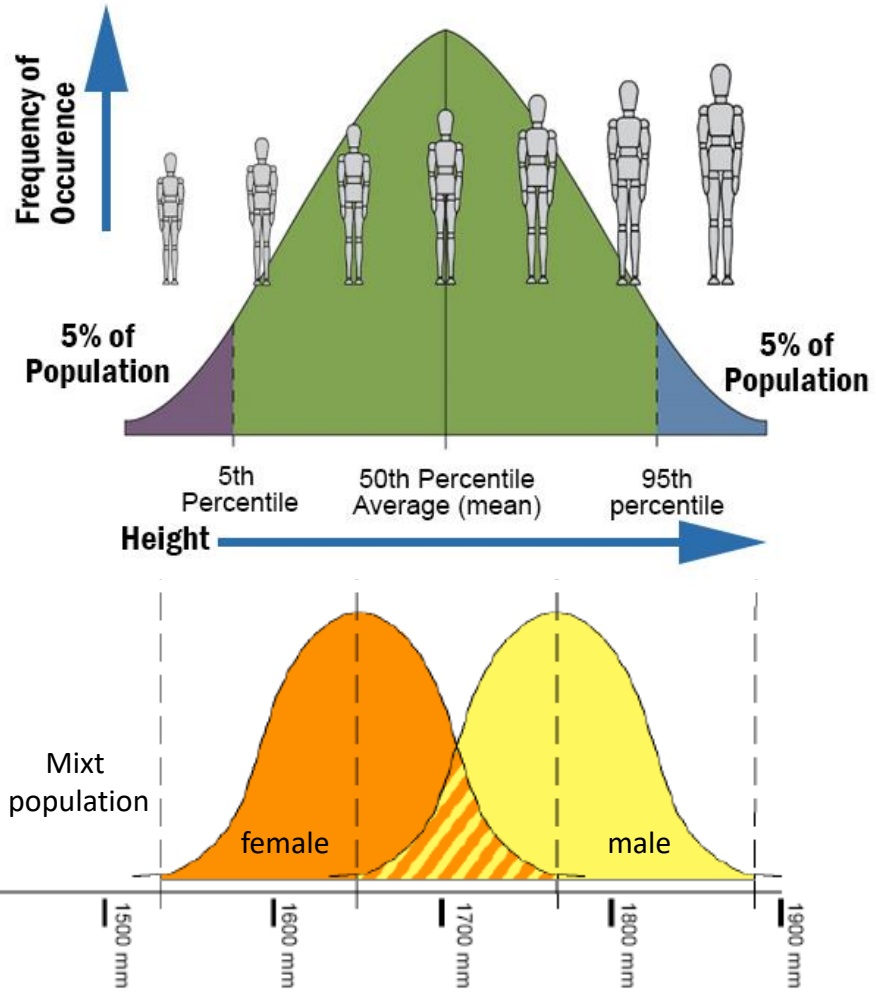
Comfort

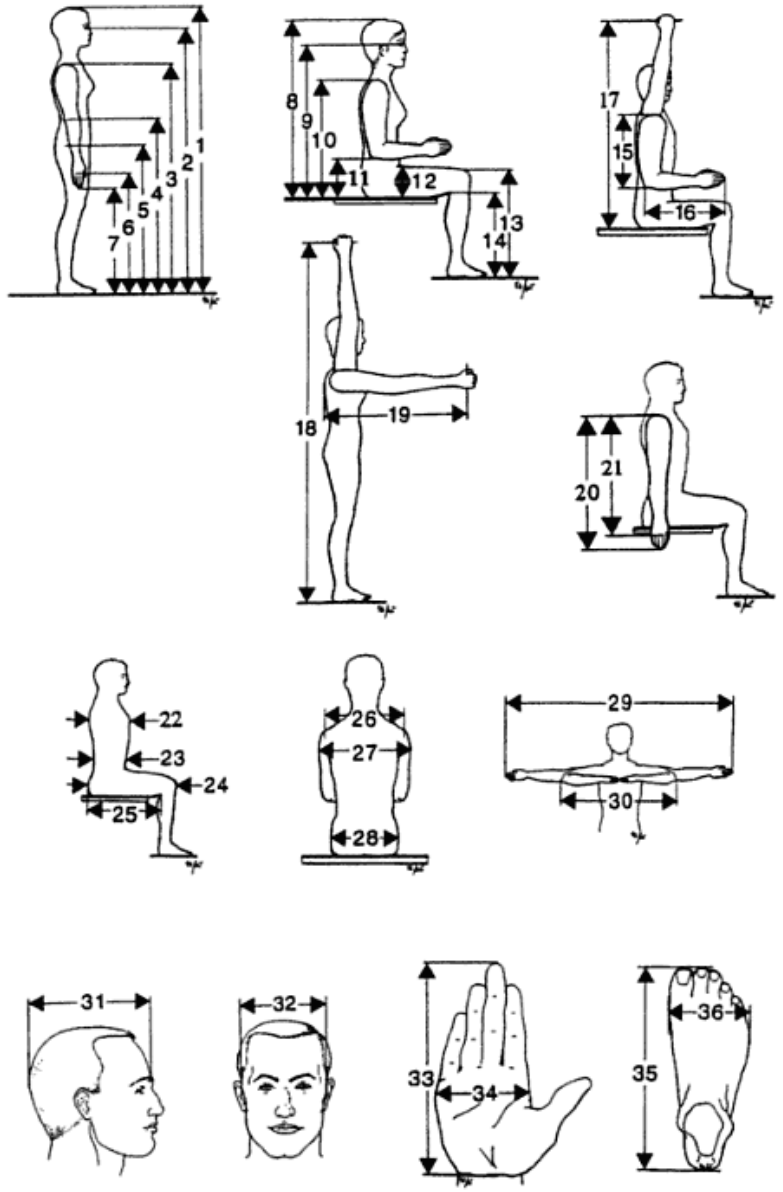
- Psychical and physical aspects related to product use

The look, feel, use and durability of a product help you make a mental determination about a product or service. Basically it lets you evaluate the quality of the item and compare that to the cost. Better ergonomics mean better quality which means you will be more comfortable with the value of the item.

Using anthropometric data in design

Anthropometric data





Karwowski W., Marras W.S., *Occupational Ergonomics: Principles of Work Design*, 2003

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Using anthropometric data in workspace (workstation) and products (worktable) design

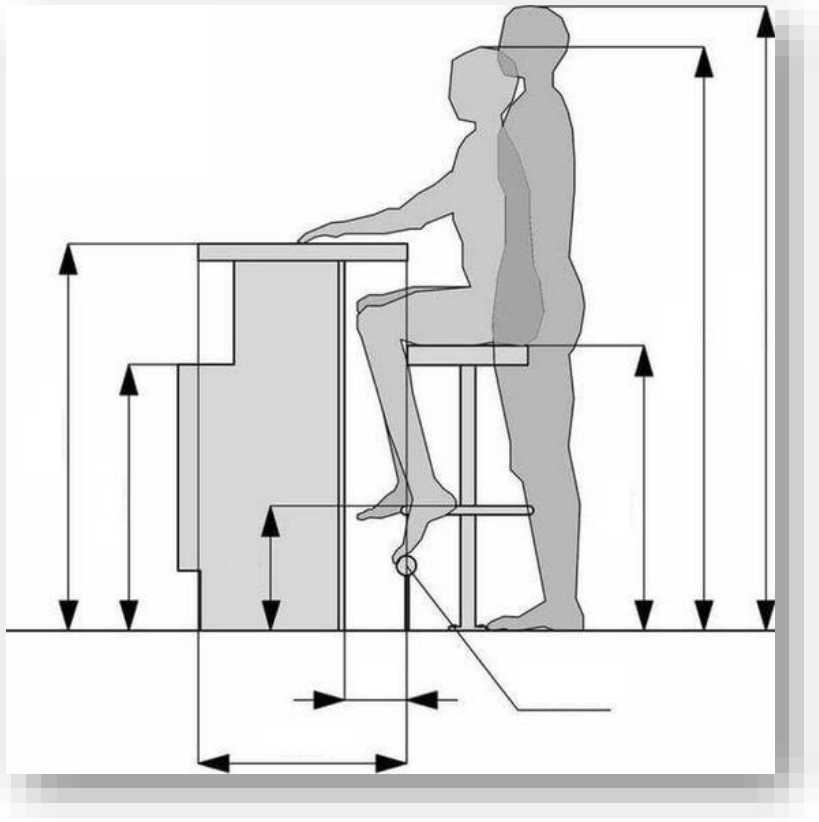
Exercise: $X_p = X_m + z_p \cdot s$

Use the anthropometric database for choosing values of mean: X_m & standard deviation: s

percentilă	a 0,5-a	a 1-a	a 2,5-a	a 5-a	a 10-a	a 16,5-a	a 25-a
(p)	0,005	0,01	0,025	0,05	0,1	0,165	0,25
z_p	-2,575	-2,327	-1,960	-1,645	-1,282	-0,974	-0,675

percentilă	a 75-a	a 83,5-a	a 90-a	a 95-a	a 97,5-a	a 99-a	a 99,5-a
(p)	0,75	0,835	0,9	0,95	0,975	0,99	0,995
z_p	0,675	0,974	1,282	1,645	1,960	2,327	2,575

Tayyari F, Smith J.L., *Occupational Ergonomics. Principles and applications*, 1997



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Workplace design procedure

Workplace design procedure

Steps of design procedure:

1. **Preparation** – all needed information related to the job to be performed in the workplace
2. **Identification of all feasible design alternatives** – all collected information is assembled to link the design components, considering: functional characteristics, their compatibility with design constraints, reliability of design alternatives under expected working conditions.
3. **Selection of the best design alternative** – all identified design solutions are compared. Criteria used for comparation and selection: economy of production, efficiency of operations, easy of maintenance, etc.
4. **Examination of the final alternative** – the selected design solution should be evaluated to ensure that the design objectives are achieved and all constraints are satisfied.

The workplace design problems may not be just of dimensions, they can also be of safety, environmental, psychosocial, or other problems.

Tayayari F., Smith J.L., *Occupational Ergonomics. Principles and applications*, Chapman&Hall, 1997, pp.128-135

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ERGO CHECKLIST

Workstation (re)design objectives:

(1) comfort and wellbeing

(2) work efficiency

(3) sustainability - workstation easy adaptability (for mixed working population, male and female)

A. COMFORT AND WELLBEING Workplace dimensions and body posture assessment		YES	NO	Arguments/ Explanations/ Remarks
A1.	The workplace design allows alternative posture (sitting / standing)			
A2.	The operator position (sitting / standing) is chosen correctly and according to the task.			
A3.	The REBA score is less than or equal to 3.			
A4.	The awkward body posture is avoided.			
A5.	The workstation design allows adjustment of the working level height (between the necessary levels and according to the task).			
A6.	The workstation design alows comfortable reach distances (arms and wrists working areas are good).			
A7.	The workstation design alows operator visibility (head and eye working areas are good).			

B. WORK EFFICIENCY Task efficiency assessment		YES	NO	Arguments/ Explanations/ Remarks
B1.	The activities are carried out in the maximum working area for the arms.			
B2.	The operating level, tools, materials, etc. are arranged so that the most common movements are carried out in the normal working area.			
B3.	The instruments and materials frequently used by the operator are placed in the normal working area for the arms.			
B4.	The instruments and materials required are arranged in the order in which they are used, so that the operator movements are continuous.			
B5.	Tools are prepositioned - for increasing work efficiency and be easily manipulated by the user.			
B6.	The operator arms movements are in different directions or symmetrical - for increasing work efficiency and accuracy.			
B7.	The torso twisting action and lifting heavy or bulky objects above shoulders is not needed during work.			

C. SUSTAINABILITY Social and eco-friendlly design assessment		YES	NO	Arguments/ Explanations/ Remarks
C1.	The workstation design alows the 5th percentile female and the 95th percentile male to adopt a good body posture.			
C2.	The workstation design is user-centered.			
C3.	The workplace design solution takes into account workplace usability and user experience.			
C4.	The project of workplace design has Economic and Financial Feasibility			
C5.	The maintainance costs for the workplace are low.			
C6.	The workstation design is eco-friendly.			
C7.	Workplace waste is recyclable			

Selection of the best design alternative

Criteria used for comparation and selection of best design solution:

- economy of production,
- efficiency of operations,
- easy of maintenance,
- **etc.**

In your opinion, what are the fundamental criteria for selecting the best design solution in sustainability context?

Main topics:

- Long-term financial impact (implementation and maintenance)
- Eco-friendly impact (”smart” use of resources)
- Social impact

Conclusion

Why do we need ergonomics?

Ergonomics is important because it helps people to keep a good health & reduces OHS risks

https://ro.pinterest.com/pin/113082640631215233/

- Good posture is important!
- Otherwise → repetitive strain injury / MSD (musculo-skeletal disorders) / more effort / more time
- Which implicate less efficiency, less focus, illness, absence, etc…

→ Ergonomics processes/ programs/ projects are needed.

https://ergoweb.com/5-essential-elements-of-a-successful-ergonomics-process/

Why do we need ergonomics?

Ergonomics aims to optimize human well-being.

ERGONOMICS

The scientific discipline:

- concerned with *understanding of interactions* among humans and other elements of a system (technology and environment)

The profession:

- that applies theory, principles, data, and methods to *design* in order *to optimize human well-being* and *overall system performance*.

https://hero-health.org

- wellbeing focuses on overall mental and physical health
- the impact of workplace health and wellbeing initiatives can be measured
- *understanding of ergonomics and applying good ergonomic practices and principles is key to successful management of human resources*

What Is Workplace Wellness Ergonomics? (Ergonomic Principles That Supports Employee Health and Wellbeing) – Open Sourced Workplace

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Conclusion

Ergonomics can contribute to:

Quality

Productivity

Comfort

Work diversity

Employees well-being

OHS injuries

Bad health

Human errors

Human effort

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- https://hero-health.org/blog/new-well-being-assessment-provides-a-tool-to-measure-broader-health-and-well-being-impact/
- What Is Workplace Wellness Ergonomics? (Ergonomic Principles That Supports Employee Health and Wellbeing) – Open Sourced Workplace
- https://ergoweb.com/5-essential-elements-of-a-successful-ergonomics-process

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C3 – Design Projects

M3 - User experience UX and usability

Jamk

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Valmet

BOSCH Invented for life

User experience UX and usability

Taking **usability and user experience** into account in product and service development

Matti Siistonen

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What is usability

- Usability vs. ergonomics
- Shackel 1986: Usability

Google:

Usability 932 M hits

Ergonomics 175 M hits
User centered design 216 M hits
Human factors engineering 498 M hits

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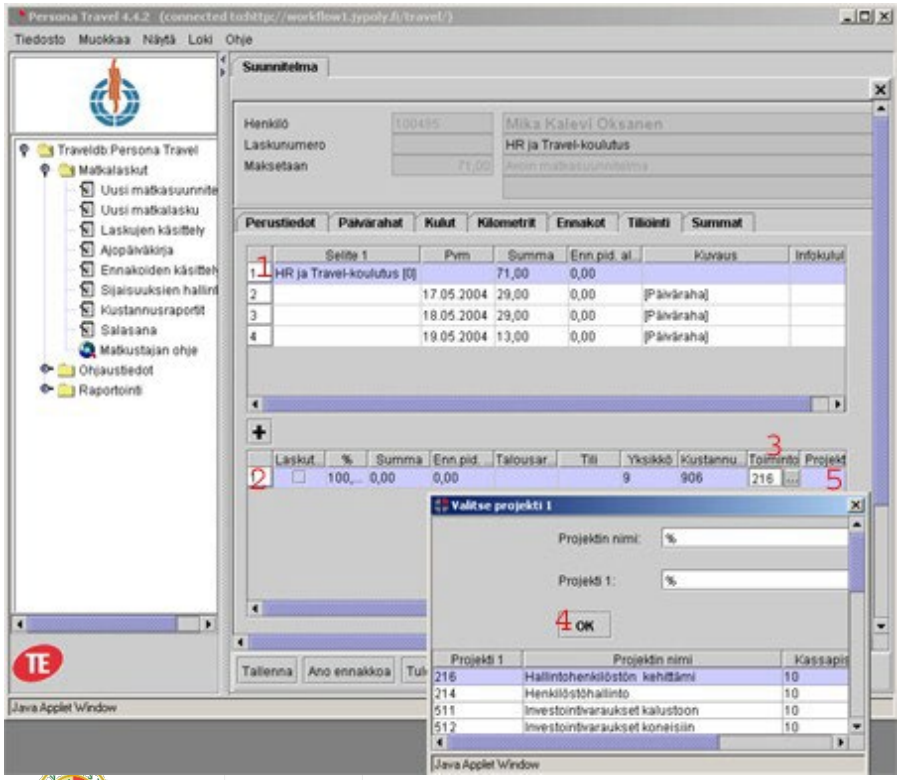
- Usability

  Capability of a product to be used by humans easily and effectively



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User Experience UX

- User experience (UX) refers to the overall experience that a person has when interacting with a product, service, system, or interface. It encompasses all aspects of the user's interaction, including their perceptions, emotions, preferences, and behaviors.

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Customer experience CX

- Customer experience (CX) refers to the overall perception and impression that customers have of a brand, company, or organization based on their interactions and experiences across all touchpoints and throughout the entire customer journey. It encompasses every aspect of a customer's interaction with a business, including pre-purchase, purchase, and post-purchase interactions.

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Customer experience CX

- Providing a positive customer experience is essential for building customer loyalty, increasing customer retention, and generating positive word-of-mouth referrals. Businesses that prioritize customer experience are more likely to succeed in today's competitive marketplace, as satisfied customers are more likely to become repeat customers and brand advocates.

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User Experience

- Design
- Fashion
- Technology
- Price
- Brand
- Usability

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User Experience UX vs Customer Experience CX

- UX and CX both prioritize creating positive user and customer experiences, UX is specific to individual products or interfaces, whereas CX is concerned with the overall customer journey and relationship with a brand. Businesses benefit from addressing both UX and CX to ensure that customers have positive interactions with their products and brand across all touchpoints.

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Not sensible, but, oh, the joy of it!

“Beauty. Charm. Delight. Excitement. Ooh. Aah. Wow! Let me at it.

In the end the iPhone is like some glorious early-60s sports car. Not as practical, reliable, economical, sensible or roomy as a family saloon but oh, the joy…

The iPhone is a digital experience in the literal sense of the word. The user's digits roam, stroke, tweak, tweeze, pinch, probe, slide, swipe and tap across the glass screen forging a relationship with the device that is like no other.”

- **Stephen Fry**

- The Guardian Saturday November 10 2007

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Emotion vs. cognition

- Emotion comes first, then drives the cognitive system.
- If the situation is attractive, the little annoyances can be overlooked.

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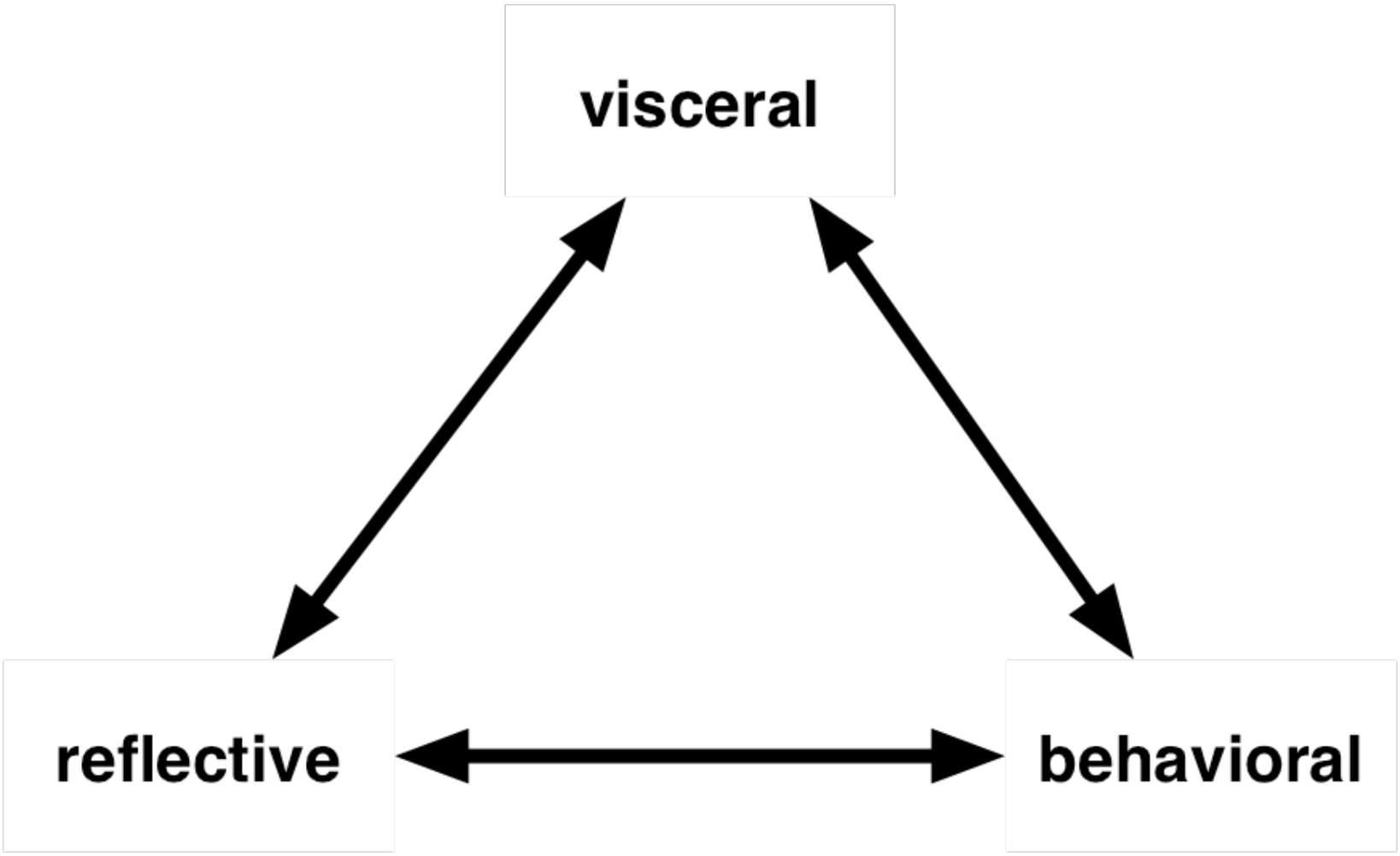
Norman's Three Aspects of Design



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Definition of usability

A product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use
(SFS-EN ISO 13407)

Property of a user interface which combines learnability, memorability, error friendliness and satisfaction
(Nielsen 1993)

Property of a product: Capability to be used by humans easily and effectively
(Shackel 1991)

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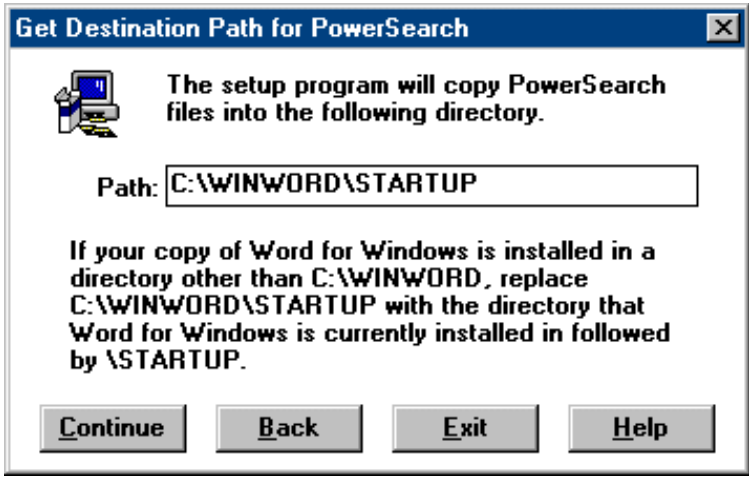
Definitions of usability

- Includes all human-machine interaction



Definition of usability

- It is difficult do define, why a product is usable.

  So we have to find the reasons why the product is not usable and improve the product

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Usability studies

- The basic idea of a usability study is
  - to study mental operations models of users in a specified context of use
  - to study similarity of the user's mental operations models and the operations model of a product. The similarity of these models generates usability of the product.

- The usability of a product can be found out objectively by usability studies only.

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Improving usability

Aeroplane?

NetShop?

CAD-program?

Car?

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Improving usability

- Note: some product are not so easy to learn to use

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Improving usability

- Product evolution vs. revolution

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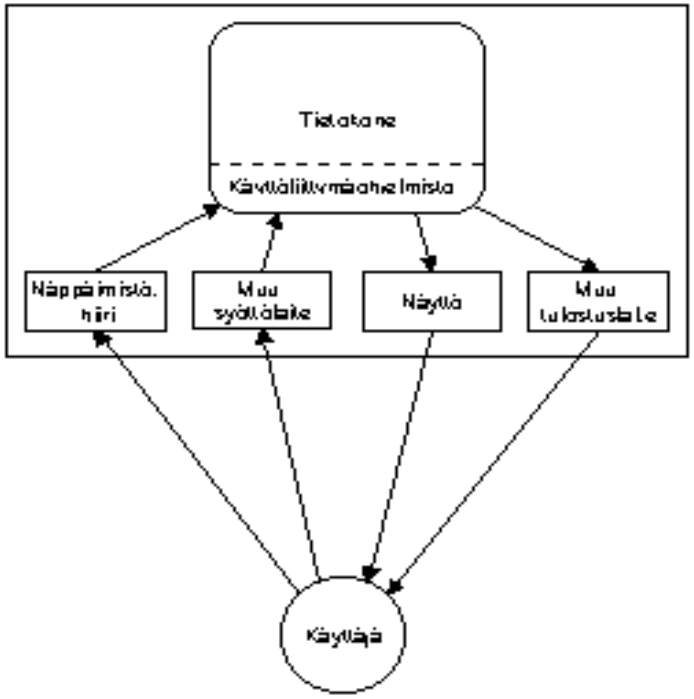
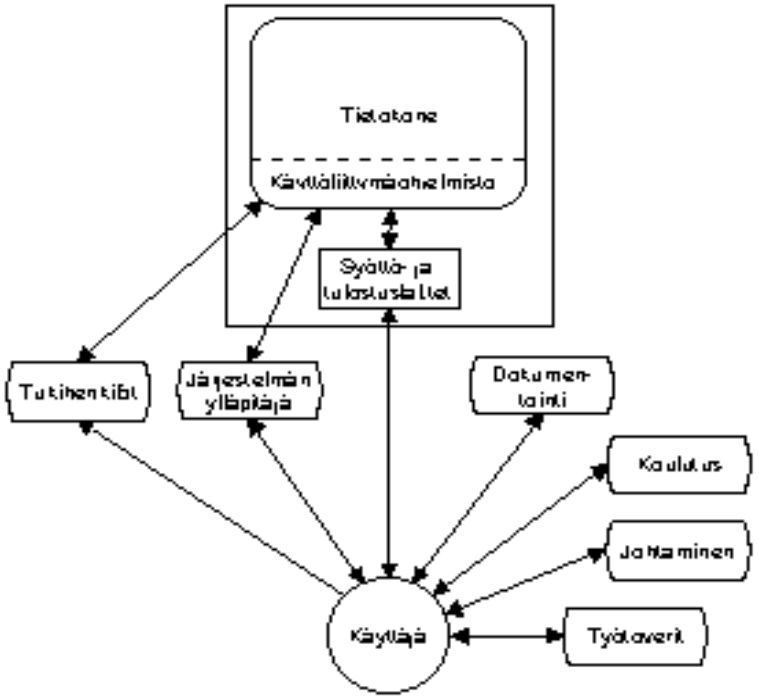
Context!!

Tietokoneen käyttöliittymä käyttäjään



Käyttäjän käyttöliittymä tietokoneeseen



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Why usability is important

Directive rules!

These rules have been valid for more than 30 years!!!:

- software must suitable for the task
- software must be easy to use
- the principles of software ergonomics must be applied

(Council Directive of May 26, 1990, on the minimum safety and health requirements for work with display screen equipment (90/270/EEC), Official Journal of the European Communities, NO. 1, 156, 21.6.1990, 14-18.)

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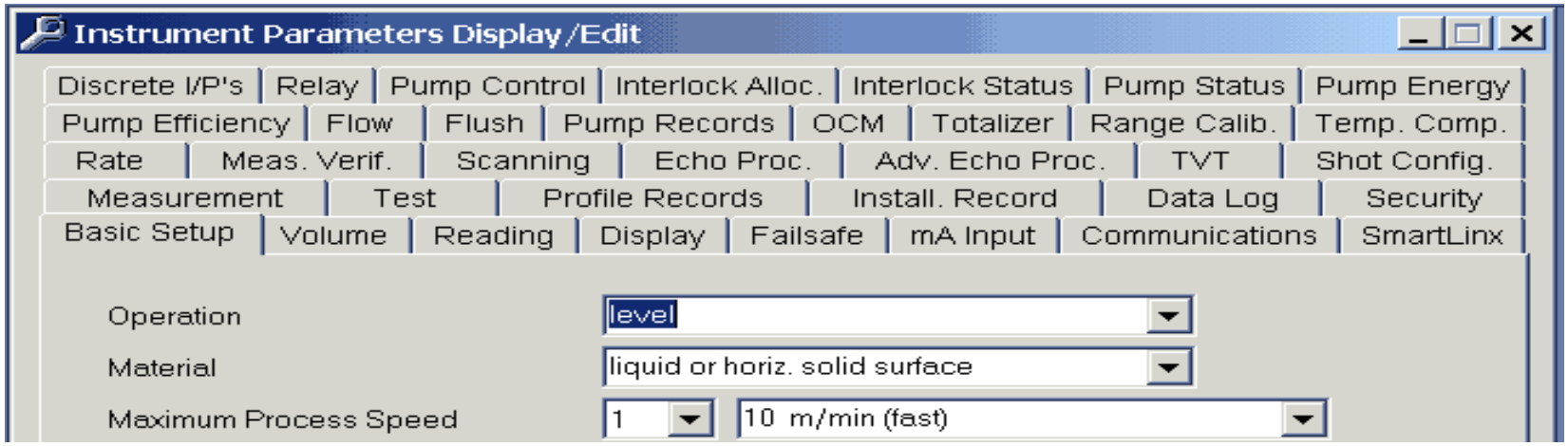
Why usability is important

Safety

- Processes
- Machines
- Services
- Products



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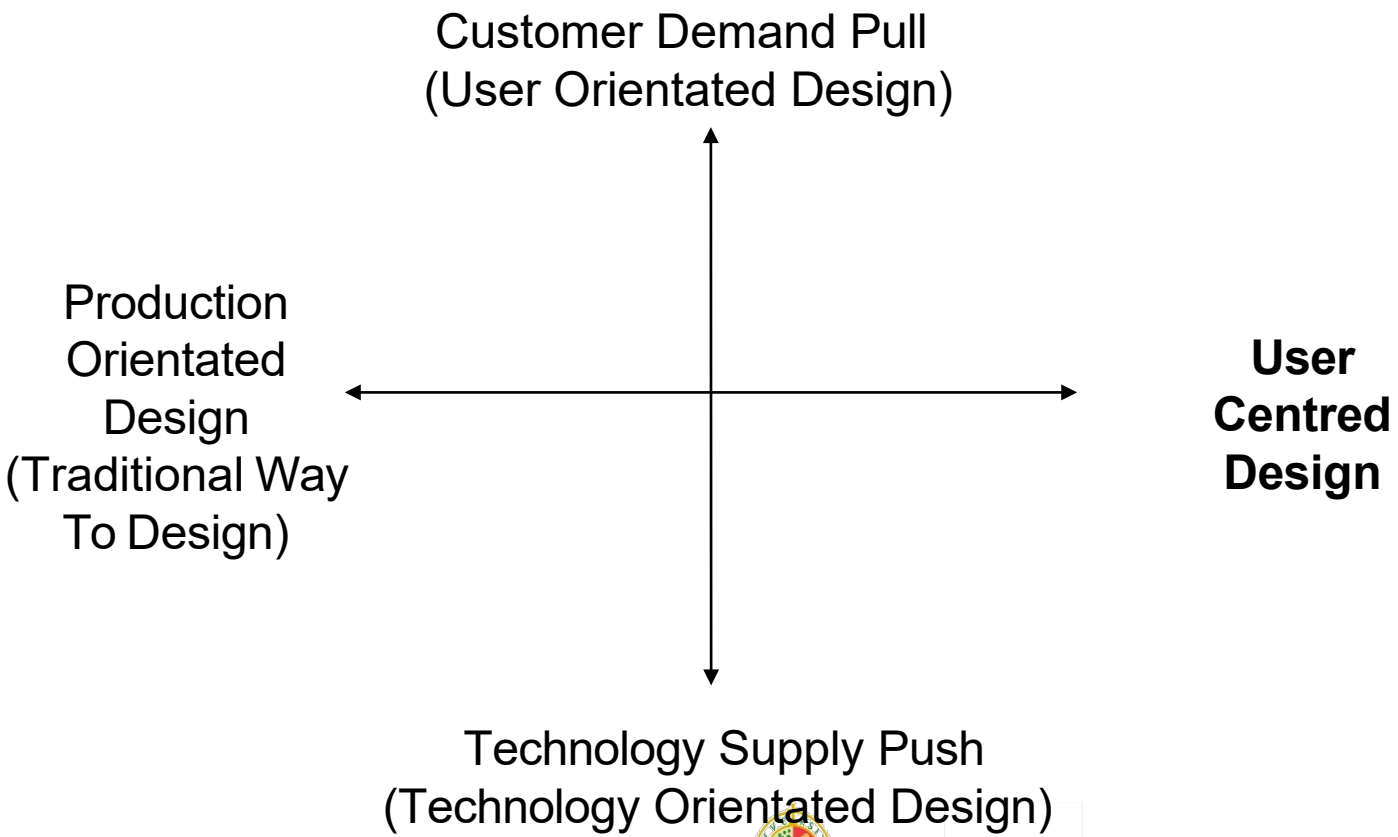
User Centred Design



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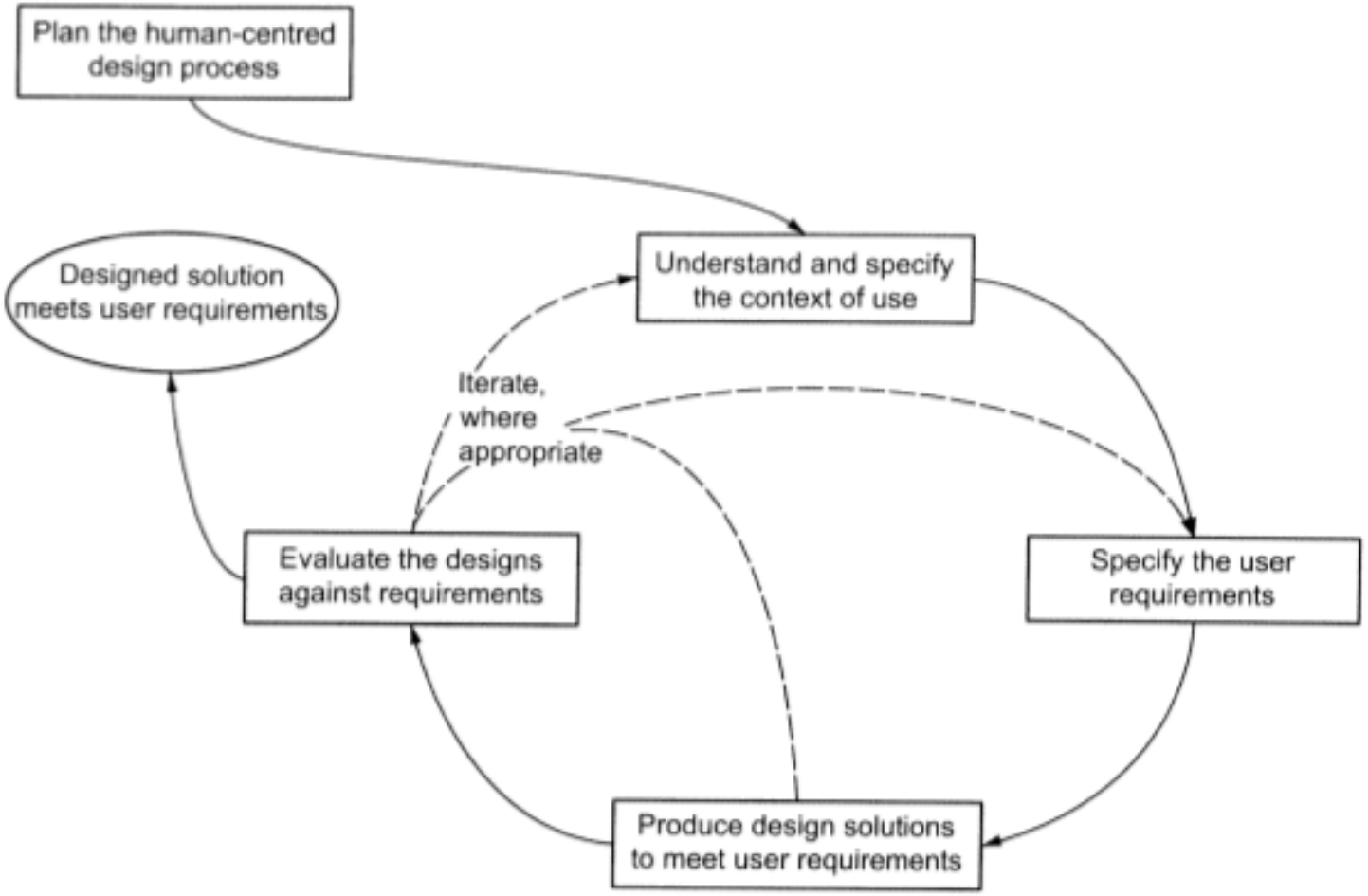
Activities of user (human) centred design – new ISO 9241-210



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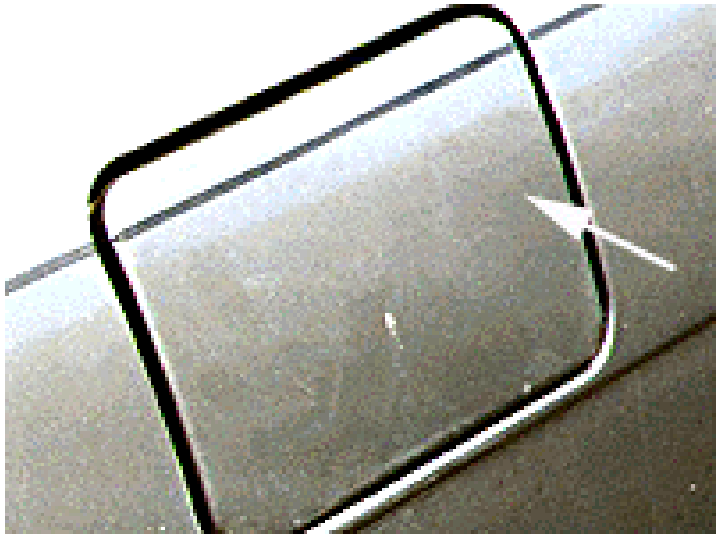
User-artefact interaction



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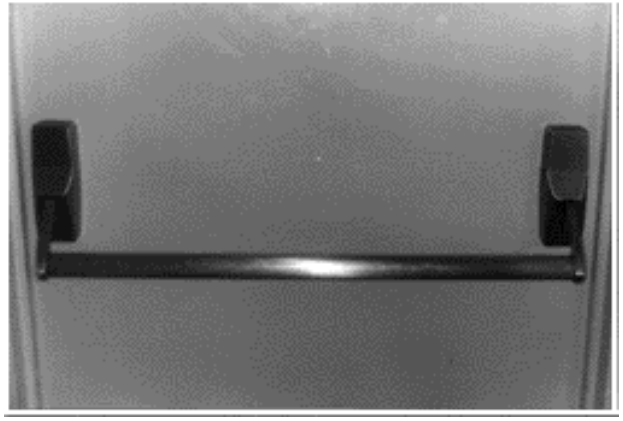
User - artefact interaction



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Usability Case

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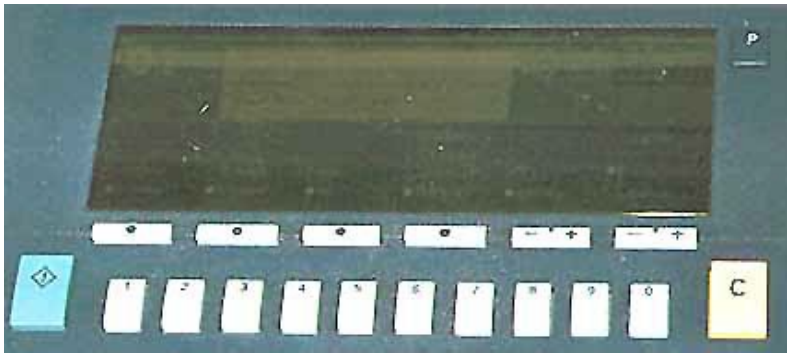
Usability Case

- Xerox



Usabilty Case

Nokia vs. iPhone

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Usability Case

- Microsoft vs. Apple

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Usabilty Case

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Methods

- Heuristic evaluation
- Interviews
- Questionnaires
- Usability testing with a paper prototype
- Field studies
  - Observation
  - Thinking aloud
  - Performance measurement

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Modelling the user interface

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Modelling the user interface

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C3 – Design Projects

M4 - General UI design principles

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International Cooperation Framework for Next Generation Engineering Students

Matti Siistonen

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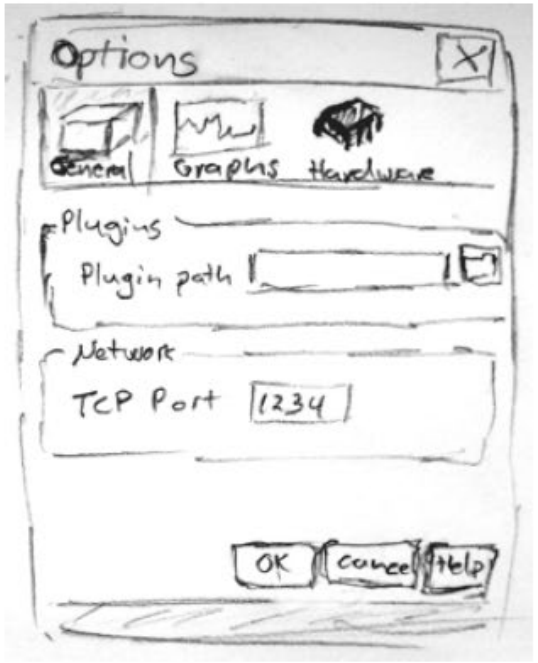
USER INTERFACE AND USER CENTERED DESIGN



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OBJECTIVES

- To suggest some general design principles for user interface design and user centered methodology

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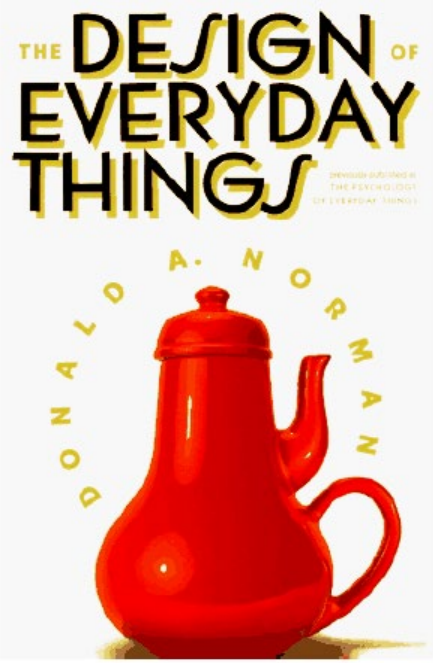
Norman's Principles of Design

The Design of Everyday Things
By Donald Norman



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Norman's Principles of Design

- **Make things visible**
- **Provide a good conceptual model**
  - **Affordance**
  - **Mapping**
  - **Constraints**
  - **Feedback**

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Overview

- Why are some everyday things difficult to understand and use?
- What are Don Norman's principles and how do they apply to the design of everyday things?
- How can we apply Norman's principles to the design of interfaces?

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Why do we remember only the bad?

- A good interface should be transparent
- Bad interfaces cause user frustration
  - "What was this product designer thinking?"

GOOD

BAD

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Psychopathology of Everyday Things

- We are surrounded by many everyday things that have poor *user experience*
  - Programming a thermostat
  - Telephone features we can't remember how to use
  - Photocopiers
    - Face down or face up?
- Many of these things can be difficult to interpret and frustrating to use if they provide no clues or false clues as to how they operate

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Why is user experience and usability important?

- poor usability results in
  - anger and frustration
  - decreased productivity in the workplace
  - higher error rates
  - physical and emotional injury
  - equipment damage
  - loss of customer loyalty
  - costs money

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Examples of Poor Design

- Trapped between doors!
- Handles **afford** pulling
- Using a flat plate would **constrain** the user to push

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NORMAN'S PRINCIPLES OF DESIGN
EXCELLENT PRINCIPLES FOR DESIGNING PRODUCTS

- Make things visible
- Provide a good conceptual model
  - **Affordance**
  - **Mapping**
  - **Constraints**
  - **Feedback**

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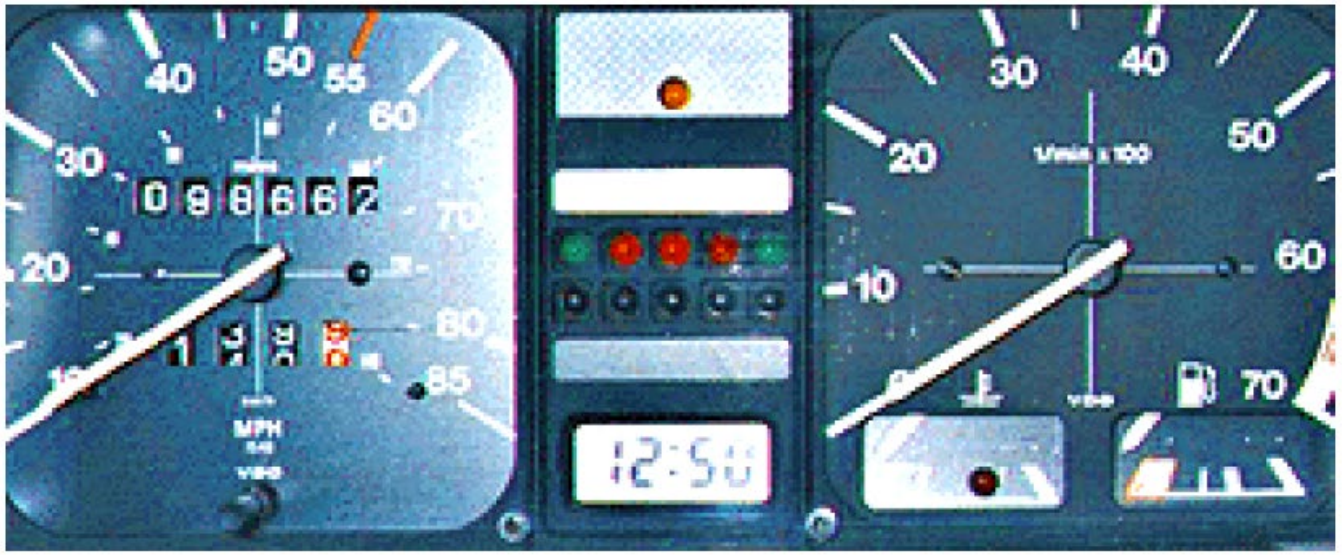
HOW FAST ARE WE GOING?



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VISIBILITY

- The correct parts must be visible and they must convey the correct message
- Natural signals are naturally interpreted
- Visibility problems occur when clues are lacking
- Just by looking the user should know
  - State of the system
  - Possible actions
- Don’t violate these principles to make something “look good”!

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PLEASE PUSH SLOWLY!

- Wonder why doors are made out of glass?

Evidently someone was smacked…

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GOOD CONCEPTUAL MODEL

- A good conceptual model allows us to predict the effects of our actions
- Without a good model we operate blindly
  - Simply follow rules without understanding a reason
  - No understanding of cause or effect
  - No recourse when something breaks

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AFFORDANCES

- The affordances of an object determine, naturally, how it can be used
  - Button affords pushing
  - Handle affords grasping
  - Chair affords sitting
  - Knob affords turning
- Just by looking at the object, a user should know how to use it
  - Example: The doors with handles to push, mop sink

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THE CASE OF THE MISTAKEN URINAL

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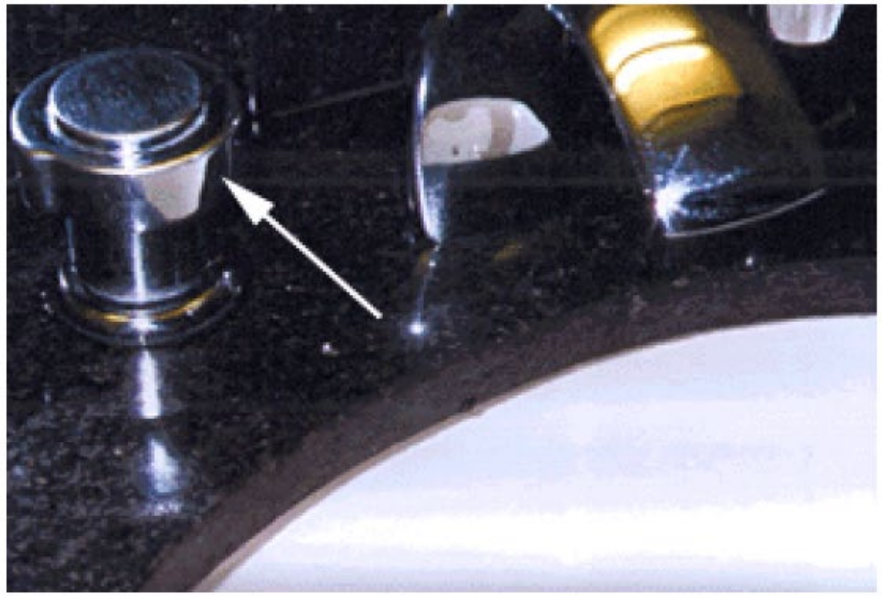
AFFORDANCE OF THIS HANDLE?



Difficult to get a grip when slippery

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HOW DO YOU OPEN THIS DRAWER?

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MAPPING

- Controls and displays should exploit natural mapping
- Natural mapping takes advantage of physical analogies and cultural standards
  - Physical: Steering wheel
  - Cultural: red means stop, green means go

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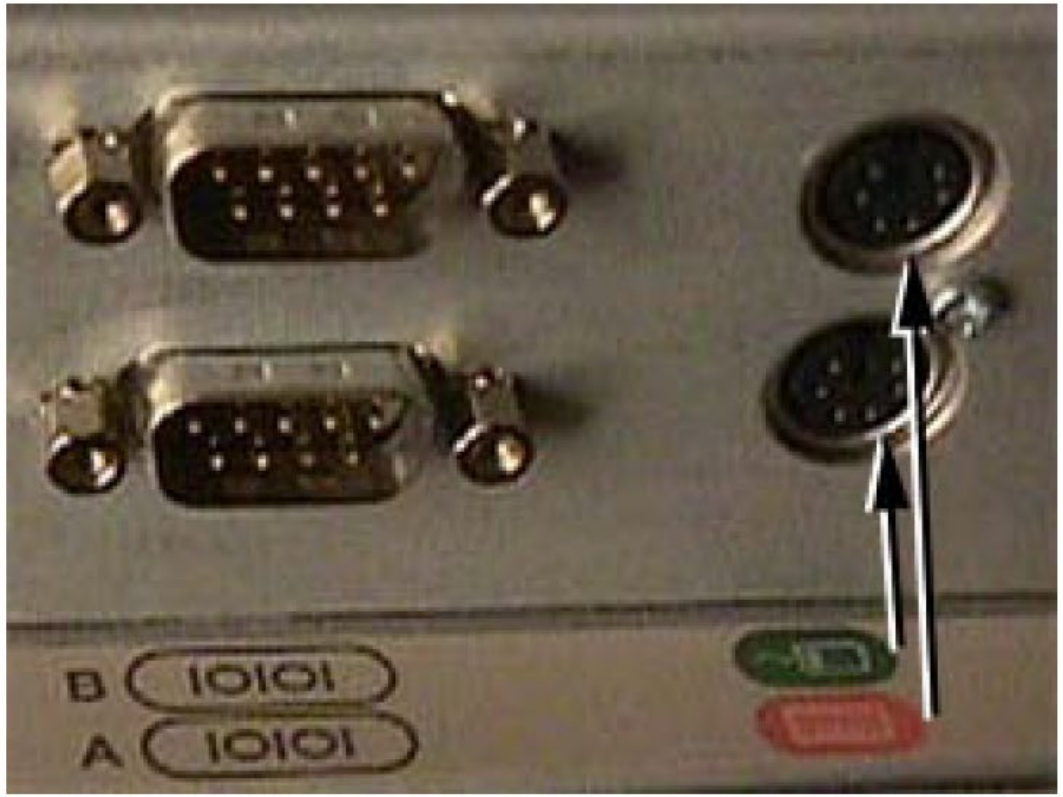
EARLIER DAYS: MOUSE OR KEYBOARD?



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WHAT KNOB GOES WHERE?

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YELLOW STREET LIGHTS

- Possible to confuse with stoplight

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CONSTRAINTS

- Constraints limit the ways in which something can be used
- Constraints can be
  - Physical
  - Semantic
  - Cultural
  - Logical

Paper scissors

Barber scisssors

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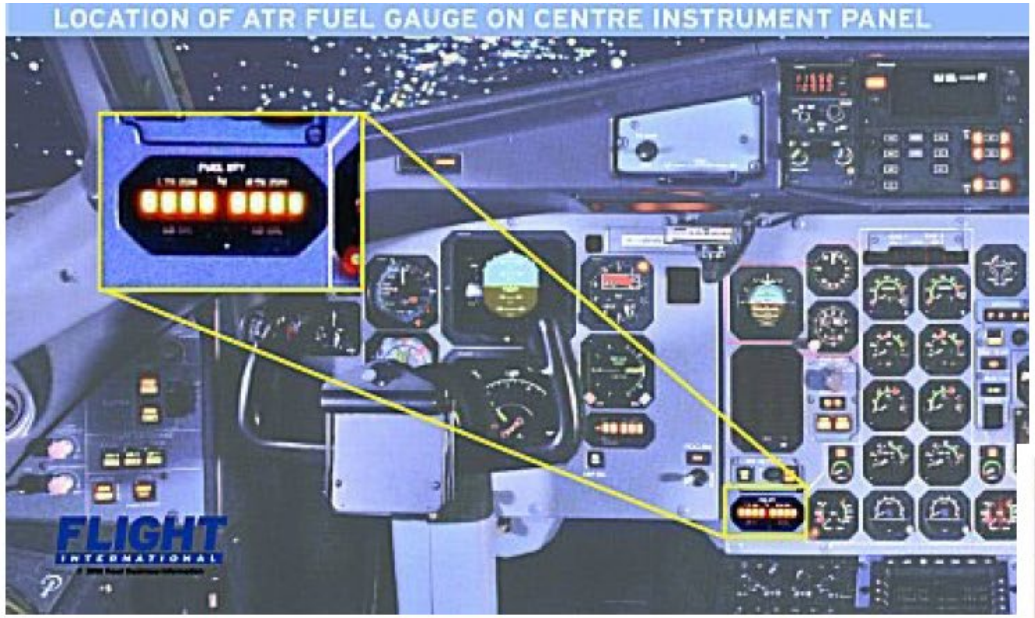

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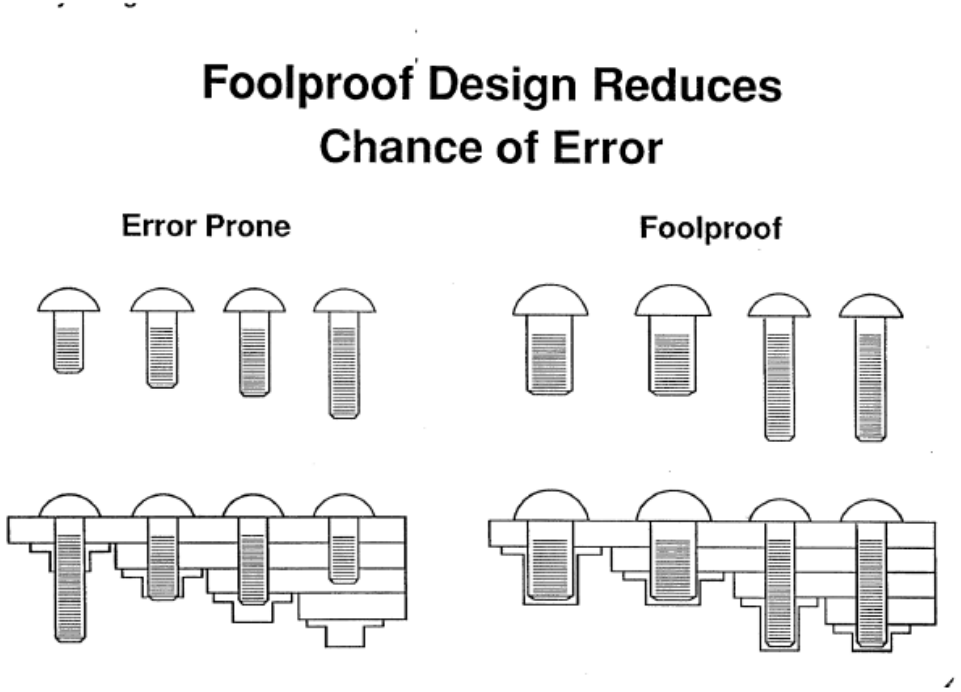
USER INTERFACE DESIGN



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FEEDBACK

- Feedback is sending back to the user information about what action has actually been done
- Visibility of the effects of the operation tell you if something worked correctly
- Systems should be designed to provide adequate feedback to the users to ensure they know what to do next in their tasks

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FEEDBACK EXAMPLES

- Telephone button press tones
  - Telephone clicks
- Clicker on your turn signal
- Animated icon while waiting for a web page to load

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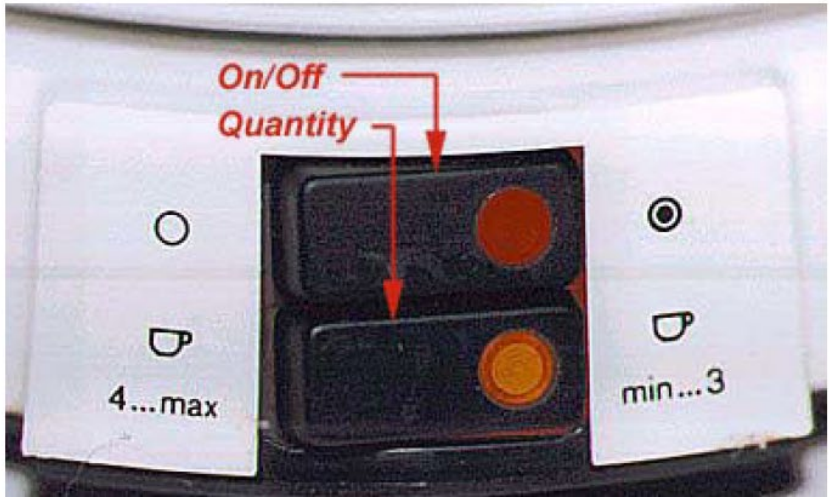
MORE OR LESS COFFEE?

- Does the light on the bottom indicate 4-max cups, or min-3 cups?



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LARSON'S DOG EFFECT

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SAME WITH SOFTWARE

Thank you for registering! We appreciate your business.
To activate your software, you will be sent an email key. After you have received the key then you will be able to click here and you can then proceed with the activation process.

Blah blah blah

NORMAN'S PRINCIPLES OF DESIGN

- Make things visible
- Provide a good conceptual model
  - Affordance
  - Mapping
  - Constraints
  - Feedback

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•Case study: PS controller

•Good or bad usability

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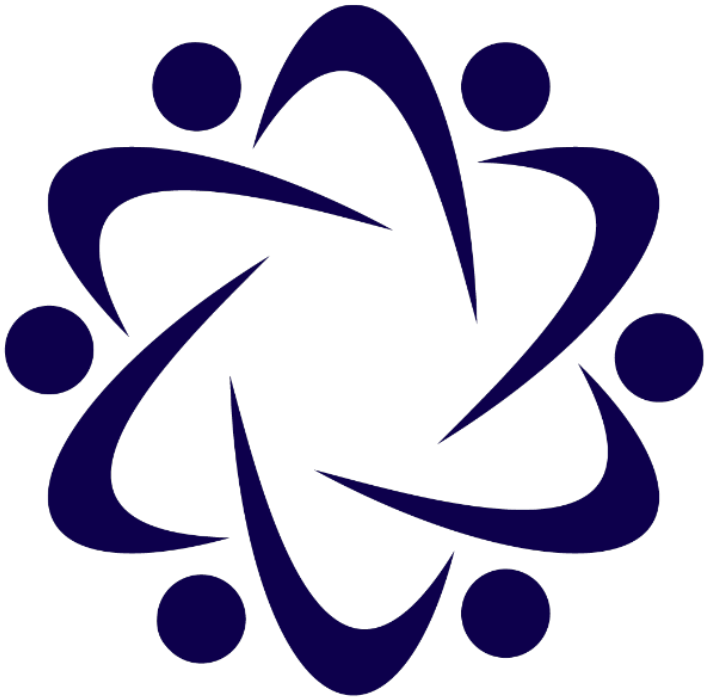

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C3 – Design Projects

M5 – Economic and Financial Feasibility of Projects

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Jamk University of Applied Sciences

University of Jaén

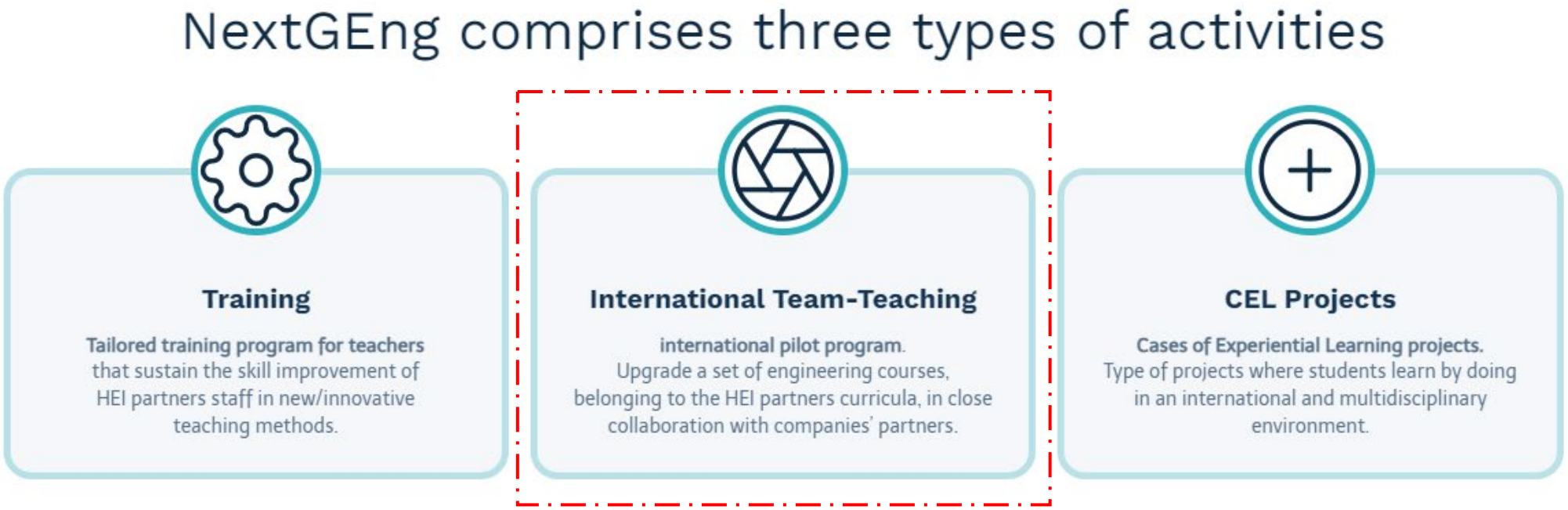
Integracion Sensorial y Robotica

Valmet Technologies Oyj

Rober Bosch SRL

About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



Economic and Financial Feasibility of Projects

From project idea and design….

…to project economic and financial feasibility

Economic and Financial Feasibility of Projects

Upon completion of this module, the student will be able to:

1) know the main economic parameters that enable the assessment of the economic viability of a project.
2) know the basic techniques of economic analysis of projects.
3) apply these techniques to determine the economic viability of a project.
4) determine the financial feasibility of a project.

Content

- Introduction
- Economic evaluation criteria for projects
- Statics Methods vs. Dynamic Methods
- Economic viability vs. Financial feasibility

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Introduction

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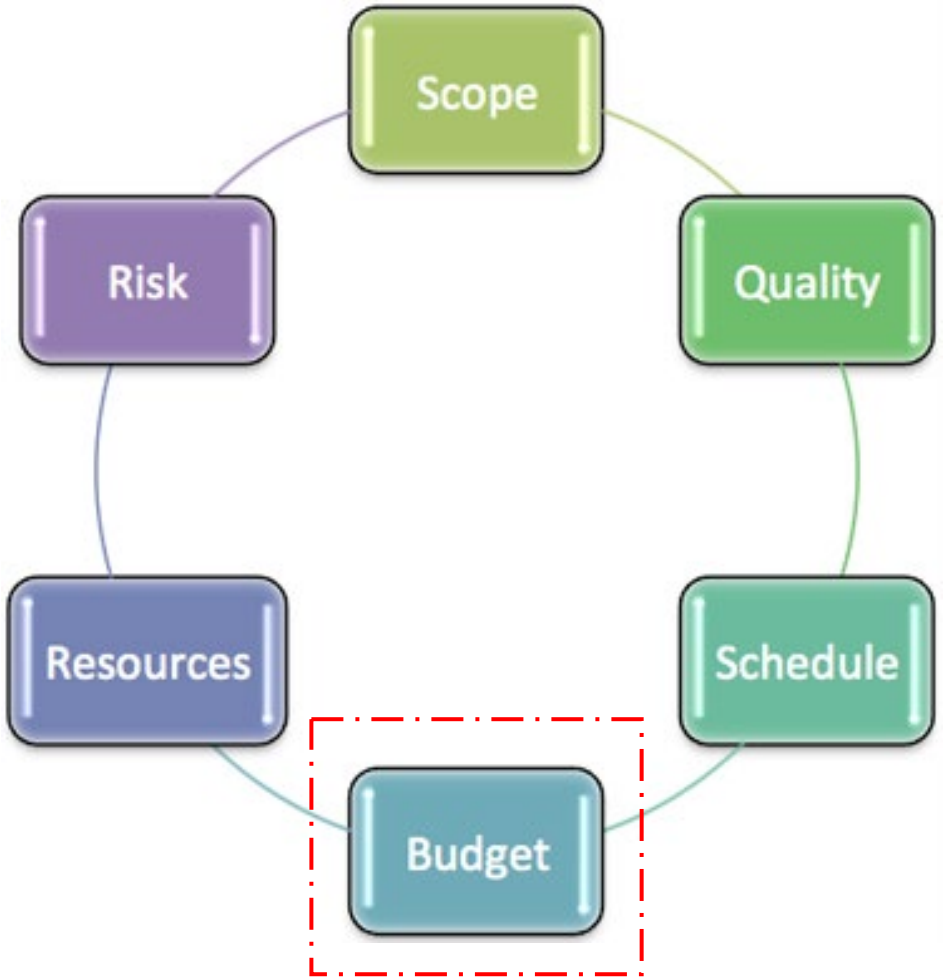
Introduction

Influencing factors when designing a project



Any project is an investment!

Introduction

If any project is an investment….

Influencing factors when designing a project

+

Influencing factors when running a project (after completion)

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Introduction

Influencing factors when designing a project

+

Influencing factors when running a project (after completion)

Land-Positive Photovoltaic Solution

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Economic evaluation criteria for projects

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Economic evaluation criteria for projects

- The criteria for the economic evaluation of projects analyse the Project (investment) from the profitability point of view. They compare the initial cost of the Project (K) with the spected benefits (Bf) throughout the lifecycle of the Project (n)
- The key factor is the **CASH-FLOW (Q)**. It is defined as the difference between the economic incomes and outcomes throughout the lifecycle of the Project (n)

- **Static Methods**

  - Do not take into consideration the temporary variation of the value of the money

- **Dynamic Methods**

  - Consider the the temporary variation of the value of the money

Economic evaluation criteria for projects

Cash-Flow

- The cash-Flow (Q) of a project is defined as the difference between the collection of payment rights (economic incomes, I) and the payments or Expenditures undertaken (economic outcomes, E) throughout the lifecycle of the Project (n).

$$Q_n = I_n - E_n$$

- In a certain period (j), the expenditures of a project are Ej, whereas the total incomes obtained in that certain period are Ij. Therefore, the cash-Flow of a project in that period is:

$$Q_j = I_j - E_j$$

Economic evaluation criteria for projects

Cash-Flow

$$¿Q_n = \sum_{j=1}^{n} Q_j\ ?$$

Year		Project A
0	Investment	-50 000 €
End of project	Cash flow	75 000 €

Year		Project A
0	Investment	-50 000 €
1	Cash flow	10 000 €
2	Cash flow	20 000 €
3	Cash flow	20 000 €
4	Cash flow	15 000 €
5	Cash flow	10 000 €

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Economic evaluation criteria for projects

Cash-Flow

$$¿Q_n = \sum_{j=1}^{n} Q_j\ ?$$

Year		Project A
0	Investment	-50 000 €
End of project	Cash flow	75 000 €

Year		Project A
0	Investment	-50 000 €
1	Cash flow	30 000 €
2	Cash flow	-10 000 €
3	Cash flow	- 5 000 €
4	Cash flow	65 000 €
5	Cash flow	45 000 €

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Statics Methods vs. Dynamic Methods

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Statics Methods vs. Dynamic Methods

Static Methods

- Do not take into consideration the temporary variation of the value of the money

- **Payback time**
- **Return of Investment**

Statics Methods vs. Dynamic Methods

Static Methods → Payback time (r)

The (simple) payback time is the **number of periods that we will need to recover the initial investement** (K) according to the cash flows (Qj) generated in the project

$$K = \sum_{j=1}^{n} Q_j$$

If the cash flows are the same in all the periods:

$$r = \frac{K}{Q}$$

If the cash flows are not the same, the mean value could be considered:

$$r = \frac{K}{Q_m}$$

Statics Methods vs. Dynamic Methods

Static Methods → Payback time (r)

Year		Project A	Project B
0	Investment	-50 000 €	-30 000 €
1	Cash flow	10 000 €	5 000 €
2	Cash flow	20 000 €	5 000 €
3	Cash flow	20 000 €	10 000 €
4	Cash flow	15 000 €	10 000 €
5	Cash flow	10 000 €	20 000 €

Payback (simple)	3 years	4 years

Statics Methods vs. Dynamic Methods

Static Methods → Return of Investment

The return of the Investment (**ROI**) is the **average Benefit generated by the project.** It is formulated as a percentage of the investment.

$$ROI = \frac{BF_{total}}{nK} = \frac{-K + \sum_{j=1}^{n} Q_j}{nK}$$

Statics Methods vs. Dynamic Methods

Static Methods → Return of Investment

Año		Project A	Project B
0	Investment	-50 000 €	-30 000 €
1	Cash flow	10 000 €	5 000 €
2	Cash flow	20 000 €	5 000 €
3	Cash flow	20 000 €	10 000 €
4	Cash flow	15 000 €	10 000 €
5	Cash flow	10 000 €	20 000 €

Total Benefit	25 000 €	20 000 €
Average Benefit	5 000 €	4 000 €
Return of the Investment (ROI)	10.0%	13.3%

Statics Methods vs. Dynamic Methods

Dynamic Methods

- Is the money worth the same today as it will be next year?
- If I have 1000 € today, how much can I have next year?
- If I am promised 1000 € next year, is it better or worse than having 1000 € today?
- Is it better or worse than having 950 € today?
- What is the interest on money?
- How much is the normal interest on money today?

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Statics Methods vs. Dynamic Methods

Dynamic Methods

- Consider the temporary variation of the value of the money

- **Net Present Value**
- **Benefit-Cost Ratio**
- **Discounted Payback Time**
- **Internal Rate of Return**

Statics Methods vs. Dynamic Methods

Dynamic Methods

- The available capital (money) has a certain value in each temporary moment. In order to know the prospective value of this capital, it is neccesary to calculate its future value. Likewise, in order to acknowledge the current value of a future capital, it is needed to calculate the present value of this money.

$$V_F = V_0 \cdot (1+i)^n$$

Current Value	100 €
n	10 years
i	4%
$(1+i)^n$	1.48 %
Future Value	148.02 €

$$V_0 = \frac{V_F}{(1+i)^n}$$

Future Value	100 €
n	10 years
i	4%
$(1+i)^n$	1.48 %
Current Value	67.57 €

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Statics Methods vs. Dynamic Methods

(discount rate)

- The discount rate is a mathematical coefficient by which present values are affected to obtain future values and vice versa.
- It is related to interest rates and to the evaluation period considered.
- We can take into account the effect of inflation:

$$(1 + i) = (1+i_n)\,(1+g)$$

Statics Methods vs. Dynamic Methods

NET PRESENT VALUE (NPV)

- The NPV represents the net profit generated by the project, obtained by financial equivalence at time zero.

$$NPV = -K + \sum_{j=1}^{n} \frac{Q_j}{(1+i)^j}$$

- The NPV represents the net profit generated by the project, obtained by financial equivalence at time zero.

$$NPV = -\sum \frac{K_j}{(1+i)^j} + \sum_{j=1}^{n} \frac{Q_j}{(1+i)^j}$$

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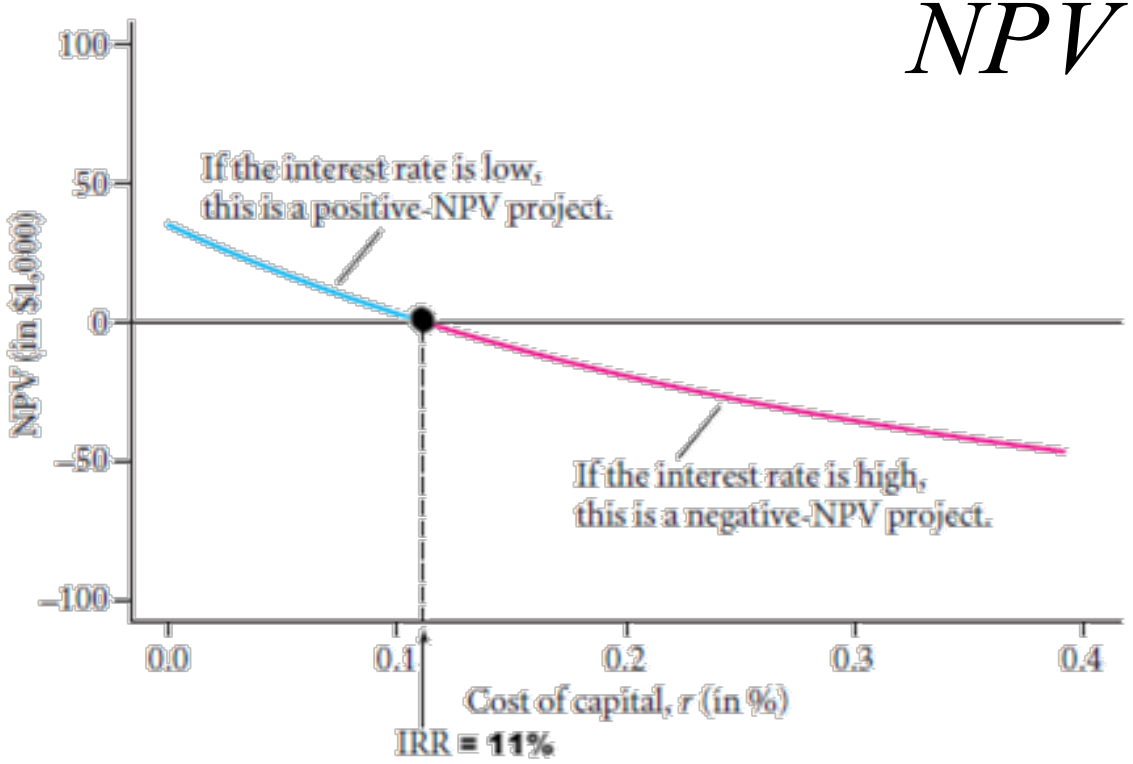
Statics Methods vs. Dynamic Methods

NET PRESENT VALUE (NPV)

$$NPV = -K + \sum_{j=1}^{n} \frac{Q_j}{(1+i)^j}$$



Statics Methods vs. Dynamic Methods

NET PRESENT VALUE (NPV)

$$NPV = -K + \sum_{j=1}^{n} \frac{Q_j}{(1+i)^j}$$

				Project A	Project B
			Updating index	Updated Cash-Flows	Updated Cash-Flows
Year	**Project A**	**Project B**	**$(1+i)^n$**	**$Q/(1+i)^n$**	**$Q/(1+i)^n$**
0	-50 000 €	-30 000 €		-50 000	-30 000
1	10 000 €	5 000 €	1.050	9 524	4 762
2	20 000 €	5 000 €	1.103	18 141	4 535
3	20 000 €	10 000 €	1.158	17 277	8 638
4	15 000 €	10 000 €	1.216	12 341	8 227
5	10 000 €	20 000 €	1.276	7 835	15 671
Discount rate		***5.0%***			
NPV				**15 117 €**	**11 833 €**

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Statics Methods vs. Dynamic Methods

BENEFIT/COST RATIO

This criterion logically discriminates between two investments with the same NPV in favor of the one with the lower payout.

Benefit-Cost Ratio Formula

$$\text{Benefit-Cost Ratio} = \frac{\text{PV of Expected Benefits}}{\text{PV of Expected Costs}}$$

$$BCR = \frac{NPV + K}{K} = \frac{1}{K}\sum_{j=1}^{n}\frac{Q_j}{(1+i)^j}$$

$$\overline{B}CR = \frac{1}{nK}\sum_{j=1}^{n}\frac{Q_j}{(1+i)^j}$$

Statics Methods vs. Dynamic Methods

DISCOUNTED PAYBACK TIME (DPBT)

The discounted payback period (**DPBT**) of an investment is understood as the number of periods that elapse from the initial moment of a project until the sum of the discounted cash flows is exactly equal to the disbursement made.

$$K = \sum_{j=1}^{r} \frac{Q_j}{(1+i)^j}$$

It is a parameter that indicates the liquidity of the project

Statics Methods vs. Dynamic Methods

INTERNAL RATE OF RETURN

The internal rate of return (IRR) is that discount rate, r, which makes the NPV zero.

Only projects that meet the "feasibility" condition will be viable: IRR > i, where i is the interest rate that corresponds to the "cost of capital".

The higher the IRR, the better the investment.

$$NPV = 0 = -K + \sum_{j=1}^{n} \frac{Q_j}{(1+IRR)^j}$$

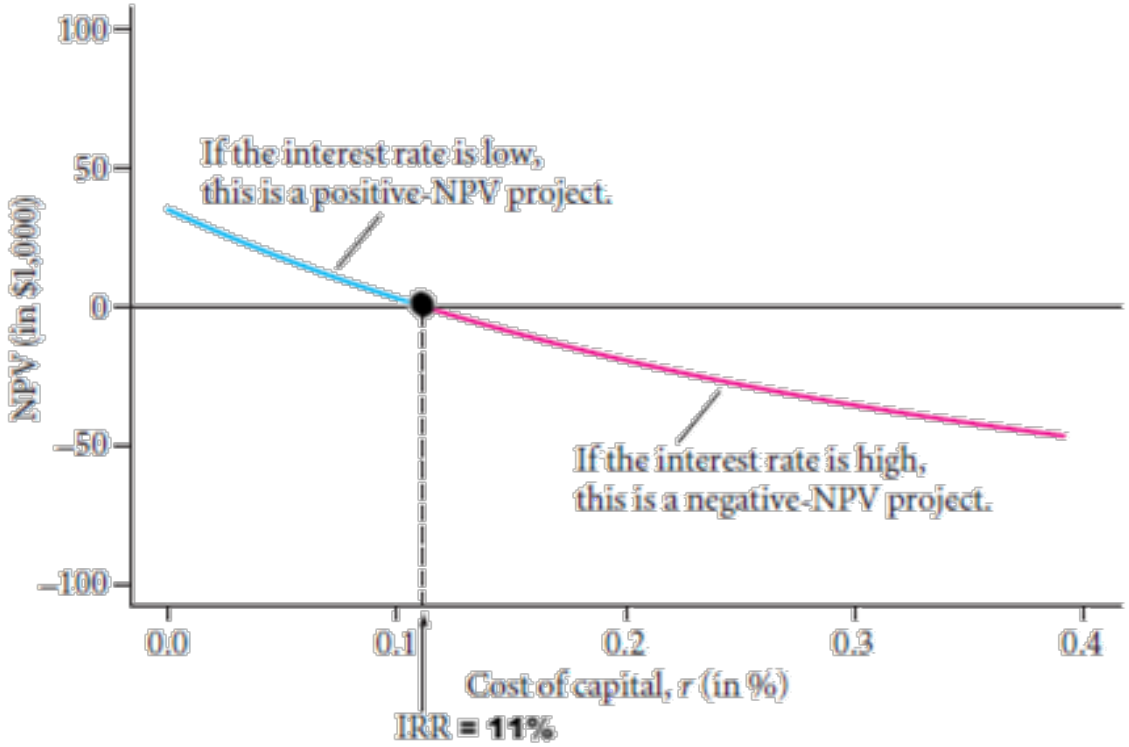
$$K = \sum_{j=1}^{n} \frac{Q_j}{(1+IRR)^j}$$

Statics Methods vs. Dynamic Methods

INTERNAL RATE OF RETURN

$$NPV = 0 = -K + \sum_{j=1}^{n} \frac{Q_j}{(1+IRR)^j}$$

$$K = \sum_{j=1}^{n} \frac{Q_j}{(1+IRR)^j}$$



Statics Methods vs. Dynamic Methods

Year	Project A	Project B	$(1+i)^n$	$Q/(1+i)^n$	$Q/(1+i)^n$	∑	∑
0	-50 000 €	-30 000 €		-50 000	-30 000		
1	10 000 €	5 000 €	1.050	9 524	4 762	-40 476	-25 238
2	20 000 €	5 000 €	1.103	18 141	4 535	-22 336	-20 703
3	20 000 €	10 000 €	1.158	17 277	8 638	-5 059	-12 065
4	15 000 €	10 000 €	1.216	12 341	8 227	7 282	-3 838
5	10 000 €	20 000 €	1.276	7 835	15 671	15 117	11 833
Discount rate		***5.0%***					

NPV	**15 117 €**	**11 833 €**
BCR	**1.3**	**1.4**
DPBT	**4 y**	**5 y**
IRR	**15.43%**	**15.40%**

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Statics Methods vs. Dynamic Methods

EXAMPLE

Land-Positive Photovoltaic Solution

PROTOTYPE

Economic viability vs. Financial feasibility

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Economic viability vs. Financial feasibility

$$¿Q_n = \sum_{1}^{n} Q_j\ ?$$

Economic viability vs. Financial feasibility

EXAMPLE

Economic viability vs. Financial feasibility

Potential Areas	Location	PV Power (kWp)	Azimuth (º)	Inclination (º)	Annual Yield (kWh·kWp^{-1})
AREA I	Building 1	101	0	30	1435
	S. Parking 1-3	3x110	40	8	1255
AREA II	Building 2	91	0	30	1435
	N. Parking 1-4	4x100	42	8	1253
AREA III	Pergola	110	25	12	1308
	Building 3	74	0	30	1418
AREA IV	N-W Parking	105	39	8	1256

UJAEN Electricity consumption

8,484,229 kWh·year^{-1}

PV Electricity estimations

1,570,684 kWh·year^{-1}

Savings

18.51 %·year^{-1}

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Economic viability vs. Financial feasibility

Factors assumed for 2014							
			Financial				
			Interest Loan (80% PVIN)		Dividends (20% PVIN)		
PV_{IN} (€·kWp^{-1})	PV_{OM} (%·PV_{IN})	ε_{PVOM} (%)	i_l (%)	N_l (y)	di (%)	g (%)	ε_{pl} (%)
1700 1900	1	2.8	6	25	5	2.8	0.5

$$\overline{LCOE}_{2014} = 0.13\ € \cdot kWh^{-1}$$

UJAEN Average electricity tariff

$$\overline{p_u} = 0.09716\ € \cdot kWh^{-1}$$

Profitability

UJAEN Electricity tariffs for 2014					
P1 (€·kWh^{-1})	P2 (€·kWh^{-1})	P3 (€·kWh^{-1})	P4 (€·kWh^{-1})	P5 (€·kWh^{-1})	P6 (€·kWh^{-1})
0.144513	0.120356	0.106787	0.097498	0.093744	0.071927

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Economic viability vs. Financial feasibility

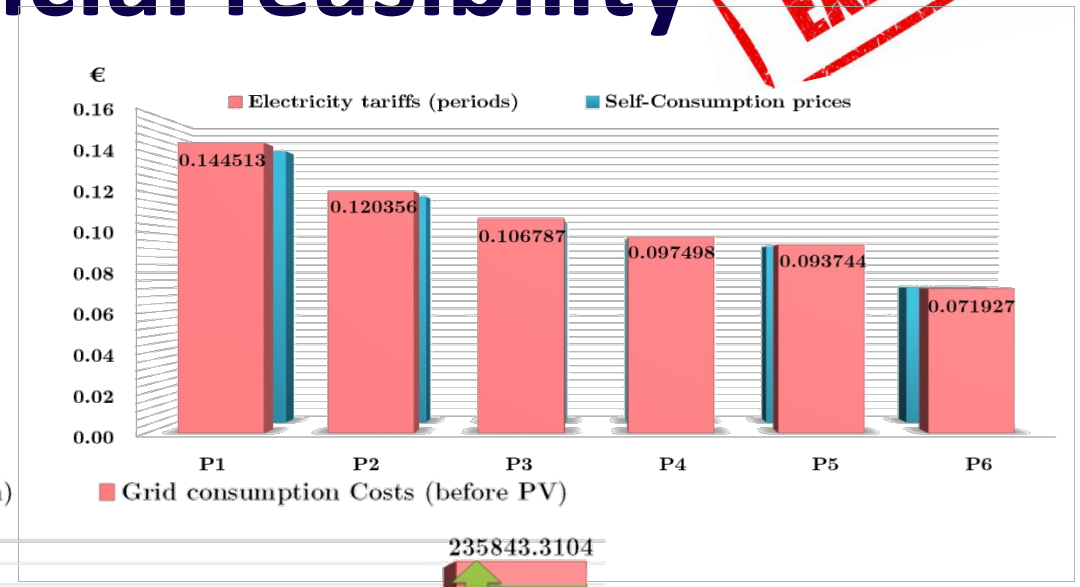
EXAMPLE

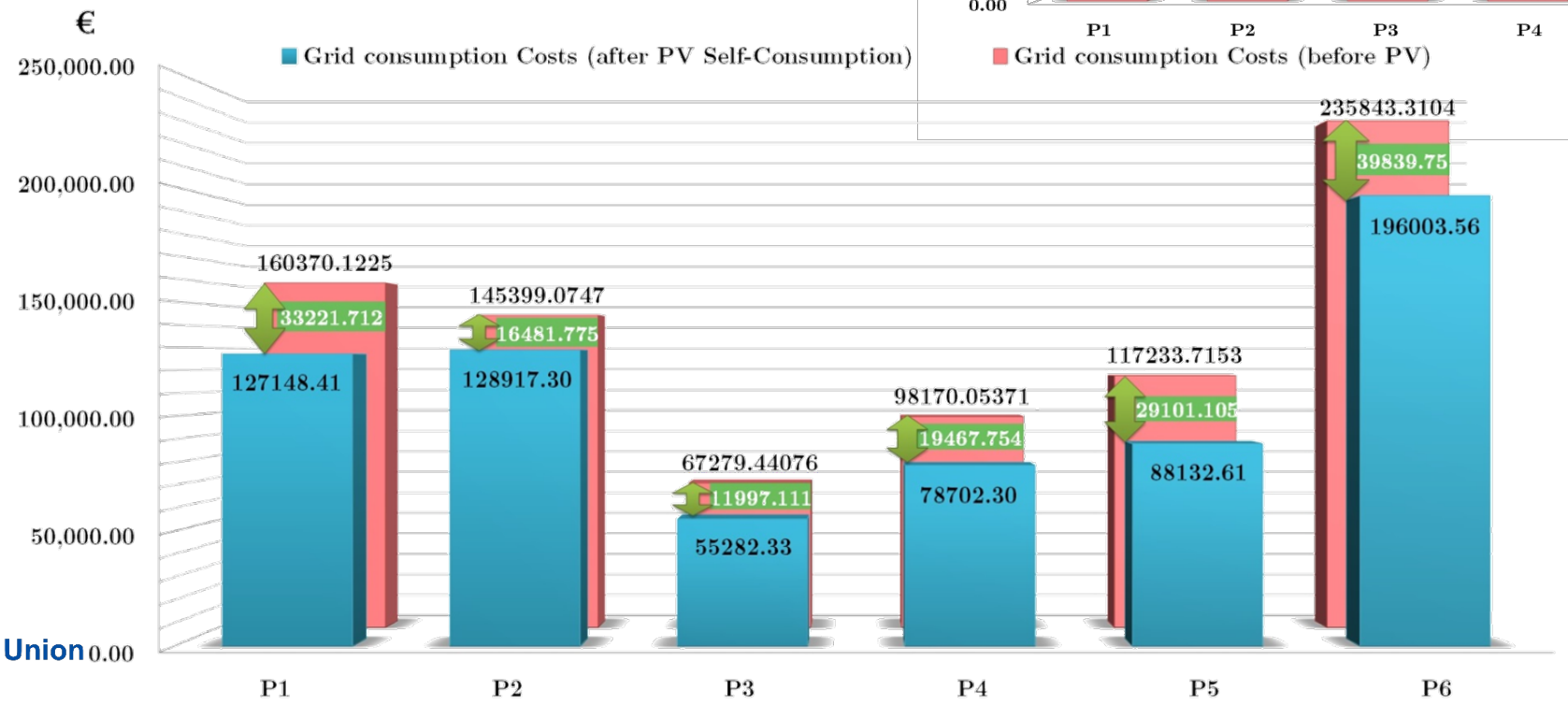
Original Energy Bill → 824,295.72 €

After PV Self-Consumption Bill

→ 674,186.52 €

Apparent savings → 150,109.20 €





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Economic viability vs. Financial feasibility

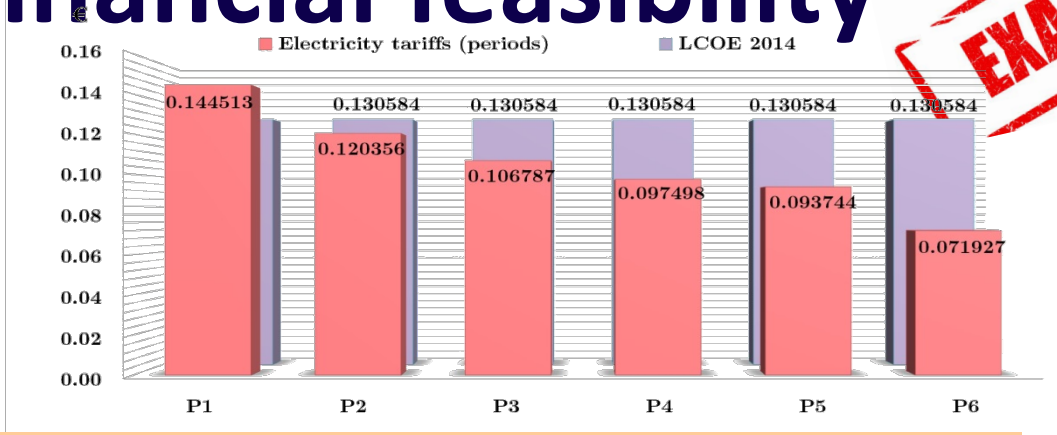
EXAMPLE

Original Energy Bill → 824,295.72 €

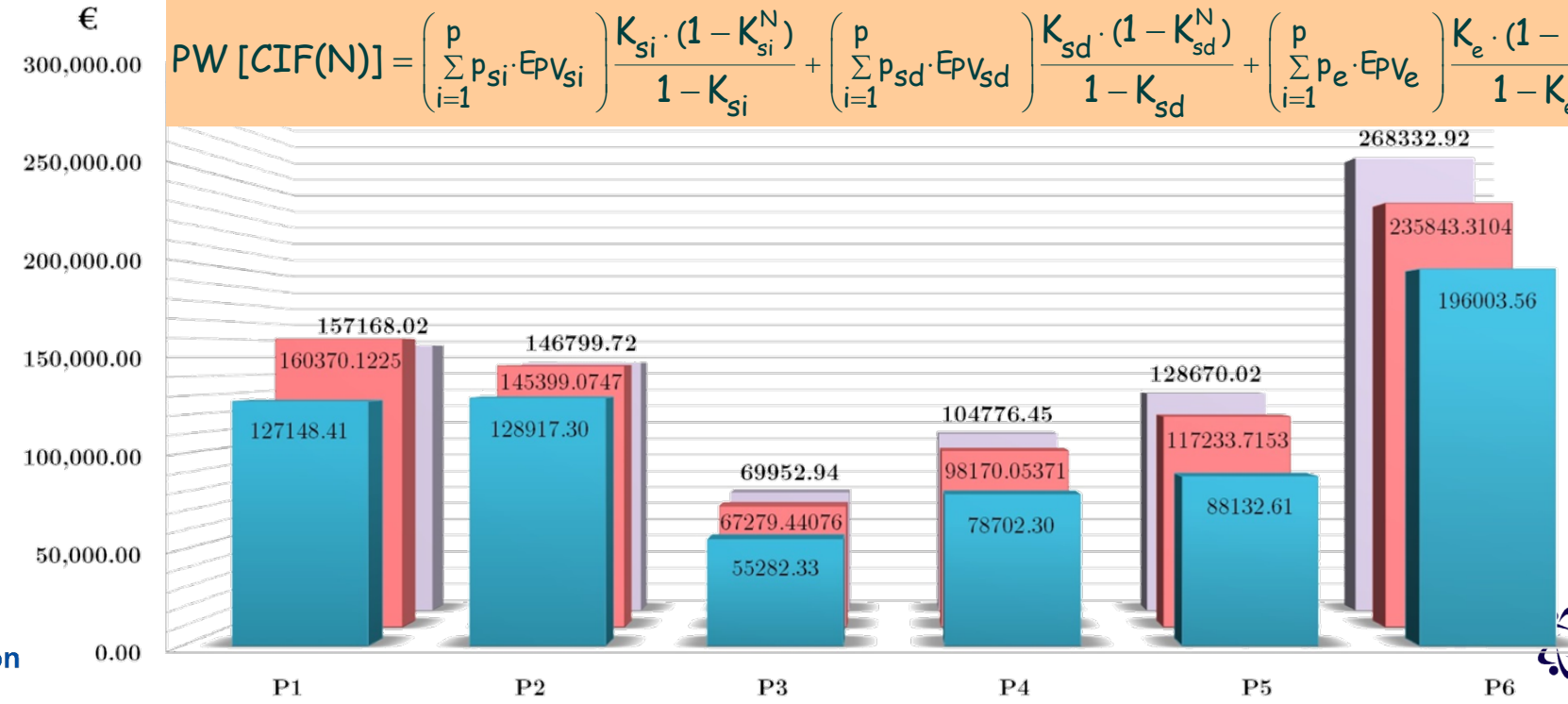
After PV Self-Consumption Bill

→ 674,186.52 €

Real "savings" → -51,404.35 €



$$PW\,[CIF(N)] = \left(\sum_{i=1}^{p} p_{si} \cdot EPV_{si}\right) \frac{K_{si} \cdot (1 - K_{si}^{N})}{1 - K_{si}} + \left(\sum_{i=1}^{p} p_{sd} \cdot EPV_{sd}\right) \frac{K_{sd} \cdot (1 - K_{sd}^{N})}{1 - K_{sd}} + \left(\sum_{i=1}^{p} p_{e} \cdot EPV_{e}\right) \frac{K_{e} \cdot (1 - K_{e}^{N})}{1 - K_{e}}$$



Project no

Economic Viable

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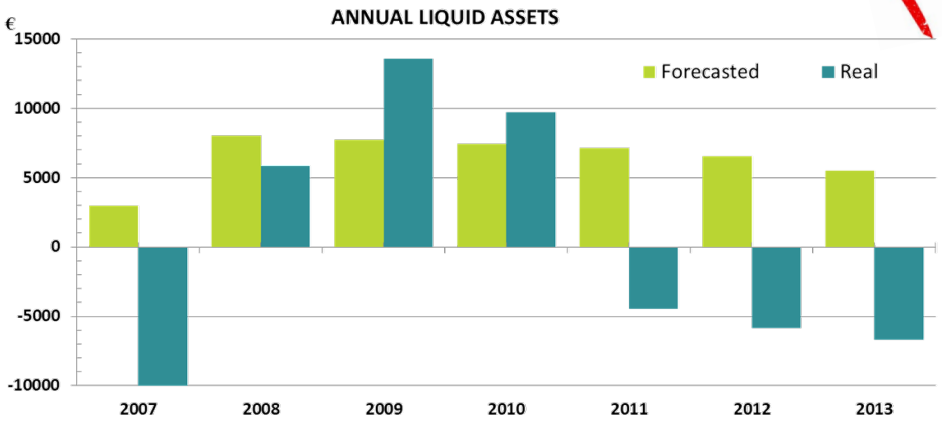
Economic viability vs. Financial feasibility

EXAMPLE



	FORECASTED 2007
IRR	10.14 %
NPV	482,204 €
IRRn	5.56 %
DPBT	11 YEARS

	REAL at 2013
IRR	8.63 %
NPV	287, 513 €
IRRn	3.51 %
DPBT	14 YEARS

Project Economic Viable but NO FINANCIAL feasible

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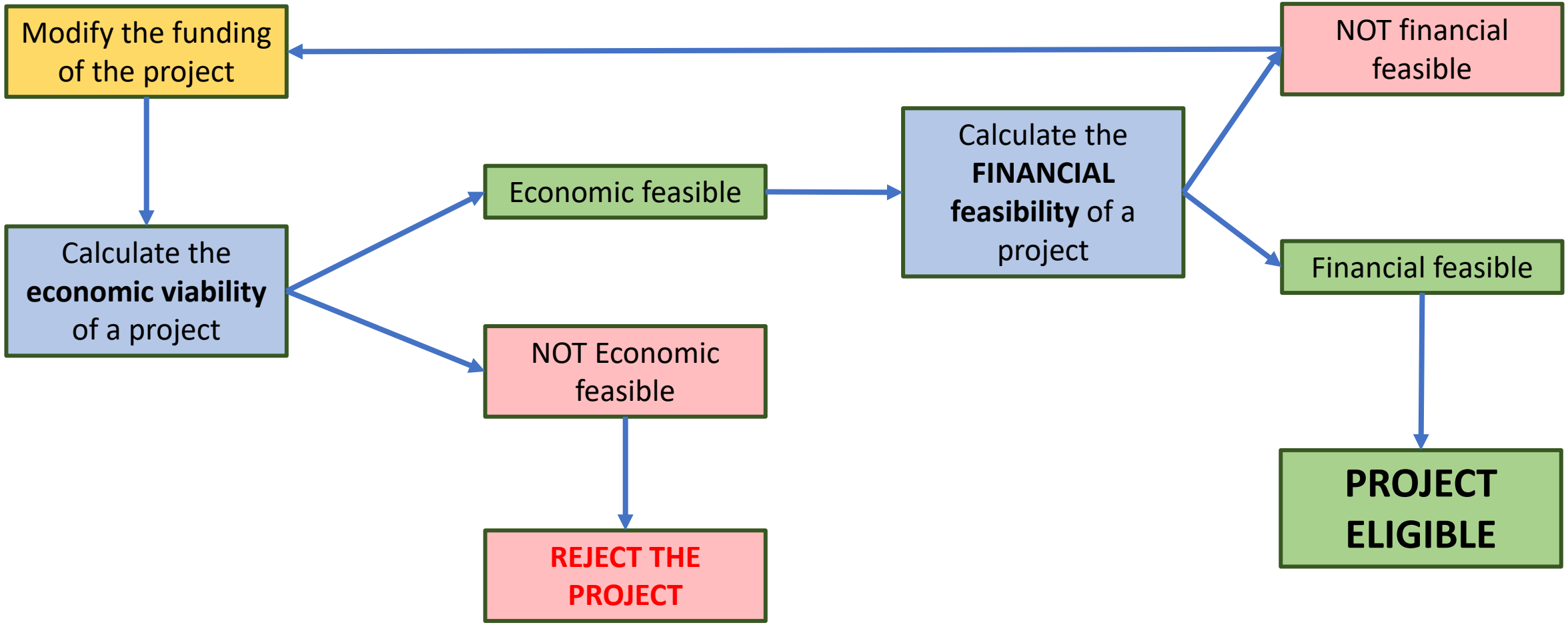
Economic viability vs. Financial feasibility



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C3 – Desing Projects

M6 – Planning and Project Control Basis

University of Jaén

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About NextGEng Project

- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Jamk University of Applied Sciences

University of Jaén

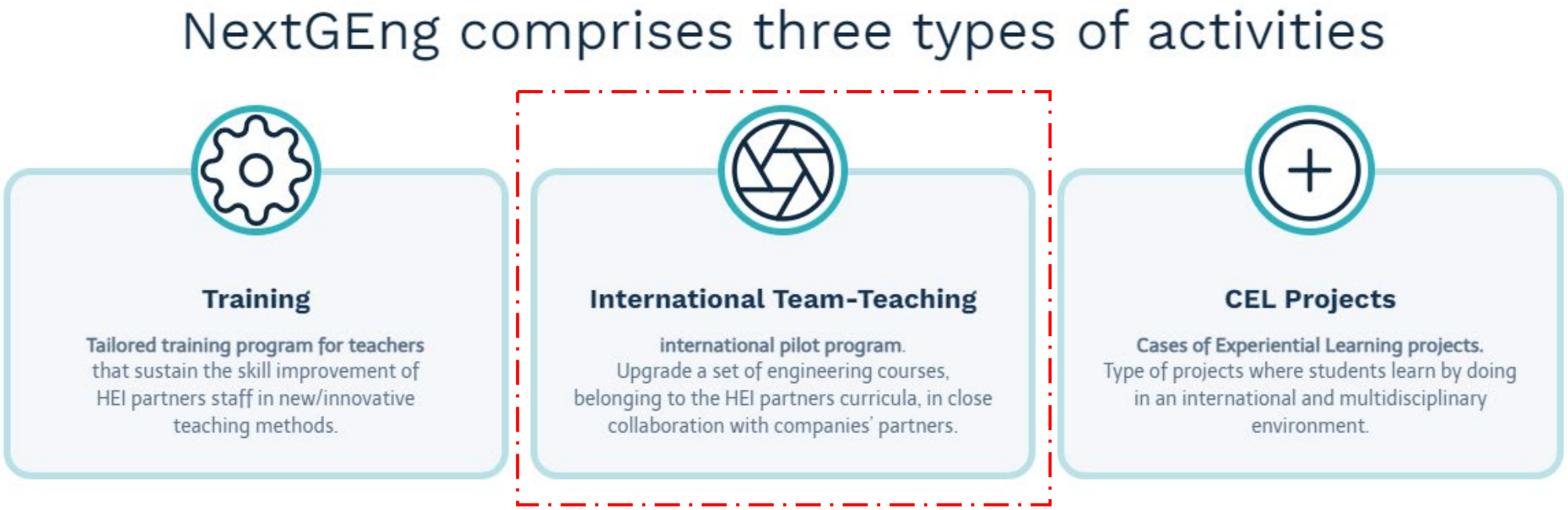
Integracion Sensorial y Robotica

Valmet Technologies Oyj

Rober Bosch SRL

About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



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Planning and Project Control Basis

Upon completion of this module, the student will be able to:

1) Understand the Fundamental Phases of Planning in Project Management .
2) Analyze the importance of Gantt Chart in project management
3) Use graphical software of a project schedule.
4) Understand Earned Value Management Method as a control tool

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Content

- Introduction of Planning in Project Management
- Key Elements of Successful Project Planning
  - Graphical Representation “Gantt Chart”
  - Gantt Chart Applications
    - Microsoft Project
- Earned Value Management Method

Planning and Project Control Basis

What knowledge do you have about project planning?

Mentimeter

CODE: 5344 4996

Introduction of Planning in Project Management

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Introduction of Planning in Project Management

What Is Planning in Project Management?

Planning is the critical step to take a project from an intangible theory to a tangible result.

Answer the questions of **who, what, why, how, and when, which** guide the execution of a project.

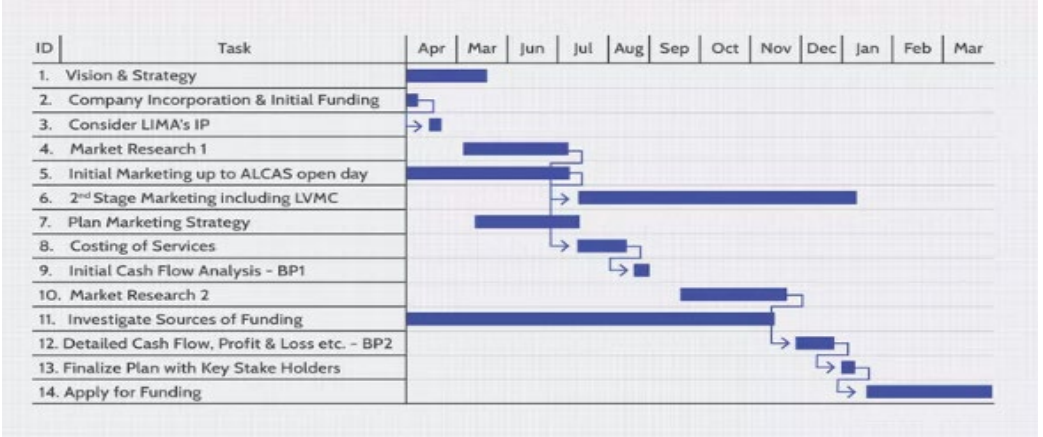
What does project planning entail?

The project plan describes the cost, scope, and schedule for the project. It lays out exactly what activities and tasks will be required, as well as the resources needed, from personnel to equipment to financing, and where they can be acquired. Good project planning also factors in risk and how to manage it, including contingency plans, and details a communication strategy to keep all stakeholders up to date and on board.

Introduction of Planning in Project Management

Before starting a new project, every manager needs to know……

Planning is the critical step to take a project from an intangible theory to a tangible result.



The objective: This states why the project should be completed. It outlines the gains and purpose.
What to do (scope): This is the list of tasks and activities. It outlines what needs to be done to reach the project's goal.
When to do it (schedule): This provides a timeline that tells you when to start and finish each part of the project.
Who will do what (assignments and resources): This determines who is responsible for each task and how much time, money, or other resources are allocated to each activity.

Introduction of Planning in Project Management

Why is a project plan important?

- **Provides clarity on how to proceed**
- **Makes project execution efficient**
- **Improves team communication**
- **Optimizes resource**
- **Facilitates goal tracking**
- **Maintains alignment among team members**
- **Impacts employee retention**

It is more than just a budget
or
task management tool

Introduction of Planning in Project Management

Key Elements of Successful Project Planning

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Graphical Representation “Gantt Chart”

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Graphical Representation “Gantt Chart”

What Is a Gantt Chart?

A Gantt chart is a commonly used graphical depiction of a project schedule. It's a type of bar chart showing the start and finish dates of a project's elements such as resources, planning, and dependencies.

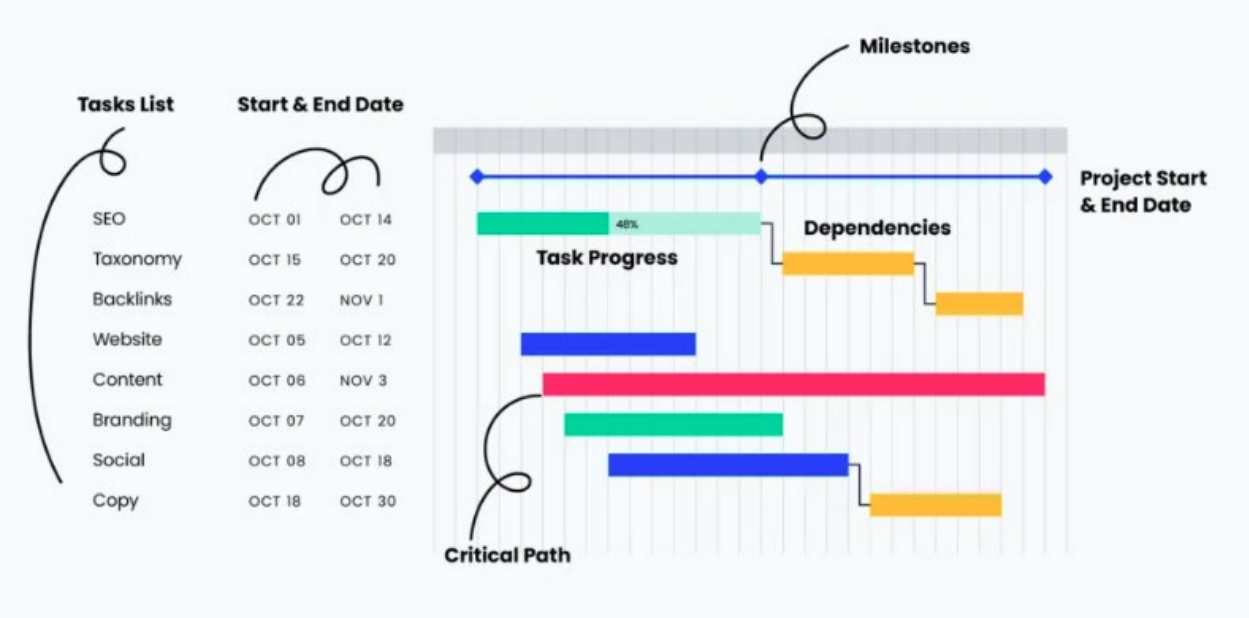
What Are Gantt Charts Used for?

Gantt charts help visualize various tasks and projects that occur simultaneously within an organization, and how far along they have progressed. They are used by management to plan and schedule such projects so that resources can be allocated in an optimal way and that projects that are prioritized can finish before less important ones begin.

Graphical Representation “Gantt Chart”

What Are the Components of a Gantt Chart?

- Tasks, their duration, status, and priority.
- Start and end dates.
- Progress.
- Timeline with the time scale.
- Milestones.
- Dependencies between tasks.
- Deadlines.
- Critical path.



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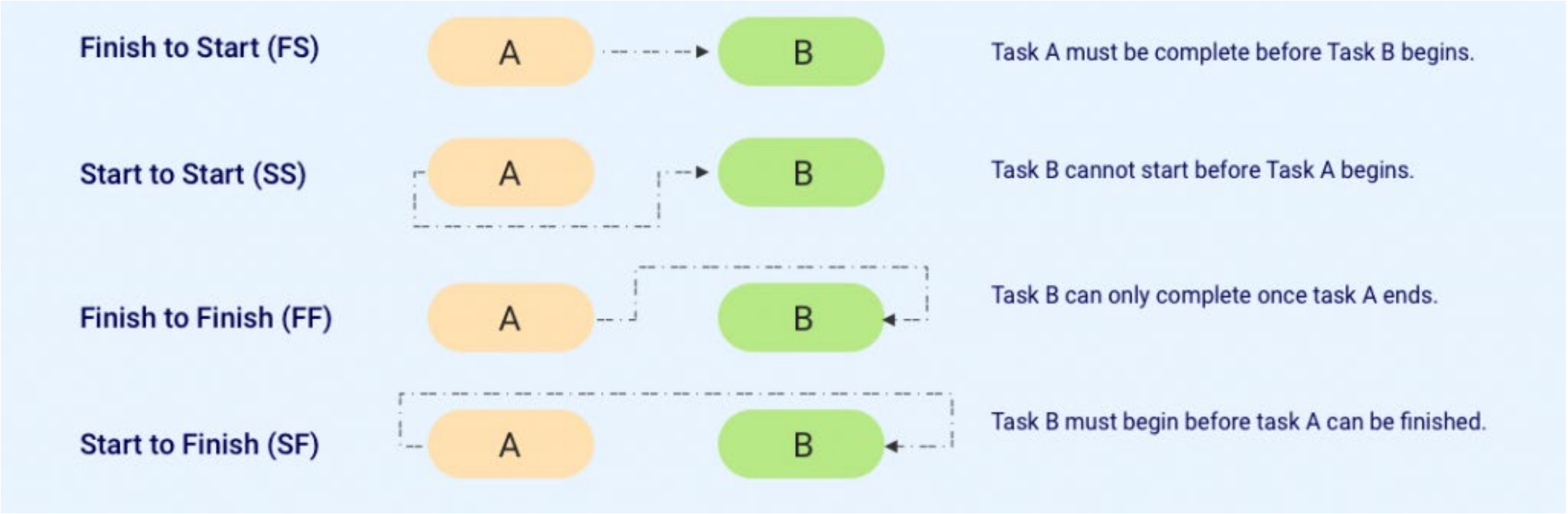
Graphical Representation “Gantt Chart”

Four Types of Gantt Chart Dependencies



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Gantt Chart

Try to identify the Tasks in the example……

Imagine you are overseeing the decoration of two rooms in a house. One room is to be painted, the other is to have wallpaper hung. You have a specific start date in mind for this project and you will have both a painter and a decorator available to paint and hang wallpaper at the same time; ensuring they are working alongside one another to guarantee a short project duration. There are two tasks required in this project.

There are two tasks required in this project.

***Task 1**: Paint room one*
***Task 2**: Hang wallpaper in room two*

Try to identify the dependence of the following examples……

Start-to-Start dependency type

Gantt Chart

There are two tasks required in this project.

First task: *Connect hospital to grid*
Second task: *Disable generators*

Try to identify the Tasks in the example……

In this hypothetical scenario, you and your team are setting up a new hospital in the outskirts of an African city. What makes the final opening of the hospital challenging is that the area isn't connected to the electrical grid yet.

For the pre-opening inspection and hospital checks you are using a generator to supply the medical equipment with electrical power. The day before the hospital's opening, the engineers are supposed to link the building to the grid system and turn off the generators. Those activities must be closely monitored

Try to identify the dependence of the following examples……

Start-to-finish dependency type

Gantt Chart

Try to identify the Tasks in the example……

There are two tasks required in this project.

Task 1: Build house structure
Task 2: Install doors and windows

For this example imagine you are a working within the construction industry overseeing the building of new homes. You have two specific tasks which are to build the structure of the house before installing the doors and windows.

The installation of the doors and windows within the house is dependent on the completion of the building's structure. This is because the joiner's cannot install the required doors and windows until the structure of the house is complete otherwise there would be nowhere for them to be installed.

Try to identify the dependence of the following examples……

Finish-to-Start dependency type

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Gantt Chart

There are two tasks required in this project.

First task: Paint interior of house
Second task: Set up furniture

Try to identify the Tasks in the example……

You are planning to move into a new home. But before moving in you want to repaint the interior so they shine in white color. For your planning, this means you first have to do all the painting before you can put up all your furniture.

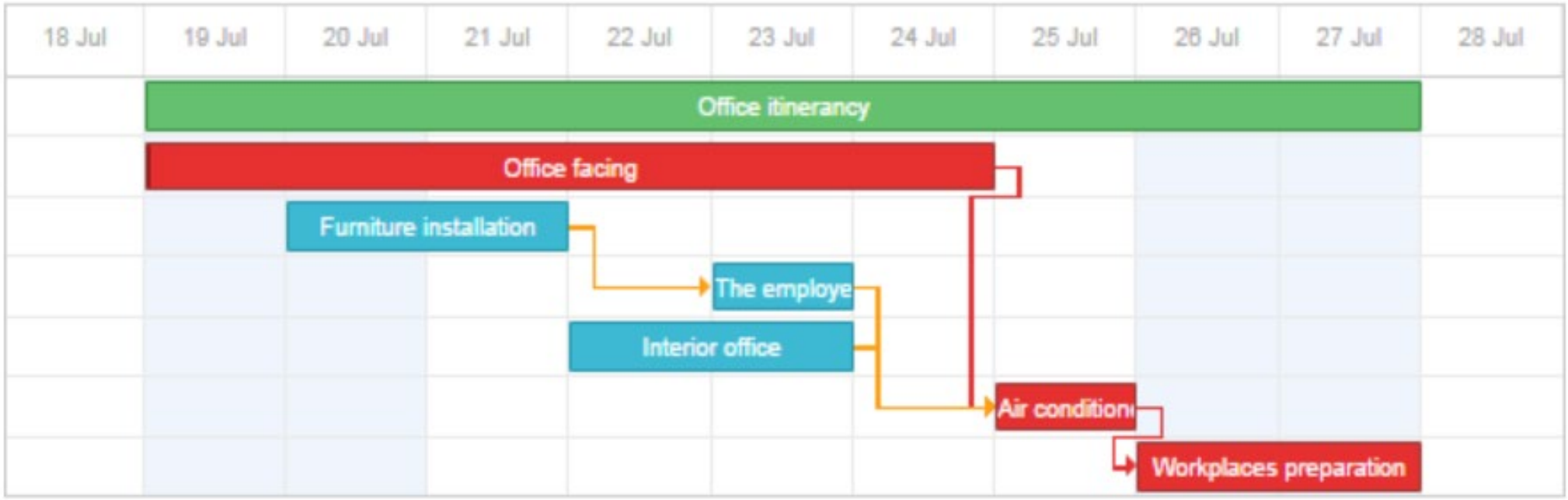
Try to identify the dependence of the following examples……

Comment: *Both tasks have a finish-to-finish dependency. Why? You can run both tasks (more or less) in parallel by painting one room after the other, waiting for the paint to dry and then start putting up furniture in the rooms that have been painted. You don't have to wait for the entire paint job to be done. I won't comment on whether that's practical or not but technically you could run both tasks concurrently.*

Finish-to-Finish dependency type

Graphical Representation “Gantt Chart”

Critical path



Graphical Representation “Gantt Chart”

Dependency type of tasks..

- **Finish to Start (FS)—The predecessor ends before the successor can begin.**
- **Start to Start (SS)—The predecessor begins before the successor can begin.**
- **Finish to Finish (FF)—The predecessor ends before the successor can end.**
- **Start to Finish (SF)—The predecessor begins before the successor can end.**

Gantt Chart Applications

Microsoft Project

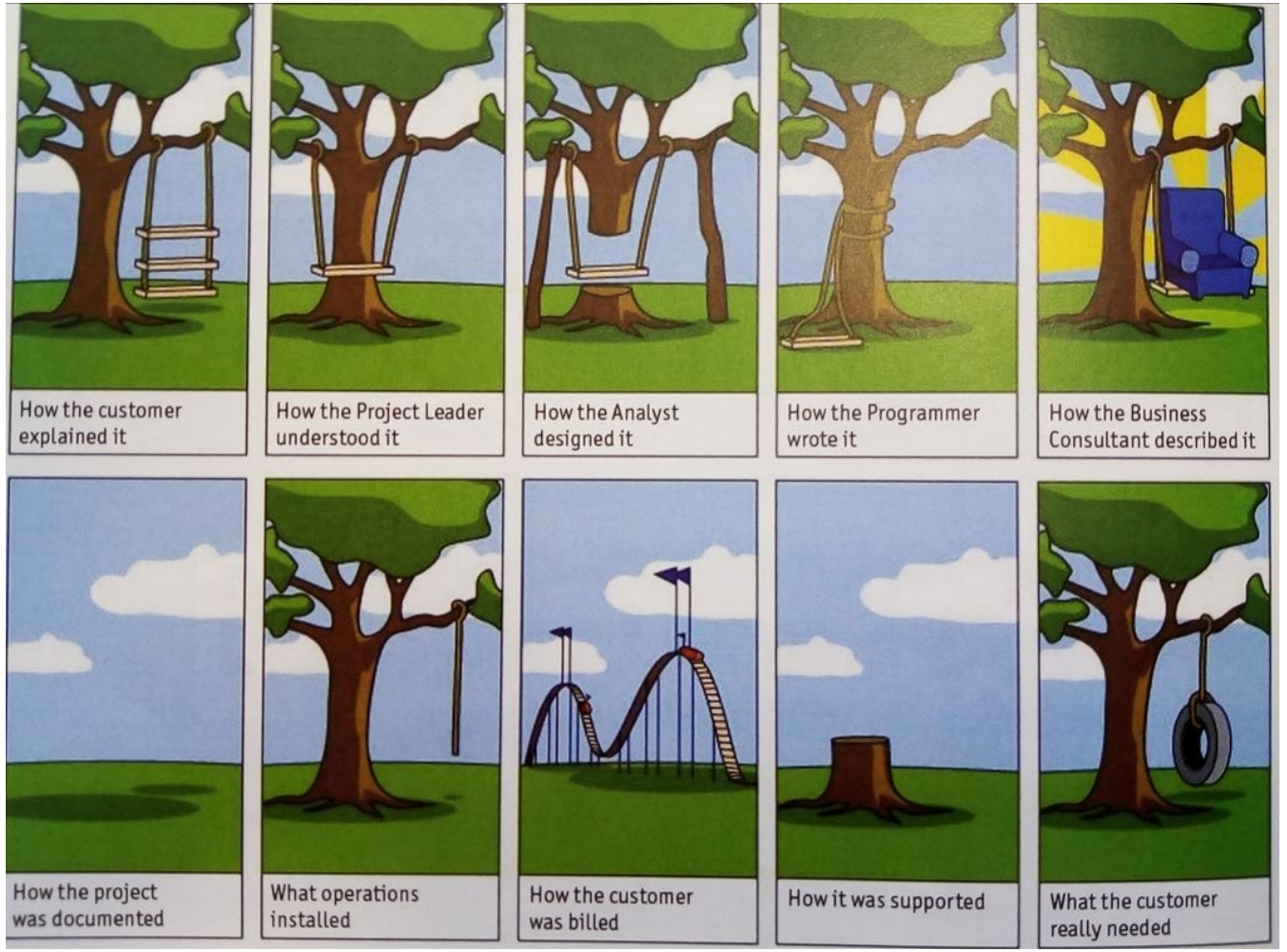
A decision Making Tool

Project Management

Resource Requirements

Project Time-lines

Resource Cost



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Microsoft Project

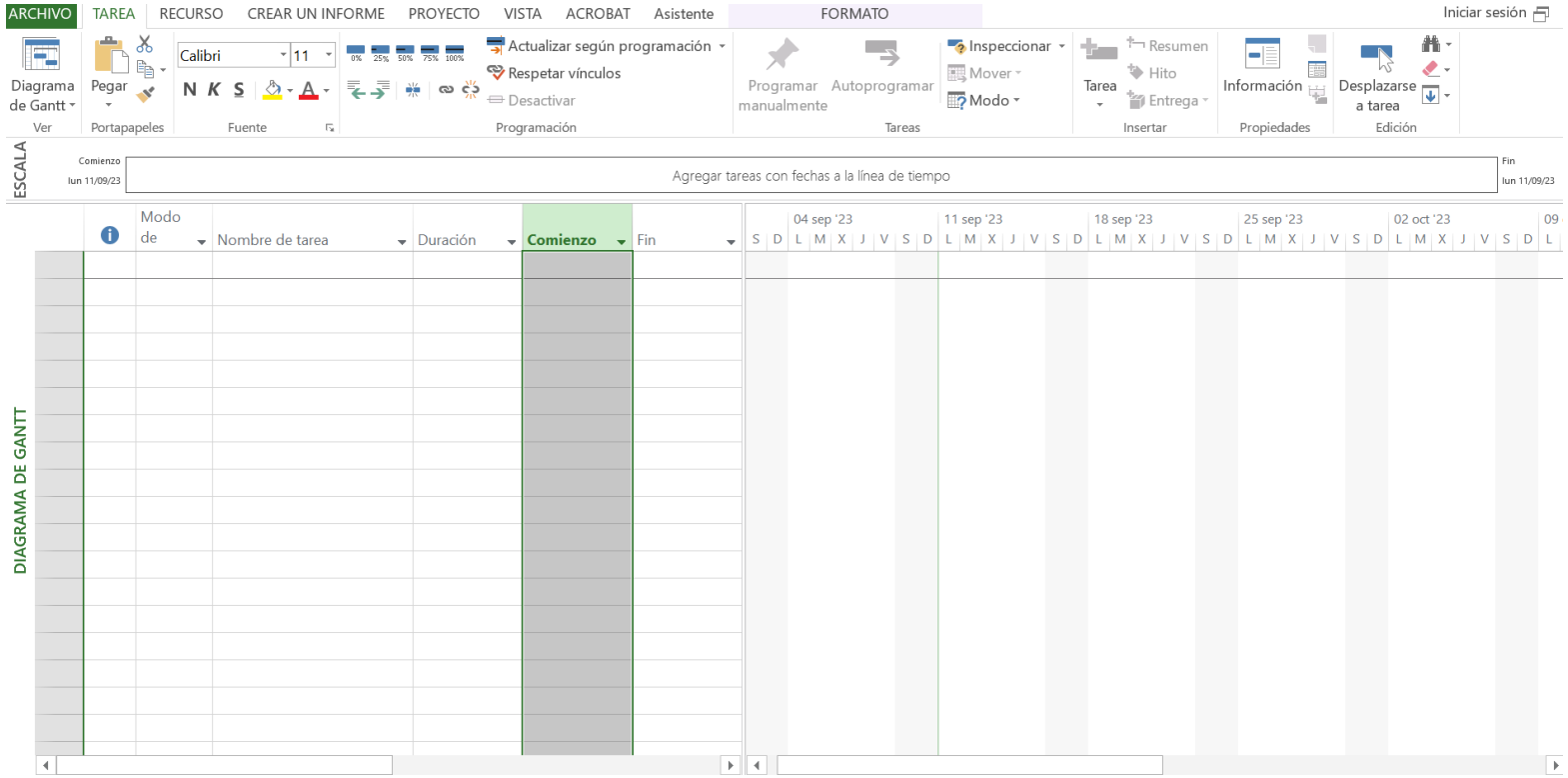
Step by Step for the first contact

Charge Working Time

Edit Working Hours

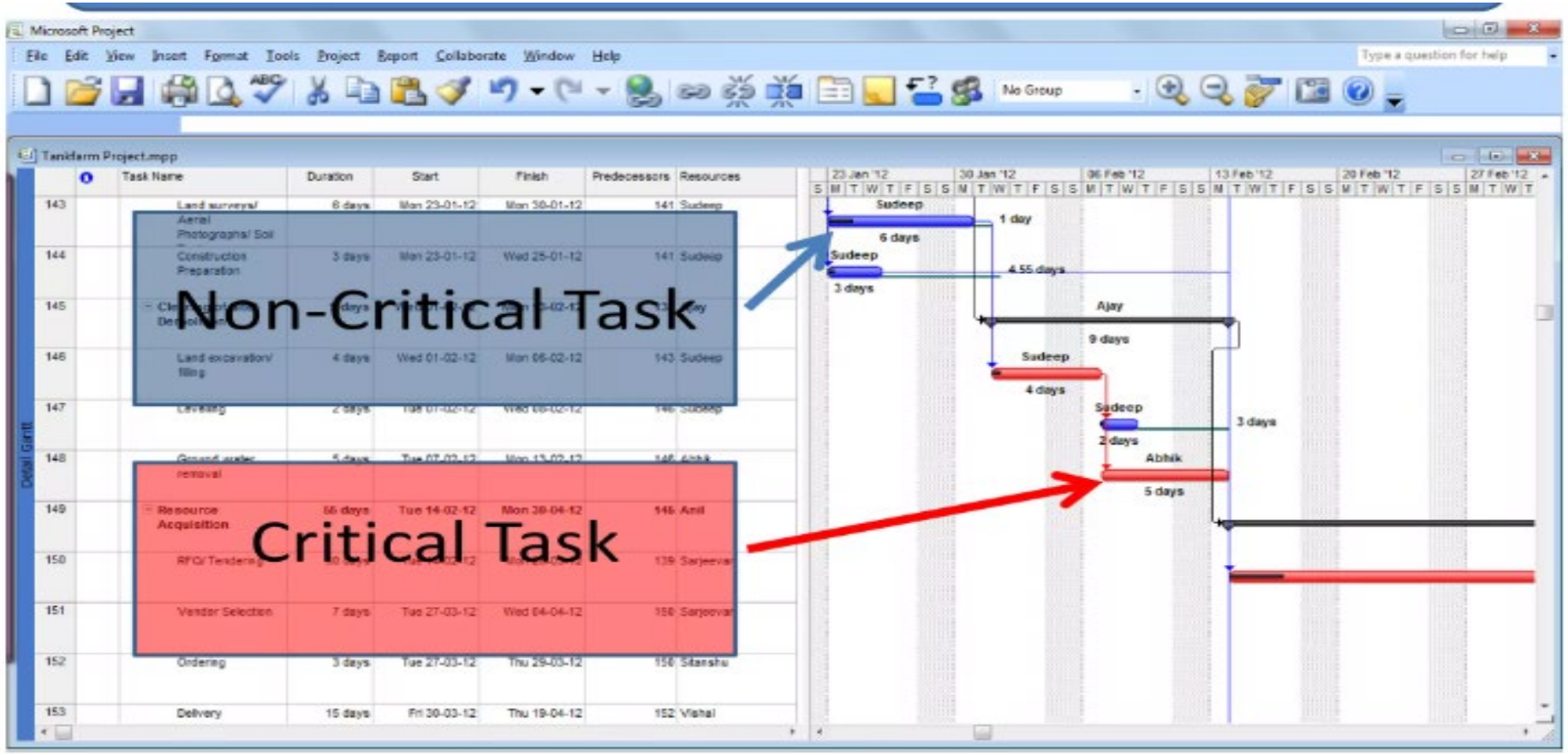
Enter Holidays one-by-one

Enter Project Data to obtain the Gantt Chart



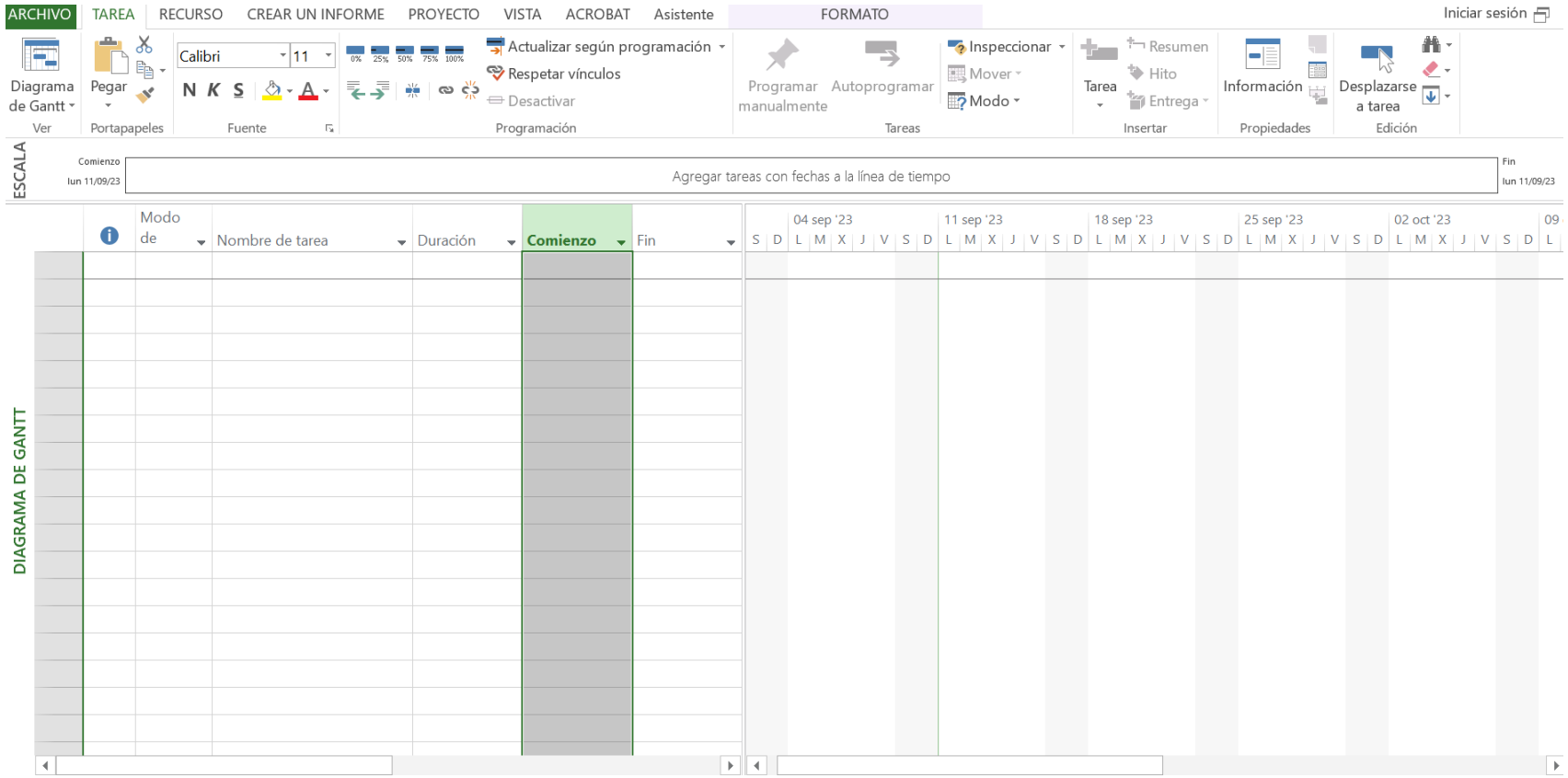
Microsoft Project

Step by Step for the first contact



Microsoft Project

Step by Step for the first contact.



Example 1

Represent the Gantt Diagram and the critical parth of this Project:

Task 1

Task 1.1

Task 1.1.1.

Task 1.1.2

Task 1.2

Task 2

Task 2.1

Task 2.2

Task 2.3

Task 2.3.1

Task 2.3.2

Task 3

Task	Duration
Task 1.1.1	3 days
Task 1.1.2	18 days
Task 1.2	9 days
Task 2.1	15 days
Task 2.2	4 days
Task 2.3.1	6 days
Task 2.3.2	2 days
Task 3	11 days

*Task 1.1.2 should not start until Task 1.1.1 finishes

*Tasks 1.1 y 1.2 must start on the same day

*Tasks 2 y 3 must be completed on the same day

*Task 2.3.2 will start 4 días after the end of Task 2.3.1

*Task 2 will start once Task 1 has completed.

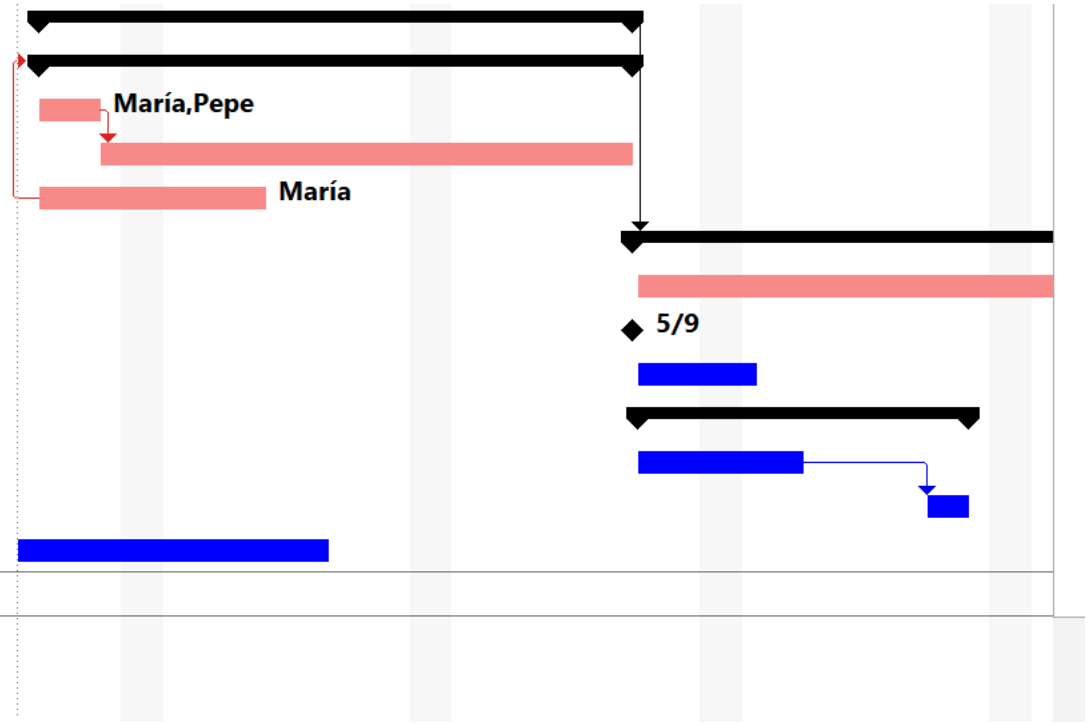
*Task 2.2 will start 3 days after the start of task 2.1

Example 1

An approximation of what you should get

…. Now we will indicate the resources

1			Task 1	21 días?	mar 4/11/23	mar 5/9/23	
2			Task 1.1	21 días?	mar 4/11/23	mar 5/9/23	5CC
3			Task 1.1.1	3 días	mar 4/11/23	jue 4/13/23	
4			Task 1.1.2	18 días?	vie 4/14/23	mar 5/9/23	3
5			Task 1.2	9 días?	mar 4/11/23	vie 4/21/23	
6			Task 2	15 días?	mar 5/9/23	mar 5/30/23	1
7			Task 2.1	15 días?	mié 5/10/23	mar 5/30/23	
8			<Hito nuevo>	0 días	mar 5/9/23	mar 5/9/23	
9			Task 2.2	4 días?	mié 5/10/23	lun 5/15/23	
10			**Task 2.3**	**12 días?**	**mié 5/10/23**	**jue 5/25/23**	
11			Task 2.3.1	6 días?	mié 5/10/23	mié 5/17/23	
12			Task 2.3.2	2 días?	mié 5/24/23	jue 5/25/23	11FC+4 días
13			Task 3	11 días?	lun 4/10/23	mar 4/25/23	



Example 2

The attached table defines the duration, budget and relationships between the activities of a project CONSTRUCTION OF AN INDUSTRIAL COMPLEX.

Tasks	Duration (month)	Precedent	Budget
Project Drafting	4	Inicio	8500 €
Licences	3	1	2500 €
Topography	3	1	7500 €
Land Movement	8	3;2	15600 €
Foundations Structures	6	4	7900 €
Structures	9	5	15500 €
Roofs	4	6	6500 €
Partition Wall	5	5;6;7	7800 €
Electric Installation	6	6;7;8	9500 €
Ventilation Installation	3	6;7;8	8050 €
Fire Fighting Installation	2	6;7; 8; 10	6500 €
Legalization	10	9;10;11	2500 €

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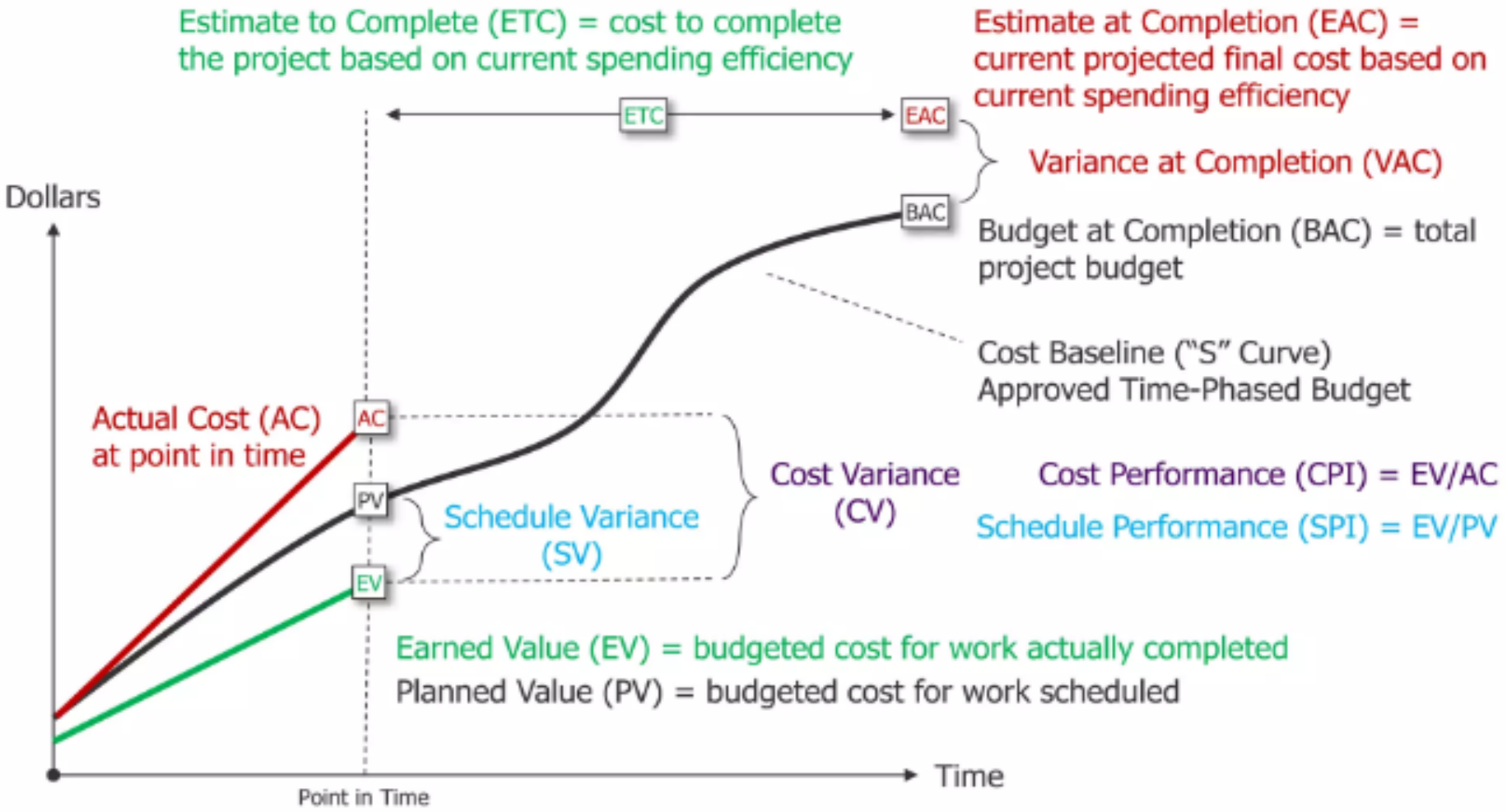
Earned Value Management Method



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C4 – Quality assurance and applied methods

M1 – Errors in Measurement

CO – Technical University of Cluj-Napoca

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Course: **Errors in measurement**

Motivation

The quality control process is based on the measurements and in order to get a certification of the measurement results we must know the errors.

Course: Metrology - Errors in measurement

Knowledge the measurement errors in Metrology.

Objectives

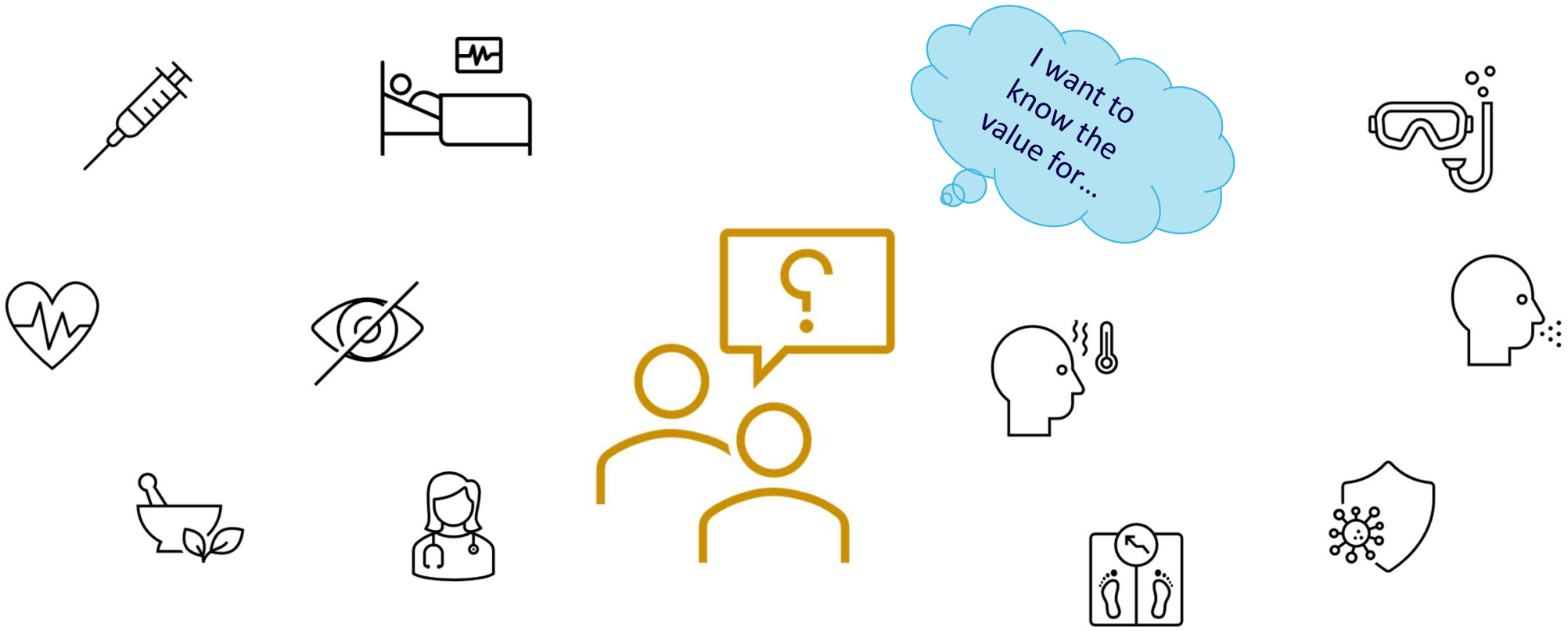
- Understanding the importance of measurements for quality assurance
- Knowledge of factors that influence measurement errors
- Classification and calculation of the errors in measurement
- Establishing the accuracy and precision in measurements

Content

- Introduction
- Measurements and errors
- Calculating the errors in metrology
- Conclusions

What do you want to measure for health?

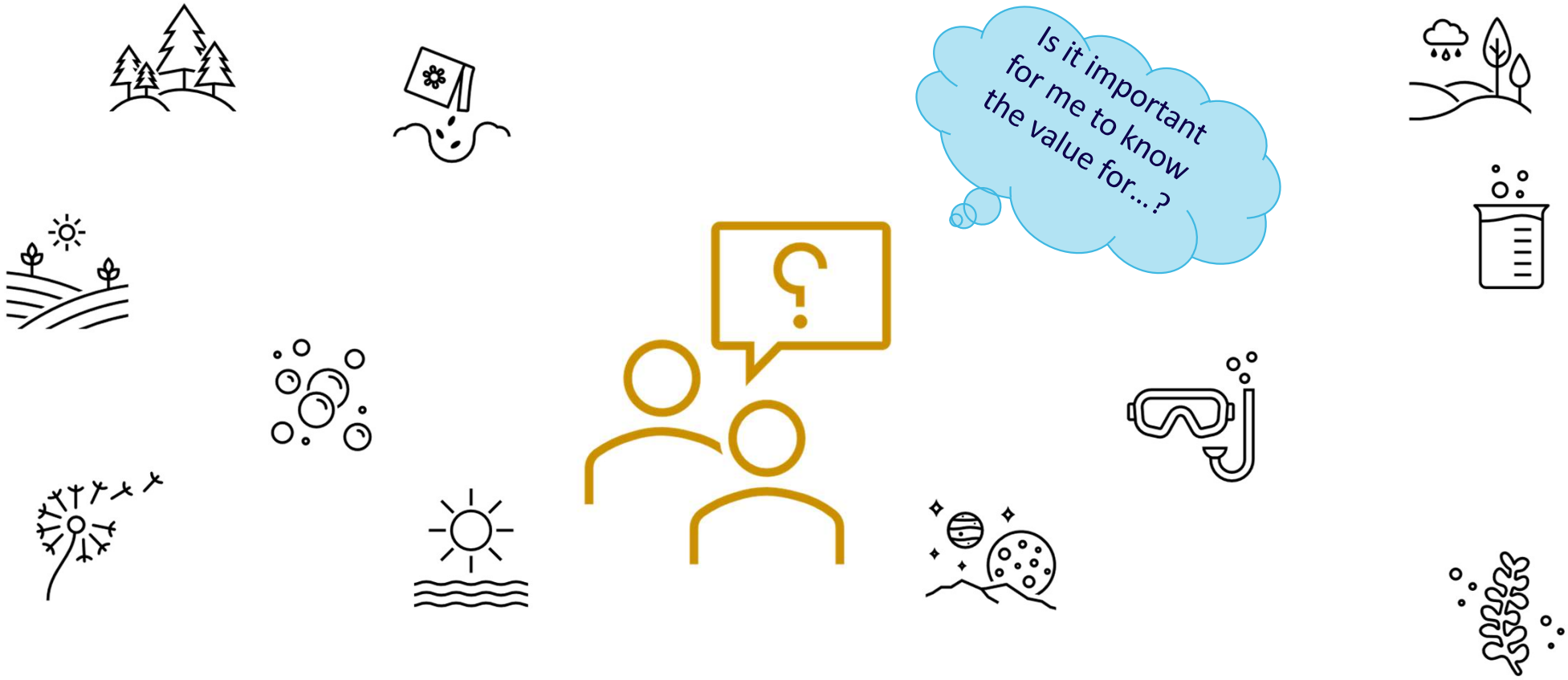
5min



Gamification – Give the answer ball to the next person!

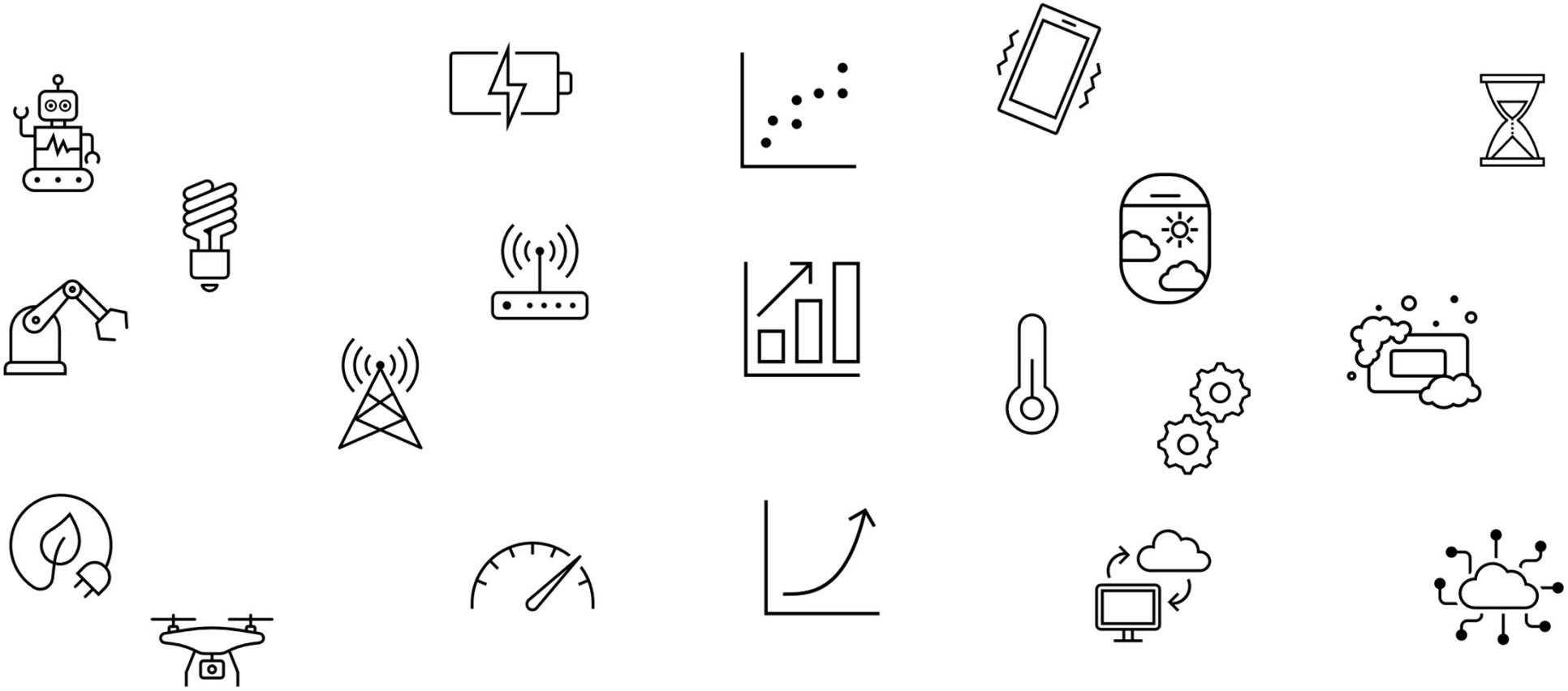
What do you want to measure from environment?

5min



Gamification – Give the answer ball to the next person!

What do we need to measure in industry ?



Interactive discussion

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Instruments and equipment's for measuring

5min

3D Coordinate Measuring Machine

Oscilloscope

Caliper, Micrometer, manometer

Vision measuring

Interactive discussions

Devices and instruments for measuring

5min

Air Quality Detector

Stethoscope

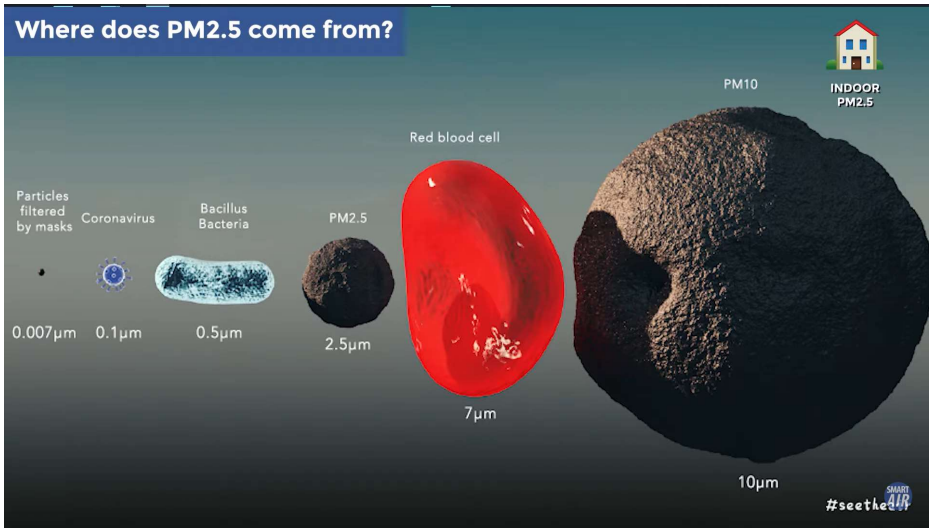
Microscope

Eyes measuring device

Interactive discussions

Air Quality Measure/Monitors

https://www.youtube.com/watch?v=2T72mEoM0nY&ab_channel=SmartAir



https://www.youtube.com/watch?v=67iLPfrSQ0I&ab_channel=SmartAir

Errors of measurements

A1. Absolute error ($\Delta x, e$) – result of a measurement minus a true value of the measurand

$$e = x_m - x = \Delta x$$

[VIM:2021, definition B.2.19]

Where: *X –the true value; Xm – the result of the measurement.*

The absolute error with changed sign is called CORRECTION!

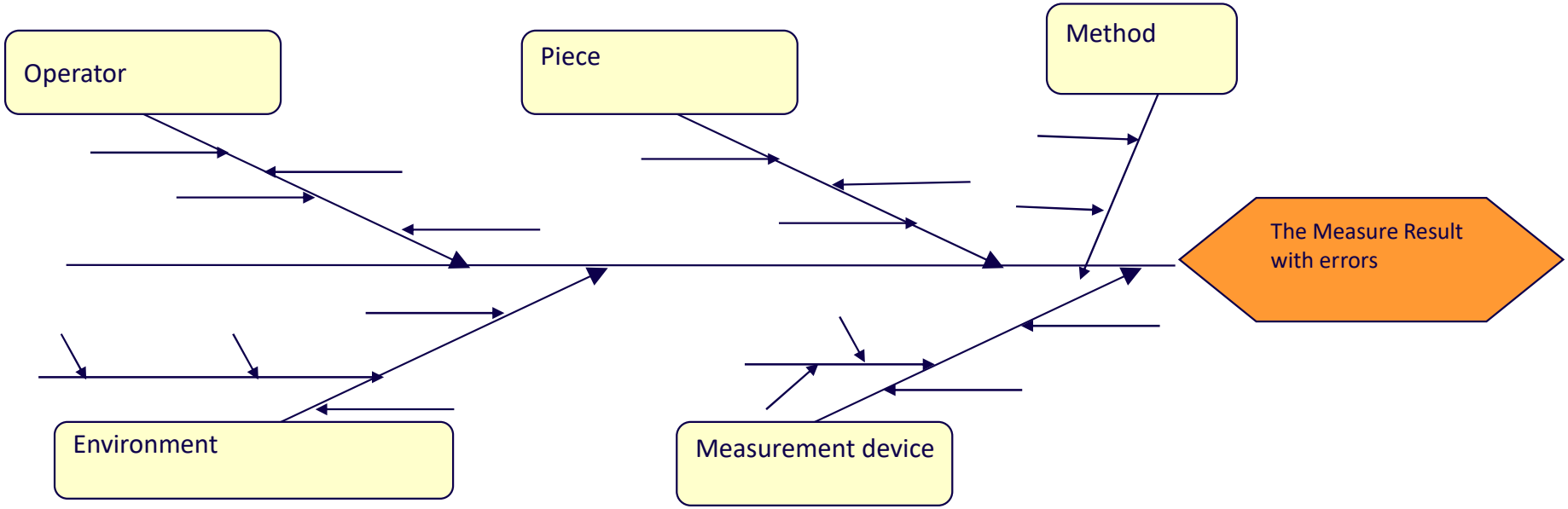
A2. Relative error (δx, e_r, ε) - error of measurement divided by a true value of the measurand

$$\varepsilon = \frac{\Delta x}{x} = \frac{x_m - x}{x} = \frac{x_m}{x} - 1 = e_r = \frac{e}{x}$$

[VIM:2021, definition B.2.20]

Influencing factors of the Measurement Error

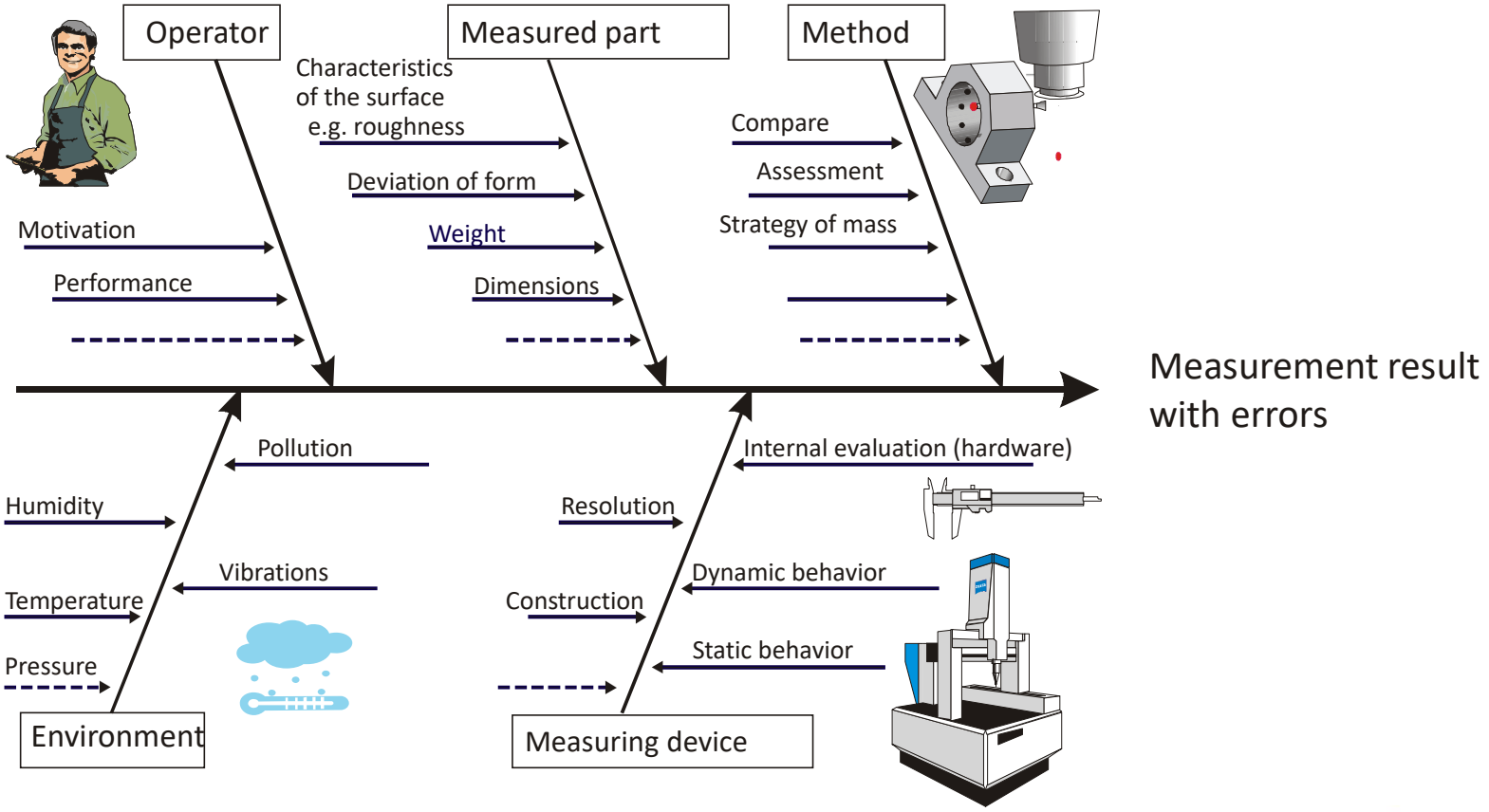
(10 min)



- Teacher gives to the students the sticky notes
- Every student writes down a factor of error and puts the Sticky notes on the flipchart
- Teacher discusses together with the students about the sources of errors in measurements.

Factors influencing the Measurement Error

comparison with sticky notes



Classification of Measurement Errors

1. By the method of choosing the nominal value:

The real error (True) ε_i– where the reference (nominal) value is taken as the actual X value of that size:

$$e_i = x_{mi} - x_a$$

Where: Xa – true value (it is an idealized notion);

Xmi – measurement result i

Apparent error ν_i - where considered as a reference value, the probable value of that size:

$$\pm\nu_i = x_{mi} - x_m$$

Where: Xm - the probable value of a quantity shall be taken to be the average in the case of measurements of the same precision or the weighted mean in the case of the measurements of different precision.

Classification of Measurement Errors

2. By their type:

A. Avoidable errors (gross) – They can be avoided by increased attention and are highlighted by a series of measurements.

Exemple: e.g. order of dimension

B. Unavoidable errors – cannot be avoided regardless of the method used or the degree of attention of the operator.

B1) ***Systematic errors*** - mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand

[VIM:2021, definition B.2.22]

B2) ***Random errors (random)*** - result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.

[VIM:2021, definition B.2.21]

Systematic and Random Errors

Systematic errors

(called systematic bias)

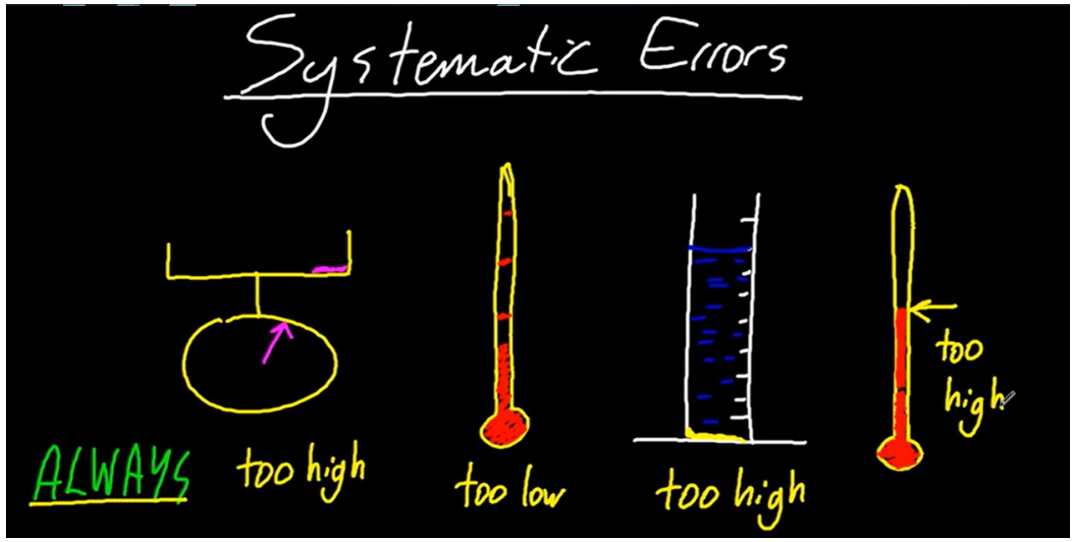
- cannot be eliminated by repeated measurements
- can be assessed easily but they are not easy to be detected
- minimization of the systematic errors increases the accuracy of the measurement
- calibration helps to reduce systematic errors
- characterization is not necessary
- are always in the same direction

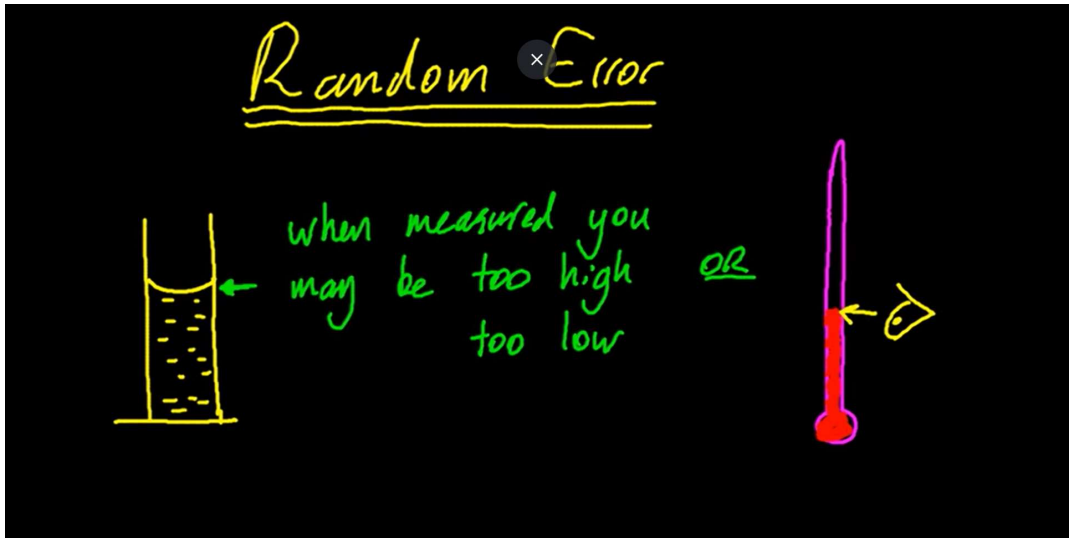
Random errors

(called unsystematic error or random variation)

- can be minimized by repeated measurements
- easy to detect but Statistical analysis required
- minimization of random errors increases repeatability and hence precision of the measurement
- calibration has no effect on random errors
- we have average, standard deviation, and variance
- can be both positive and negative

Systematic and Random Errors





https://www.youtube.com/watch?v=50iFTcCsG_Y&ab_channel=RichardThornley

Systematic Errors

Case study:

If an etalon, that we use for measuring the distance, is 0.03 mm shorter, for each introduction of the etalon within the distance to be measured, there is an error that retains its value and sign.

The result is a constant systematic error, propagating according to the law of multiplication, e.g. the total error is equal to the unit error multiplied by the number that shows how many times the unit error occurs in the final result*:*

$$e_{st} = n \cdot e_s = 50 \cdot 0.03 = 1.5 \text{ mm}$$

Debate about effects into industry applications

Where: e_{st} - total systematic error;

n – the number showing how many times the standard is contained in the measured quantity (n=50);

e_s- unitary constant systematic error (0.03).

How to reduce the systematic errors?

Reducing systematic errors can be done by:

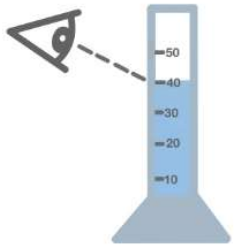
- Improving the method of measurement
- Applying the corrections to the result
- Better adjustment of measurement equipments
- Minimising the percent of observations for which systematic errors could not be removed

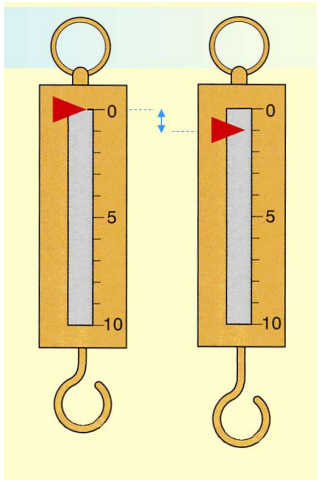
Systematic errors can also be **constant** or **variable**.

Identifing the systematic and random errors

(10 min)

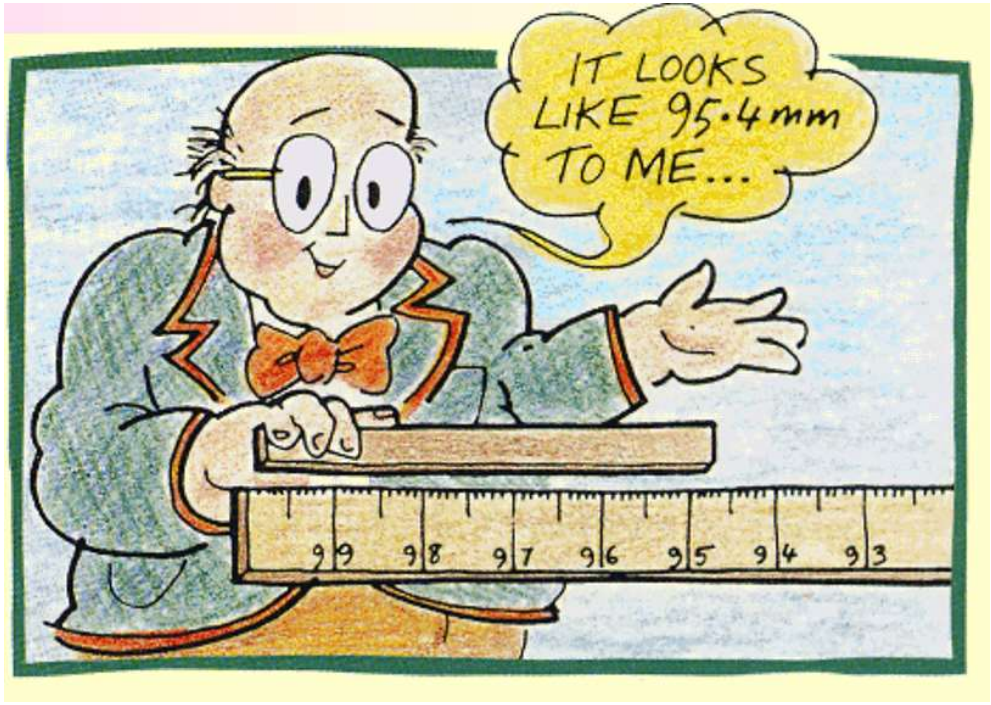
Scan Me!





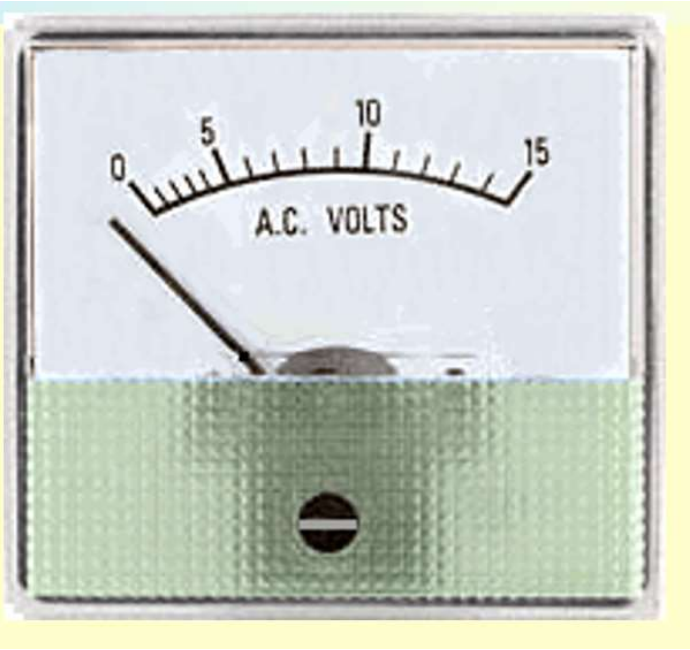
https://jamboard.google.com/d/1xpA38r9sJFGBC_5JsfK9Wx66Zifr2TaIfdGcisQGp2Q/edit?usp=sharing

Do you identify mistakes in the figure?



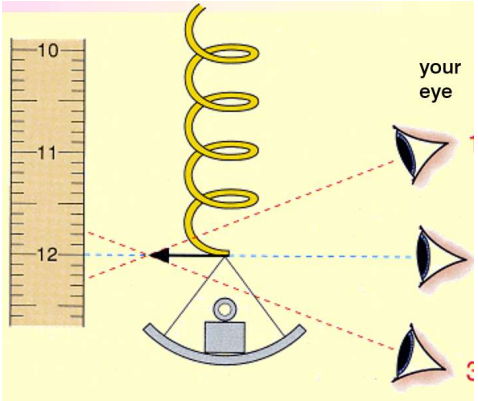
(10 min)

What error is in the figure? What effect does it have?



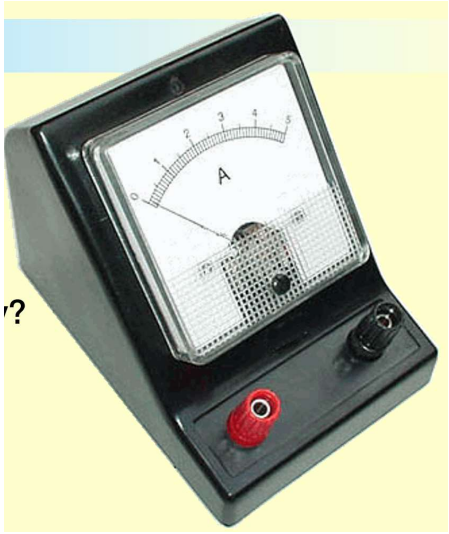
https://jamboard.google.com/d/1xpA38r9sJFGBC_5JsfK9Wx66Zifr2TaIfdGcisQGp2Q/edit?usp=sharing

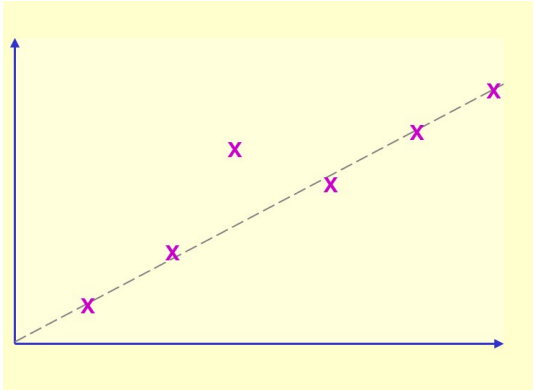
How should the position of the eye be?



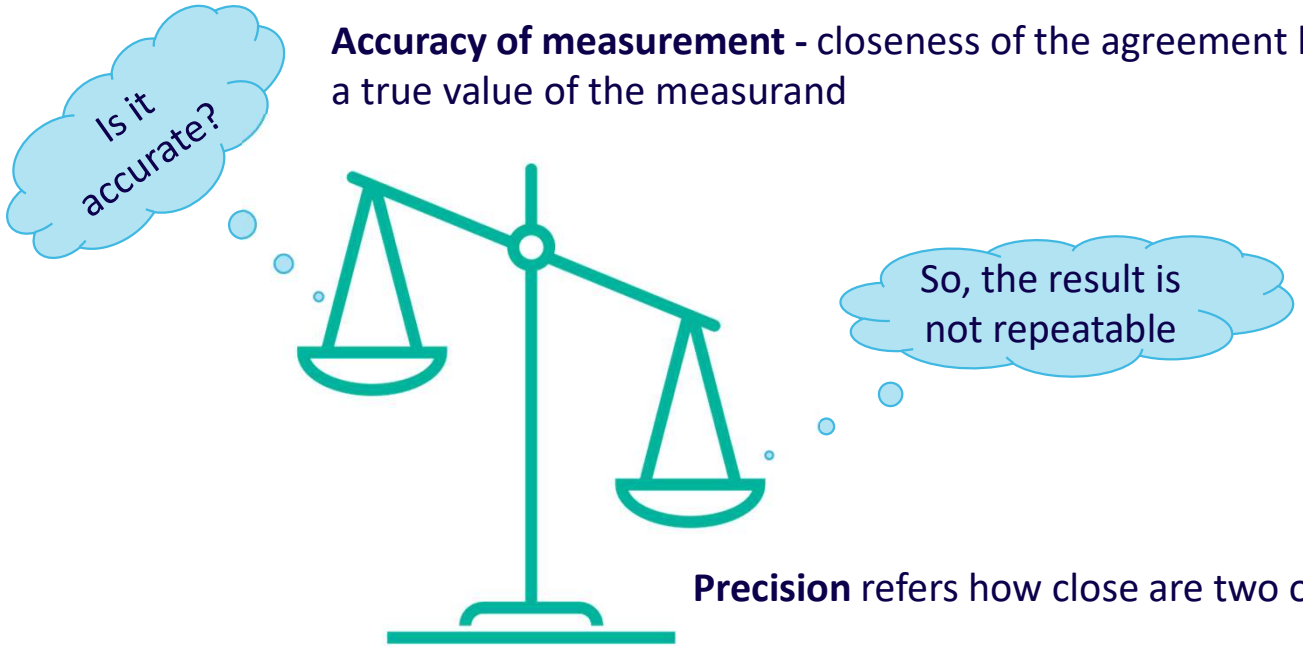
How do we solve the problem of the result with an error ?

Is it a systematic error?





Accuracy and Precision in measurement



Accuracy of measurement - closeness of the agreement between the result of a measurement and a true value of the measurand

[VIM:1993, definition 3.5]

Precision refers how close are two or more measurements to each other.

Accuracy and Precision

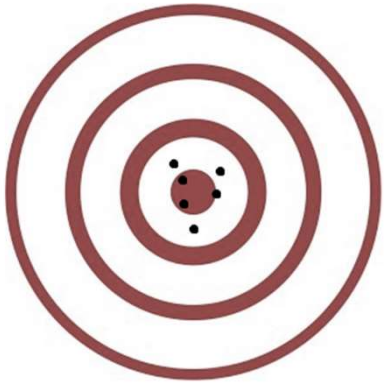
11[mm]
10.99 [mm];]11.01 [mm];
11. 02[mm].

High Accuracy and High Precision

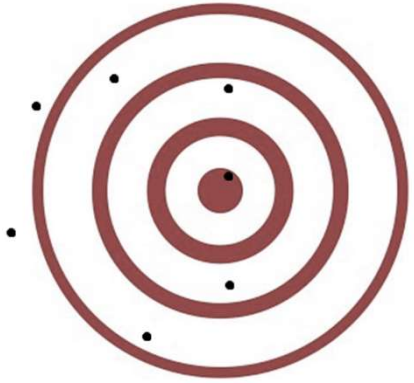
High Precision but Low Accuracy

11[mm]
11.98 [mm]; 12[mm];
12.01[mm].

11[mm]
10.78 [mm]; 11.42 [mm];
11.21[mm].



High Accuracy but Low Precision



Low Accuracy and Low Precision

11[mm]
9 [mm];]10 [mm];
12.01[mm].

Express Accuracy and Precision

Accuracy

relates to the quality of a result.

often referred as Bias error

is measuring near the target or true or reference value

Precision

Precision relates to the quality of the operation by which the result is obtained.

often referred as Repeatability and Reproducibility errors

is getting consistent results of repeated measurements

Bias is the difference between the observed average value and the true or reference value.

Repeatability is the variation in measurements when the same appraiser/person measuring the same part repeatedly with the same instrument.

Reproducibility is the variation in measurements when different appraisers/persons measuring the same part using the same instrument.

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Express Errors

$$\% \text{ error} = \frac{\text{True value} - \text{measured value}}{\text{True value}} \times 100\%$$

Standard mean square deviation

$$S = \pm \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

Where:

Xi – Value of the i measurement;

$\bar{x}$ – the average of the results of the measurements taken into consideration

Average:

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n}$$

Where:
Xi – value of the one measurement;
n - number of repeated measurements

Accuracy and Precision

5min

Case study:

A phone has been passed around to several groups of students. Each group is asked to measure the length of the phone. Each group has five students, and each student independently measures the phone and records his or her result (u.m. = mm).

Group	Student 1	Student 2	Student 3	Student 4	Student 5	Average
Group A	101.0	104.0	96.00	99.9	108.21	**101.82**
Group B	101.35	102.27	102.01	100.11	101.55	**101.46**
Group C	121.4	121.7	121.5	121.4	121.8	**121.56**
Group D	100.5	108.2	80.14	115.1	107.7	**102.33**
Group E	100.0	110.0	100.01	100	100	**102.0**

Which group has the most precise results?

Group C has the most precise results because the results of the measurements are very close

Every student gives an answer with raised hand and the teacher counts the answer.

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Accuracy and Precision

5min

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Group E	100.0	110.0	100.01	100	100	**102.0**

Which group is most accurate?

The group is Unknown because the true value is not known

Every student gives an answer with raised hand and the teacher counts the answer.

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Accuracy and Precision

5min

Case study:

We now receive a report from the **company** where the phone was manufactured. This very reputable firm certifies the phone to be **4 inches long** to the nearest thousandths of an inch. Answer the questions below given this new information.

Group	Student 1	Student 2	Student 3	Student 4	Student 5	Average
Group A	101.0	104.0	96.00	99.9	108.21	**101.82**
Group B	101.35	102.27	102.01	100.11	101.55	**101.46**
Group C	121.4	121.7	121.5	121.4	121.8	**121.56**
Group D	100.5	108.2	80.14	115.1	107.7	**102.33**
Group E	100.0	110.0	100.01	100	100	**102.0**

Which group is least accurate?

Group C is least accurate because the goup C is at the greatest distance from the value given by the company

4 inches = 4x25.4 mm =101.6 mm

Every student gives an answer with raised hand.

Accuracy and Precision

5min

Case study:

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Group E	100.0	110.0	100.01	100	100	**102.0**

Which group is least precise?

The results of group D are the least accurate because they have the maximum variation between results

4 inches = 4x25.4 mm =101.6 mm

Every student gives an answer with raised hand.

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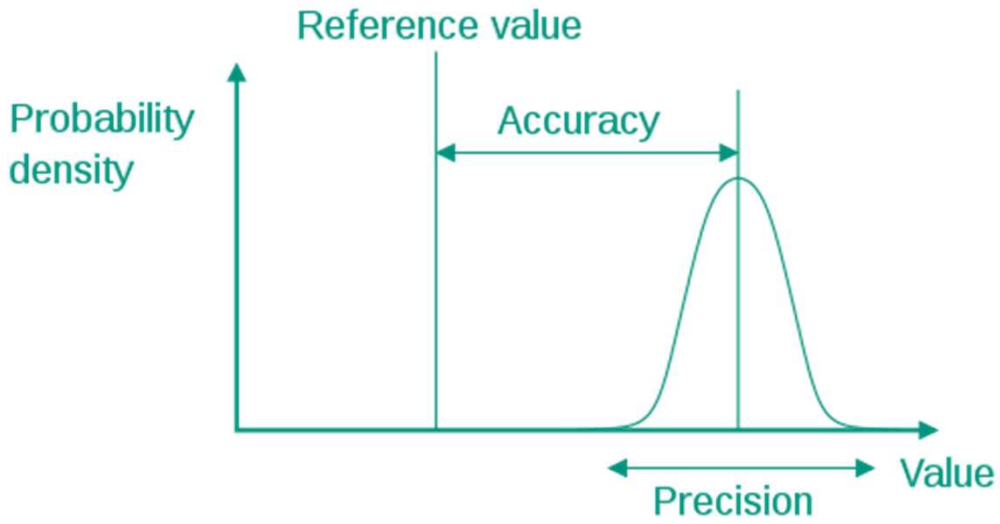
Accuracy and Precision

Accuracy relates to the quality of a result.



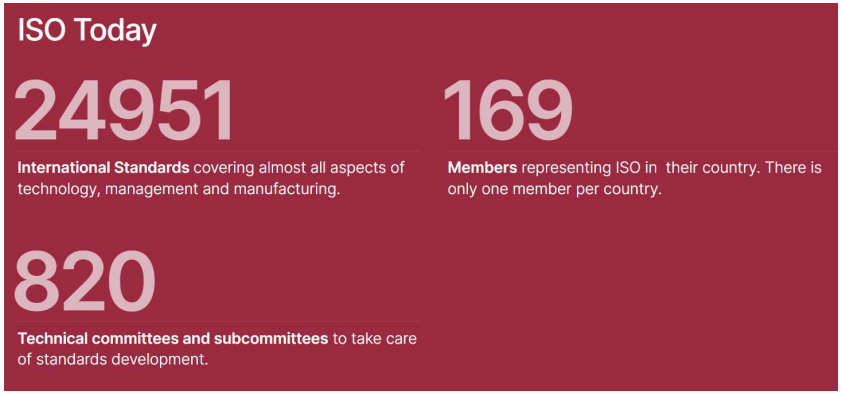
Precision is an indication of the repeatability and reproducibility of a result.

Ensure safety and production quality

https://www.atlascopco.com/ro-ro/itba/service/service-offerings/maintenance/calibration/faq-why-calibrate

International Organization for Standardization

"ISO - is an independent, non-governmental international organization
- was founded with the idea of answering a fundamental question: "what's the best way of doing this?""



"ISO is derived from the Greek "isos", meaning equal. Whatever the country, whatever the language, we are always ISO".

Source: https://www.iso.org/about-us.html

Standards

"When things don't work as they should, it often means that standards are absent".

"Think of them as a formula that describes the best way of doing something.

It could be about making a product, managing a process, delivering a service or supplying materials – standards cover a huge range of activities.

Standards are the distilled wisdom of people with expertise in their subject matter and who know the needs of the organizations they represent – people such as manufacturers, sellers, buyers, customers, trade associations, users or regulators."

https://www.iso.org/about-us.html

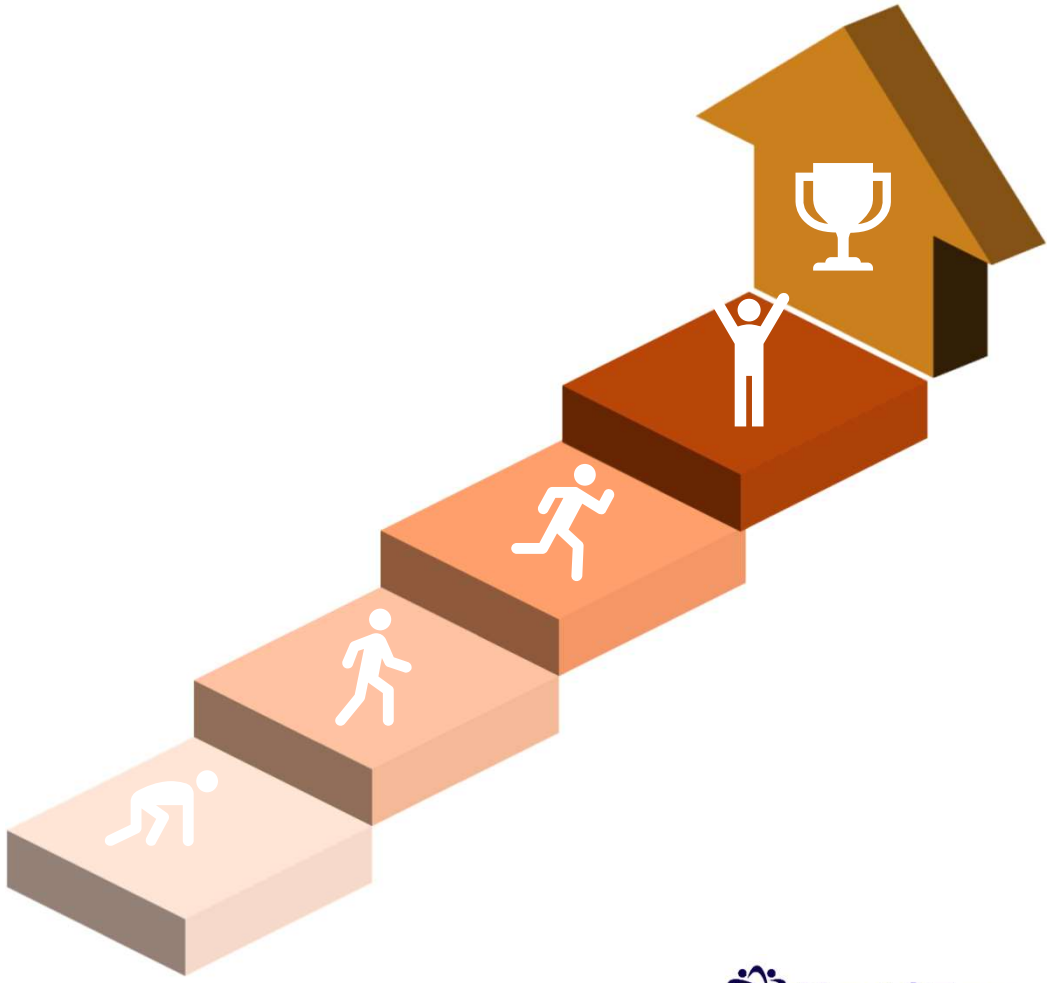
ISO and the environment

https://www.iso.org/iso-14001-environmental-management.html

Conclusions

As a result, you know:

- ☑ What the measurement errors are
- ☑ The classification of the measurement errors
- ☑ The calculation of the measurement errors
- ☑ How to establish the accuracy and precision of the measurements



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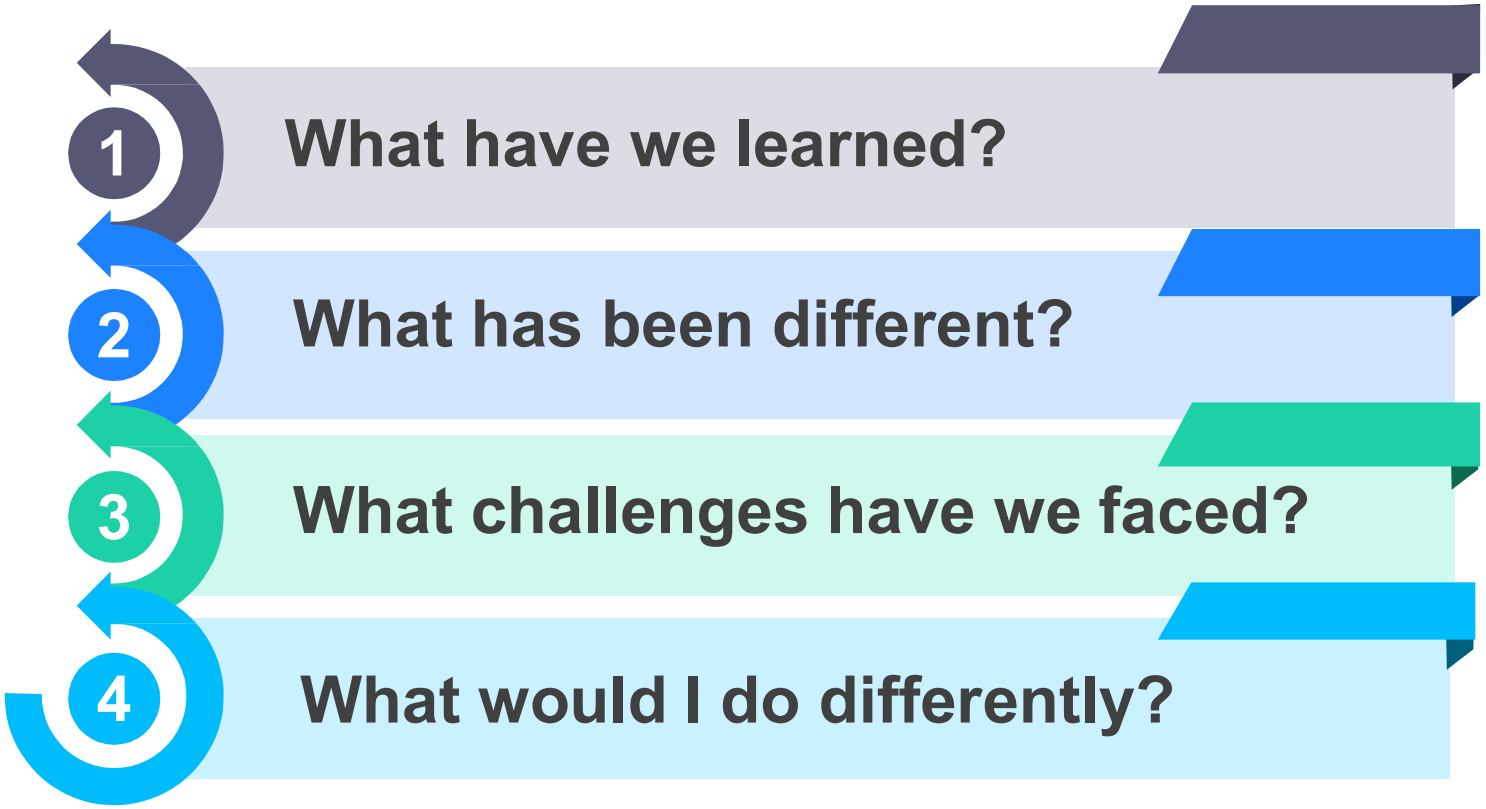
Feedback



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Thank you for your interaction!

Assoc.prof. **Simona NOVEANU** Ph.D.

- Email: simona.noveanu@mdm.utcluj.ro

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https://www.iso.org/standards.html

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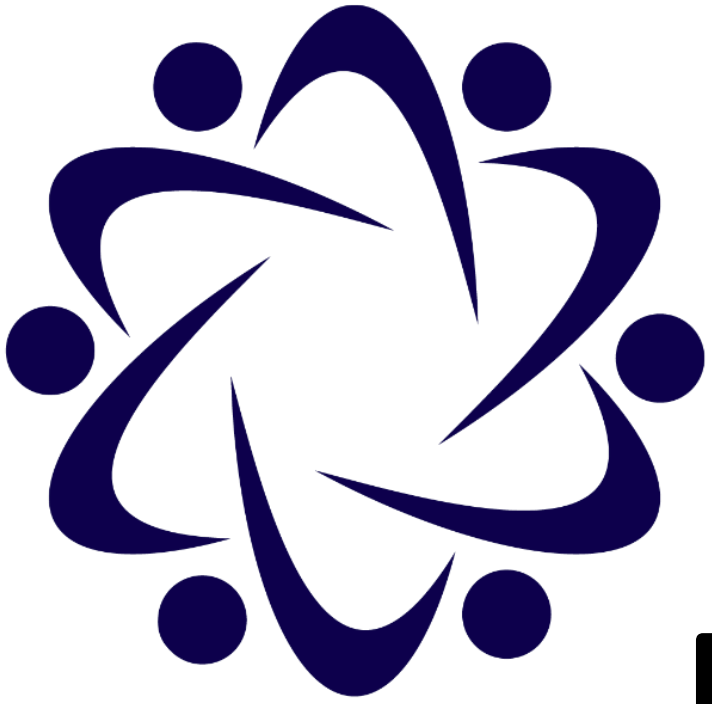
Thank you!

Kiitos!



Gracias!

Mulțumesc!

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C4 – Quality assurance and applied methods

M2 – Uncertainties in the Measurement

CO – Technical University of Cluj-Napoca

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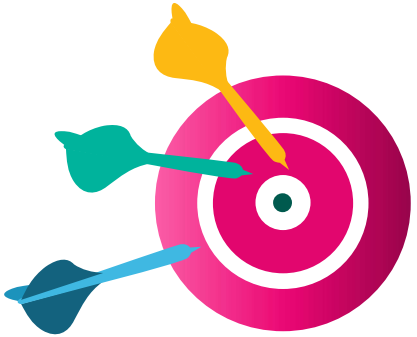
Aim

Knowledge to determine the measuring uncertainties for the quality assurance.

Objectives



- ☑ Knowledge about measurements and standards
- ☑ Understanding the measurement uncertainty
- ☑ Calculating the uncertainties for a product
- ☑ Knowledge the calibration
- ☑ Knowledge the transability at quality assurance

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Content

- Introduction
- Measurements and standards in metrology
- Measurement uncertainties
- Calibration, Trasability and quality assurance
- Conclusions

Motivation

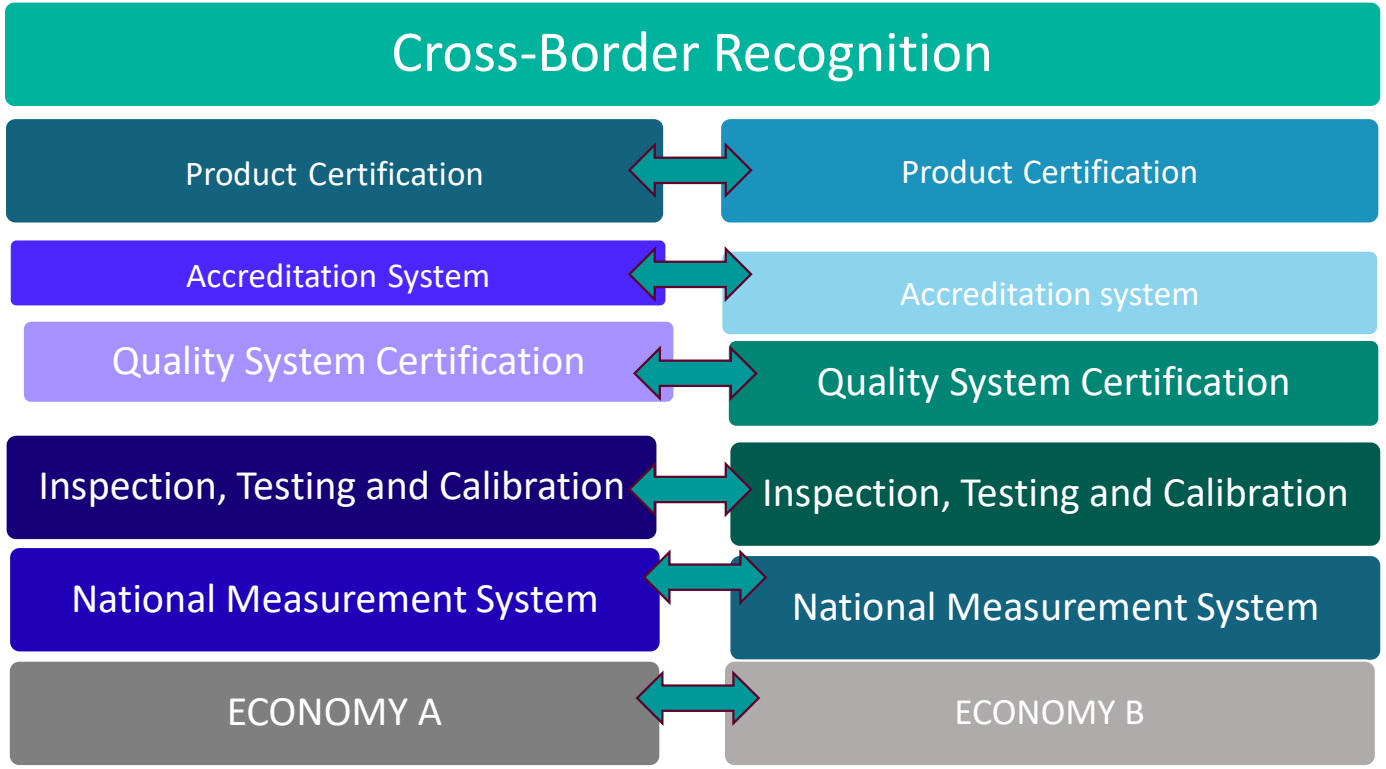
The quality control process is based on the measurements and in order to get a certification of the measurement results we must know the uncertainties.

International Market

(5 min)

Debate

Confidence in results of measurements prerequisite to international trade.



Trade dispute

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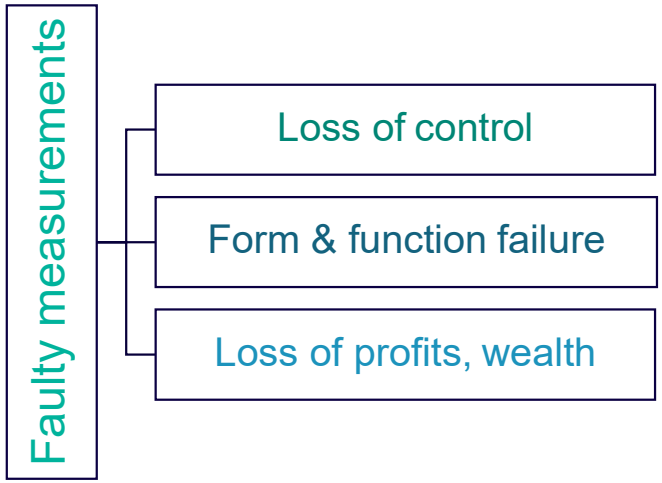
Measurements and Metrology

"Metrology is the science of measurement and its application"

[VIM:2021, definition 2.2]

Metrology includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.



What content any Standard?

- **Be measurable**
- Consensus of expert opinions
- Assurance for a fair competition of products and services
- Coherence and credibility
- Core requirements, terminology, definitions
- Harmonized across borders with other standards
- Transparency and accountability.

Pillars of sustainable development

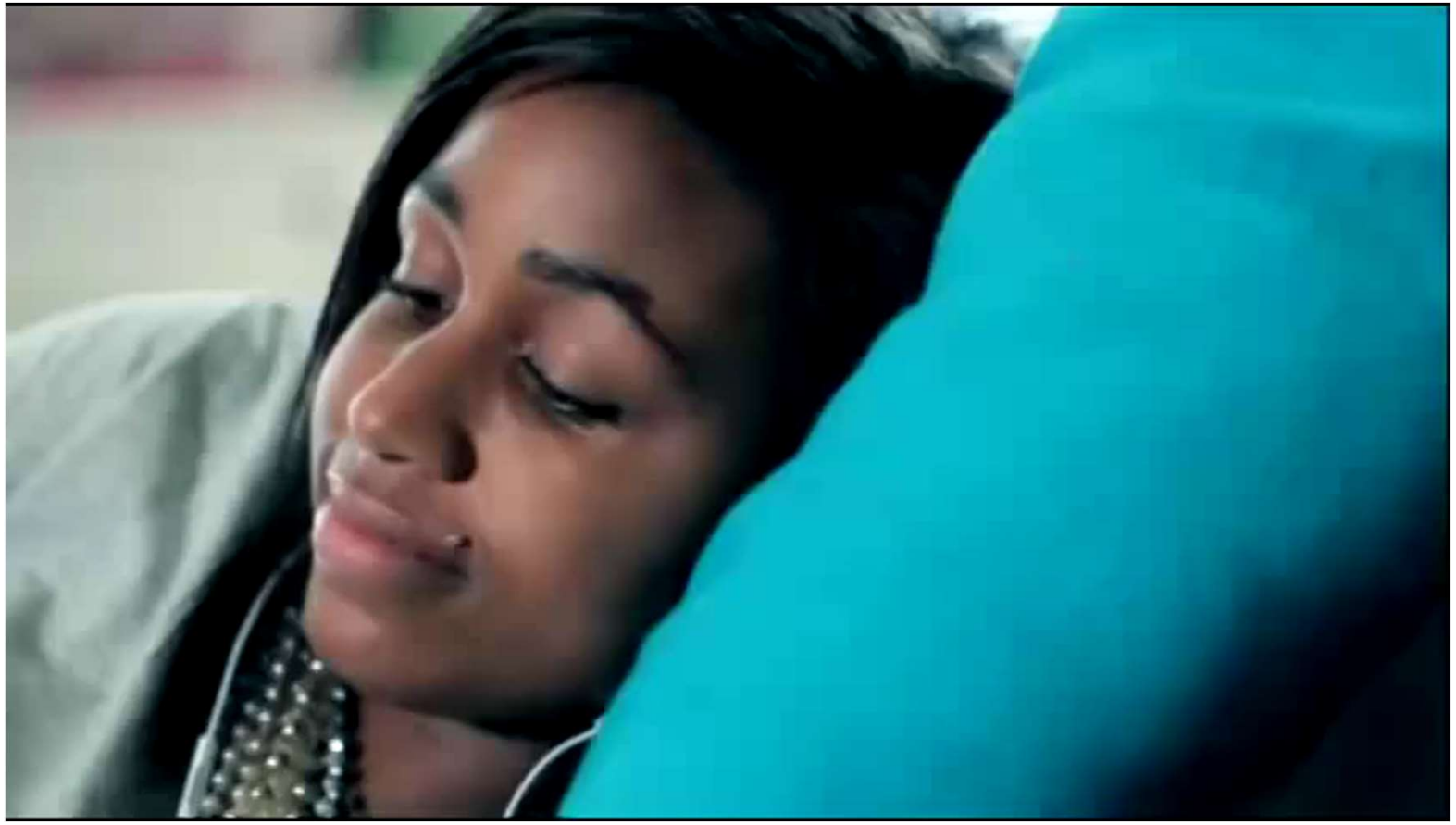
Pillars as a technical basis of Quality Measurements and Sustainable Development:

Express what is wanted	• Standardization – Documentary standards
Deliver what is expressed	• Conformity Assessment
Measure what is delivered	• Metrology – Measurement standards

Standards are important tools to implement sustainability.

International Organization for Standardization

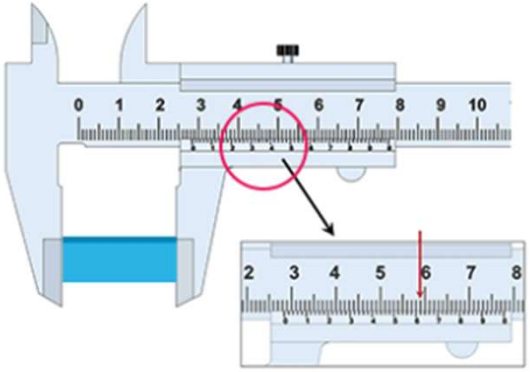
ISO

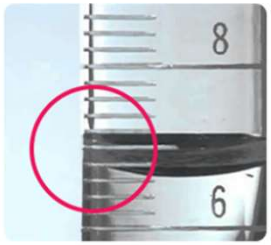


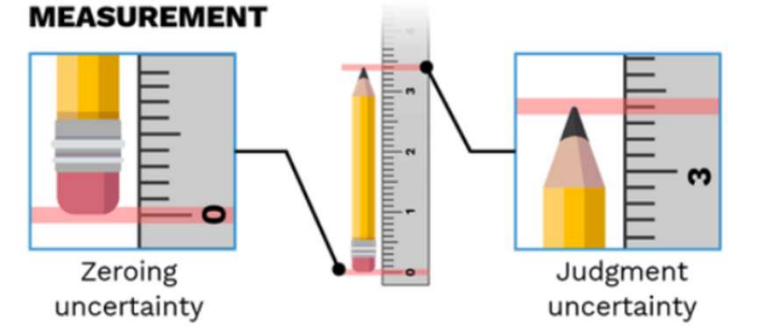
https://www.iso.org/benefits-of-standards.html

Uncertainty (of measurement)

(5 min)







https://byjus.com/chemistry/uncertainty-in-measurement/

https://www.labster.com/blog/make-measurements-uncertainty-approachable

Debate

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Error

- takes into consideration the **true value** of the measurand

- appears as a **qualitative** expression

- has a **deterministic** character

- is defined so that the measurement result is presented by the **simple expression**, **x +e** or **x - e**

Uncertainty

- takes into consideration the **measured value as** an interval centred around the true value

- appears as a **quantitative** expression

- has a **probabilistic** character

- is defined so that the measurement result is presented by the simple **symmetrical expression**, **x ±U.**

Uncertainty (of measurement)

[VIM:2021, definition 3.1]

Is a parameter characterizing the dispersion of the values being attributed to a measurand, based on the information used

A way to interpret measurement uncertainty is as indecision or doubt, either about the essentially unique true value of the measurand that remains after making a measurement, or about the measured value to be chosen to represent a measurement result	The parameter characterizing dispersion is either positive or zero. It may be, for example, a **standard uncertainty** (or a specified multiple of it), or the half-width of an interval, having a stated **coverage probability**.	Measurement uncertainty includes components arising from systematic effects, such as components associated with **corrections** and values attributed to quantities of **measurement standards**. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated.	Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by **Type A evaluation** from the probability distribution of the values from series of **measurements** and can be characterized by standard deviations. The other components, which may be evaluated by **Type B evaluation**, can also be characterized by standard deviations, evaluated from probability distributions based on experience or other information.	In general, for given information, as mentioned in the definition, it is understood that the measurement uncertainty is associated with a stated value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.	Measurement uncertainty is generally part of a **measurement result**. If instead a measurement result is reported as a single **measured value**, then only significant digits should be reported.

Mean and Standard deviation

ISO/IEC GUIDE 98-6:2021 pp. 26

For a set of values x_i, i = 1,. .. , n, which may be repeated observations, obtained independently, of some quantity, formula for their mean $\bar{x}$ and standard deviation.

- **Mean (average):**

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots + xn}{n}$$

- **Standard deviation:** $S = \pm\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$

Where:

Xi – Value of the first measurement;

$\bar{x}$ – the arithmetic mean of the results of the measurements taken into consideration

n - number of repeated measurements

- **Standard deviation of the average:** $S_m = \frac{S}{\sqrt{n}}$

Measurement uncertainty

- **Standard measurement uncertainty:** u (x) is the expression of the uncertainty value in the dispersion (s or σ). It contains the measurement error or the effect of several influential elements.

$$s = u(x)$$

- **Expanded measurement uncertainty** is the multiple of the measurement dispersion. It contains all the effects of random and systematic factors as well as dispersion factors. The coverage factors k are the uncertainty multipliers:

$$U = k \cdot u(x)$$

- **Coefficient of variation** - the ratio between the standard deviation and the arithmetic mean of the determinations, expressed as a percentage. An internal quality control sample is taken into consideration.

$$CV = \frac{S \cdot 100}{\bar{x}}$$

Combined standard measurement uncertainty

Combined standard uncertainty: u(y) is the resultant, the combination of one or more standard uncertainties. Based on their role or participation in the size of the measurement error, they can be weighted.

$$u(y) = \sqrt{\sum_{i=1}^{n} u(x_i)^2}, \text{ where n is number for standard uncertainties}$$

$$U_c = \pm\sqrt{\sum_{i=1}^{n}(U_i)^2} = \pm\sqrt{U_{B1}^2 + U_{B2}^2 + U_{B3}^2 + U_{B4}^2 + \cdots + U_{Bn}^2},$$

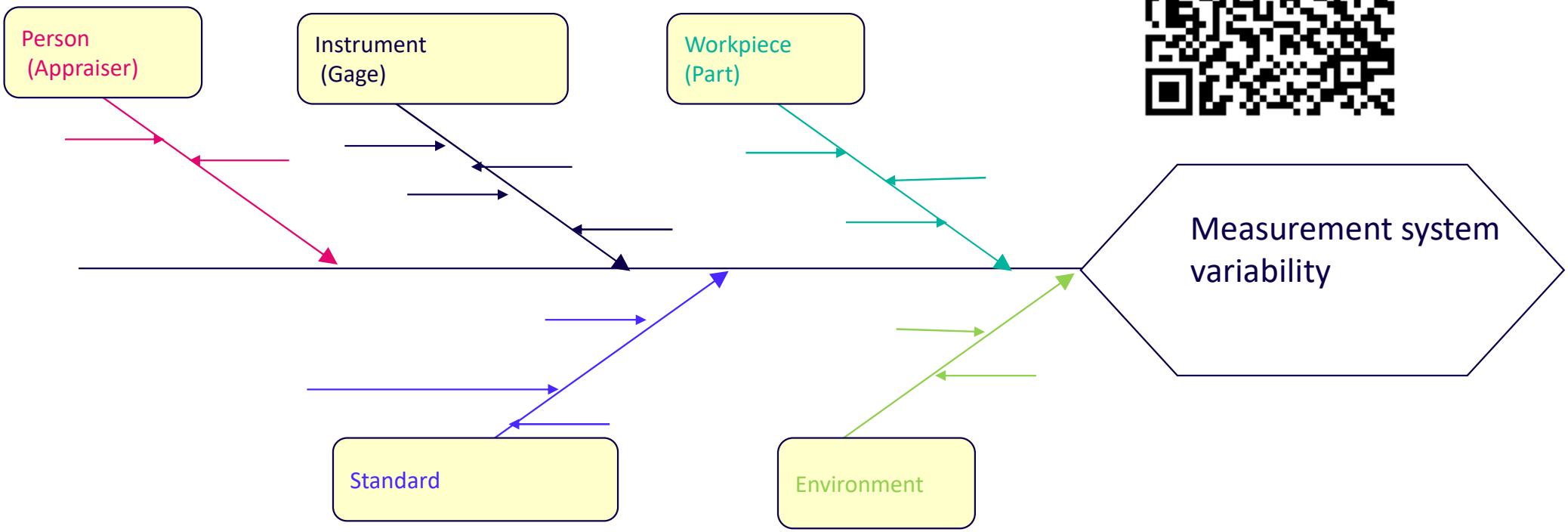
where U_{Bi} is the value of the sources

Extended combined standard uncertainty: $U_c = 2 * u_c$, (if k = 2)

The uncertainty sources

(10 min)

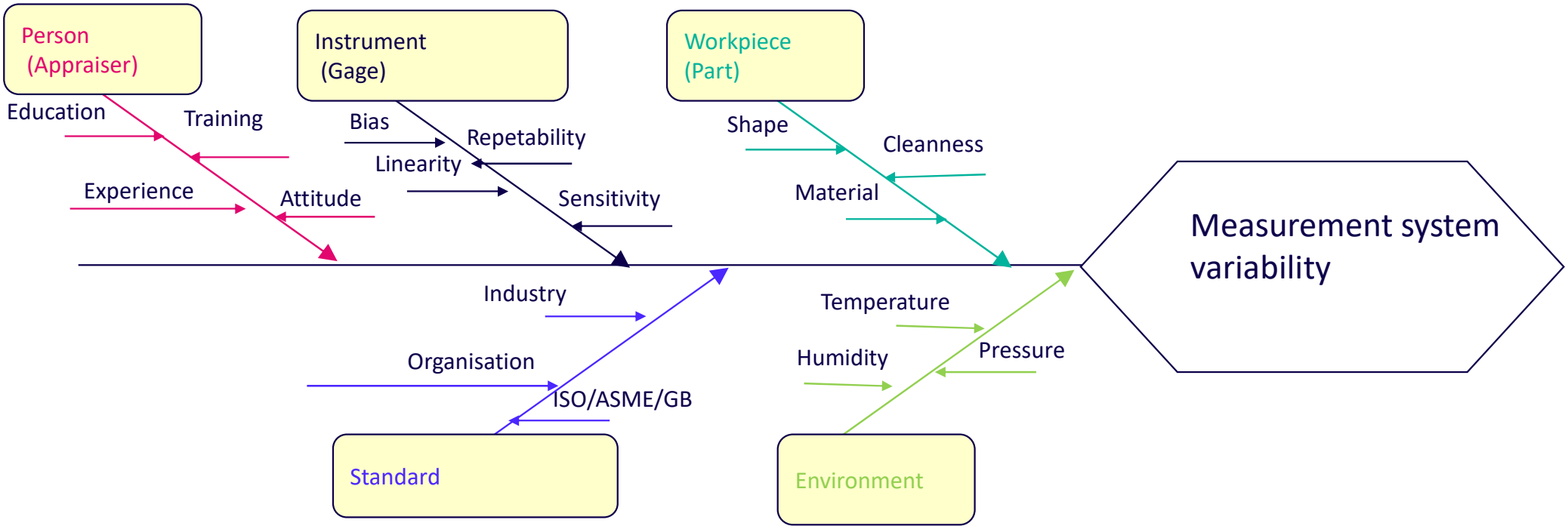
Scan Me!



Gamification – Fill the sticky notes on the jamboard file!

The uncertainty sources

Comparison jamboard files with selections from ISO/IEC GUIDE 98-6:2021 pp. 83



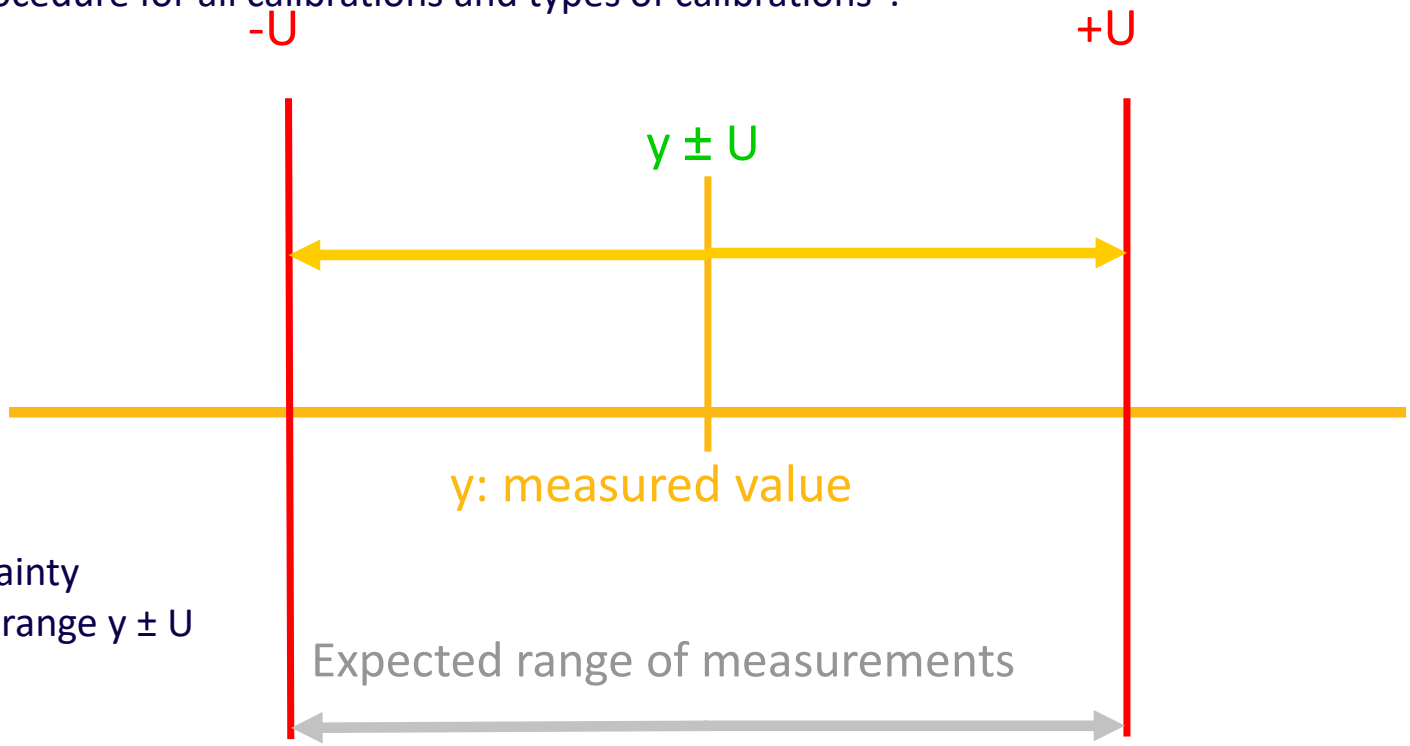
Free discussion

Measurement uncertainty

SR EN ISO 17025:2007

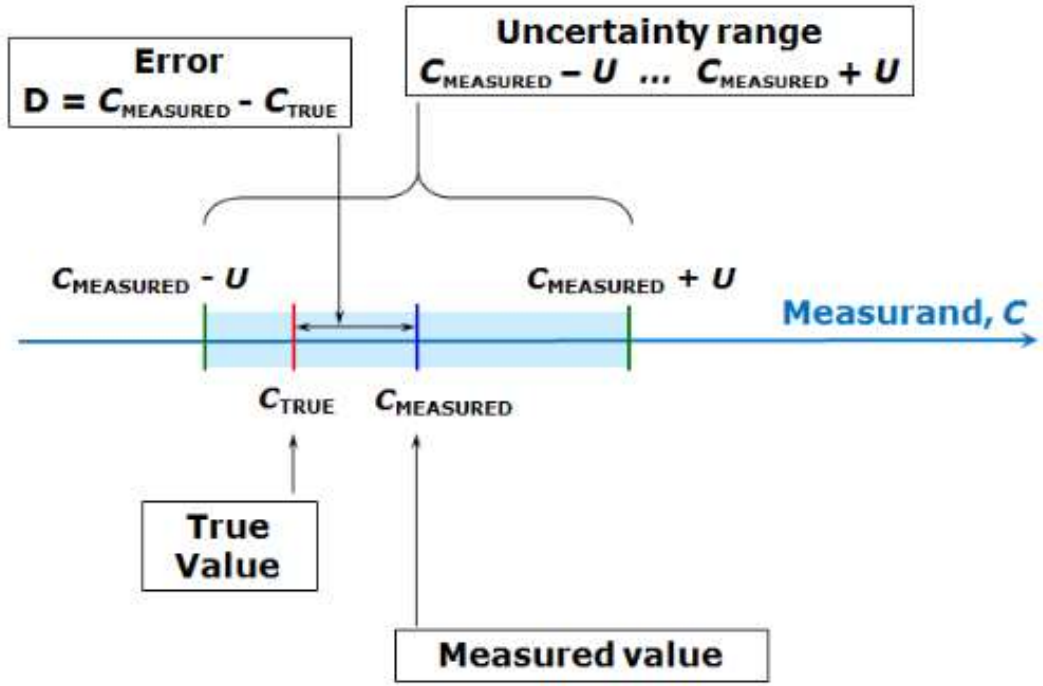
5.4.6 Estimation of measurement uncertainty

- "A calibration laboratory or a testing laboratory that performs its own calibrations must have and apply a measurement uncertainty estimation procedure for all calibrations and types of calibrations".



y – measurement value
U – measurement uncertainty
The "true value" is in the range y ± U

Error and Uncertainty



Estimation of measurement uncertainty

- SR EN ISO 17025:2007

"In certain cases, the nature of the test methods may not allow a rigorous, metrological and statistically valid calculation of the measurement uncertainty. In this case, at least, the laboratory must try to identify all uncertainty components and make a reasonable estimate"

"A reasonable estimate must be based on knowledge of the method's performance and measurement range and use, for example, previous experience and validation data."

"When estimating measurement uncertainty, all uncertainty components that are important in the given situation must be taken into account, using appropriate analysis methods."

The GUM steps/method

Identify all the important components of measurement uncertainty

- There are many sources that can contribute to the measurement uncertainty. Apply a model of the actual measurement process to identify the sources. Use measurement quantities in a mathematical model.

Calculate the standard uncertainty of each component of the measurement uncertainty

- Each component of measurement uncertainty is expressed in terms of the standard uncertainty determined from either a type A or type B evaluation.

Calculate the combined uncertainty

- The principle: The combined uncertainty is calculated by combining the individual uncertainty components according to the law of propagation of uncertainty.
- In practice: a) For a sum or a difference of components, the combined uncertainty is calculated as the square root of a sum of the squared standard uncertainties of the components; b) For a product or a quotient of components, the same “sum/difference” rule applies for the relative standard uncertainties of the components.

Calculate the expanded uncertainty

- Multiply the combined uncertainty with the coverage factor k.

State the measurement result on the form $Y = y \pm U$

Guide to the Expression of Uncertainty in Measurement

(GUM)

1. A measured quantity X, whose value is not known exactly, is considered as a stochastic variable with a probability function.

2. The **result x** of the measurement is an estimate of the expectation value.

3. The **standard uncertainty u(x)** is equal to the square root of an estimate of the variance.

4. **Type A evaluation.** Expectation and variance are estimated by statistical processing of repeated measurements.

5. **Type B evaluation.** Expectation and variance are estimated by other methods. The most commonly used method is to assume a probability distribution e.g. a rectangular distribution, based on experience or other information.

Type A evaluation of measurement uncertainty

[VIM:2021, definition 3.4]

Type A - evaluation of a component of **measurement uncertainty** by a statistical analysis of **measured values** obtained under defined **measurement** conditions.

- NOTE 1 For various types of measurement conditions, see repeatability condition of measurement, intermediate precision condition of measurement, and reproducibility condition of measurement.
- NOTE 2 For information about statistical analysis, see for example the GUM.
- NOTE 3 See also the GUM, entry 2.3.2, and the ISO 5725 series of International Standards, Accuracy (trueness and precision) of measurement methods and results, ISO 13528, Statistical methods for use in proficiency testing by interlaboratory comparison, ISO/TS 21748, Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty estimation, ISO 21749, Measurement uncertainty for metrological applications – Repeated measurements and nested experiments

State the measurement result on the form $Y = y \pm U$

Type B evaluation of measurement uncertainty

[VIM:2021, definition 3.5]

Type B - evaluation of a component of **measurement uncertainty** determined by means other than a Type A evaluation

- associated with authoritative published values,
- associated with the value of a property of a certified reference material,
- obtained from a calibration certificate,
- about drift,
- obtained from the accuracy class of a verified measuring instrument,
- obtained from limits inferred through personal experience.
- NOTE See also the GUM, entry 2.3.3.

State the measurement result on the form Y = y ± U

The method of evaluating the uncertainty

The ideal method for evaluating and expressing the uncertainty of a measurement result should be:

universal: the method should be applicable to all types of measurements and to all types of input data used in the measurements.

The actual quantity used to express the uncertainty should be:
internally consistent: it should be directly derivable from the components that contribute to it, and also independent of how these components are grouped, as well as the decomposition of components into subcomponents;

transferable: it is necessary that the uncertainty assessed for a given result can be used as a component in the assessment of the uncertainty of another measurement in which the first result is used.

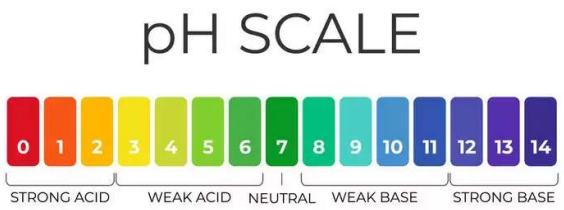
Statistic Uncertainty - Example

World Health Organization

Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda (March 2022)

The pH value = 6.5-8.5

https://cdn.who.int/media/docs/default-source/wash-documents/water-safety-and-quality/dwq-guidelines-4/4th-ed.-inc-1st-and-2nd-add-summary-of-changes-with-2nd-addendum.pdf?sfvrsn=8735b15b_7



We want to know the quality of tap water (pH – acidity or basicity) to determine whether it is safe to drink or not, it is necessary to take a sample and to performed many measurements.

We made several measurements and get the values for pH: **6.99, 7.0, 6.95, 7.02, 7.01**.

In this case, it is very likely that the true value is around **7.**

Average: $\bar{x} = \mathbf{6.994}$

Standard deviation: $S = \mathbf{0.027018512}$

Extended uncertainty: **U =** 0.054037024

Result: Is in the value limits from World Health Organisation.

Categories of drinking water parameters are:

- *Physical - sediment or organic material.*
- *Chemical - salts, pesticides and metals.*
- *Biological or microbial - bacteria, viruses and parasites.*
- *Radiological - cesium, plutonium and uranium.*

Source: https://www.directenergy.com/learning-center/tap-water-impurities

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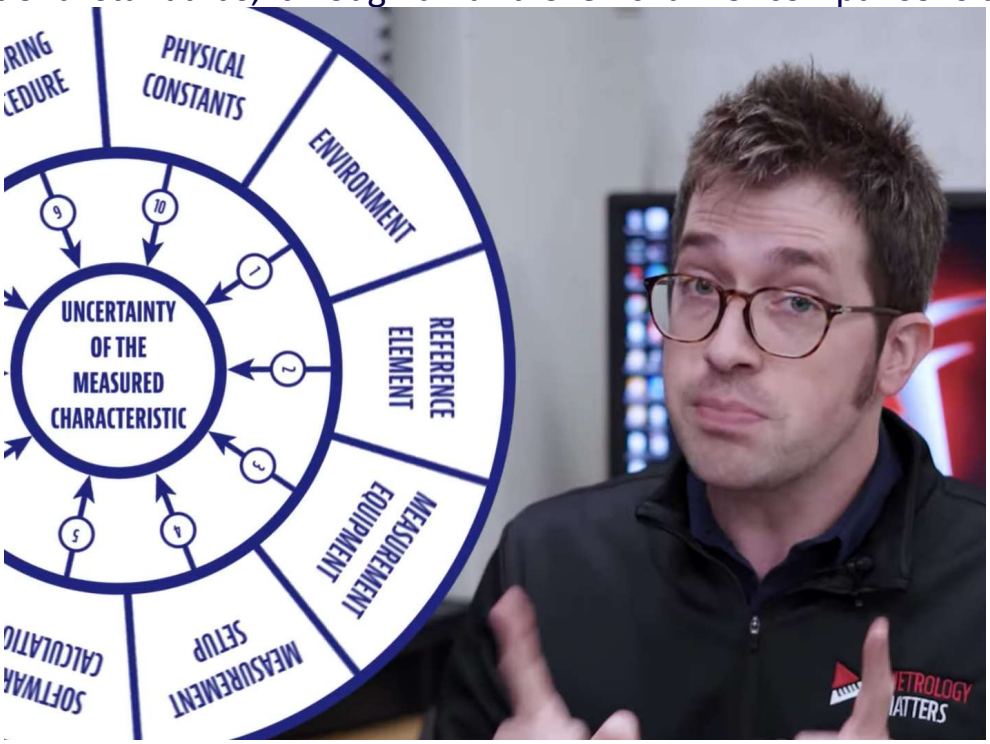
Traceability and Uncertainty

"Traceability is property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties."

[International Vocabulary of Basic and General Terms in Metrology]



https://www.youtube.com/watch?v=LBx39DYCuLw&ab_channel=ProductivityQuality

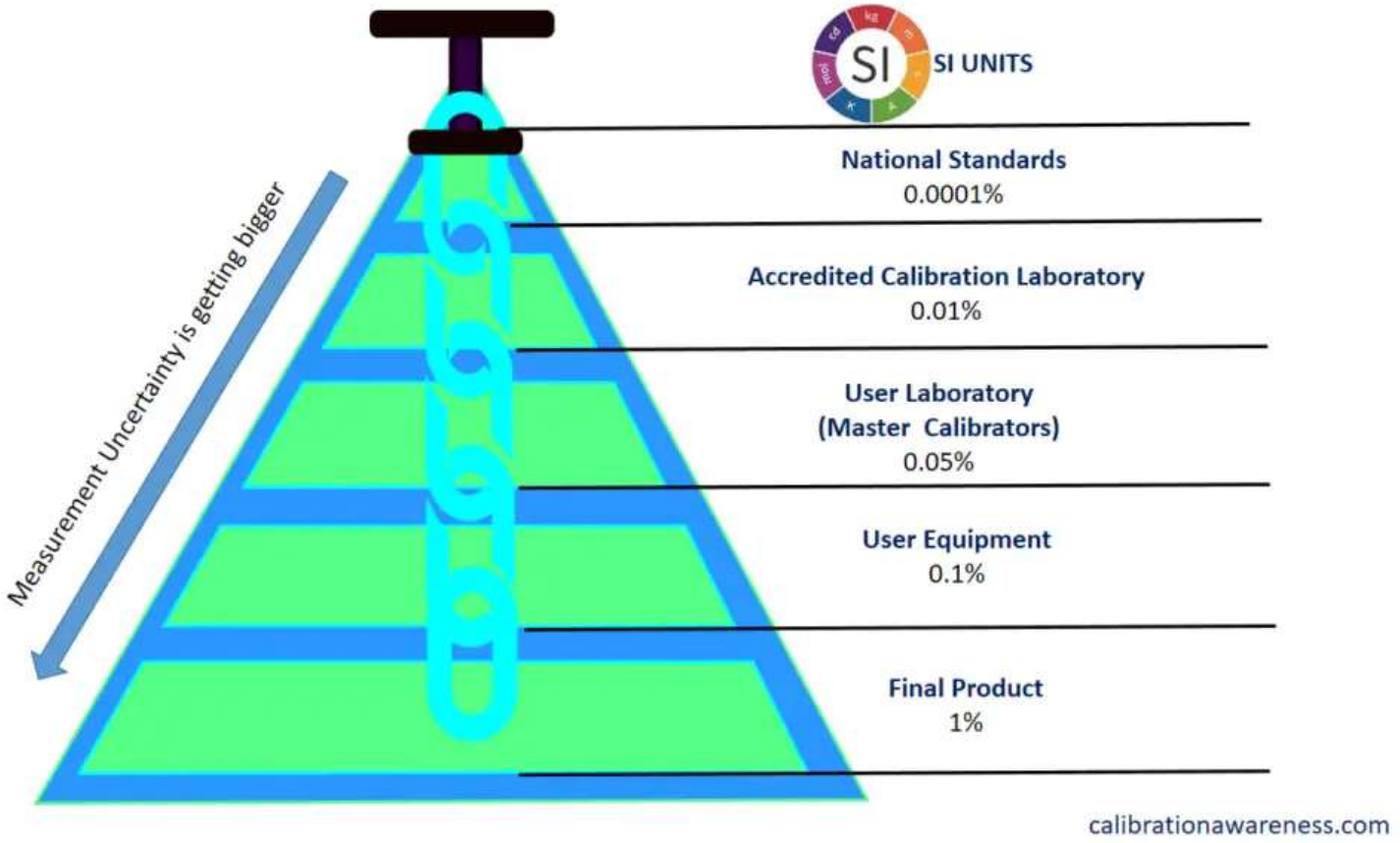
Customer needs to be sure that the measurements are correct.

Traceability

https://manufacturing-software-blog.mrpeasy.com/traceability/

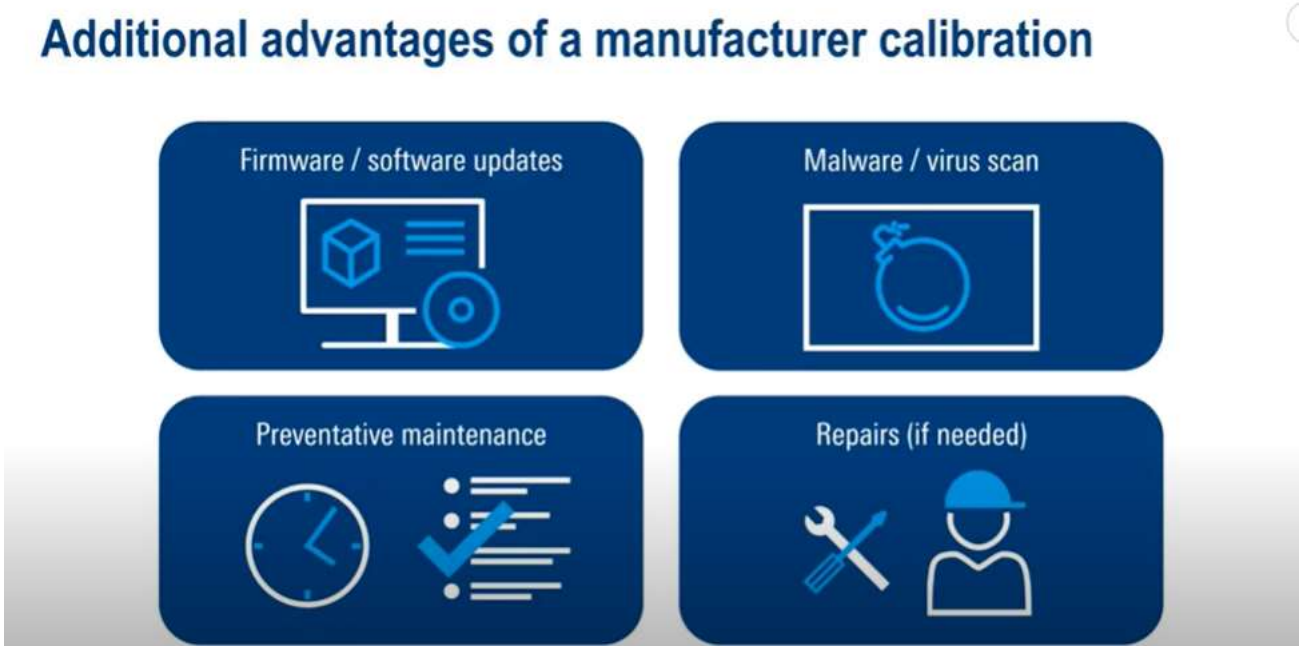
Gamification – Say an example and give the answer ball to the next person!

Traceability and Calibration



Advantages of Calibration

General requirements for the competence of testing and calibration laboratories - SR EN ISO/IEC 17025:2018



https://www.youtube.com/watch?v=psvw2tPLkKQ&ab_channel=RohdeSchwarz

Benefits of Traceability

https://manufacturing-software-blog.mrpeasy.com/wp-content/uploads/2021/03/traceability-benefits-2-e1614679186869.png

Traceability and Calibration

In the technical field we want to have traceable measurements, for this we need:

- A list of the significant uncertainty contributors for the measurement.
- A list of the equipment (serial no. etc.) used in the measurement that adds a significant uncertainty to the final result.
- A reference to traceability has to be mentioned for each part of equipment (Calibration scope, calibration source, calibration date and calibration id, e.g. certificate number).

Traceability and Calibration

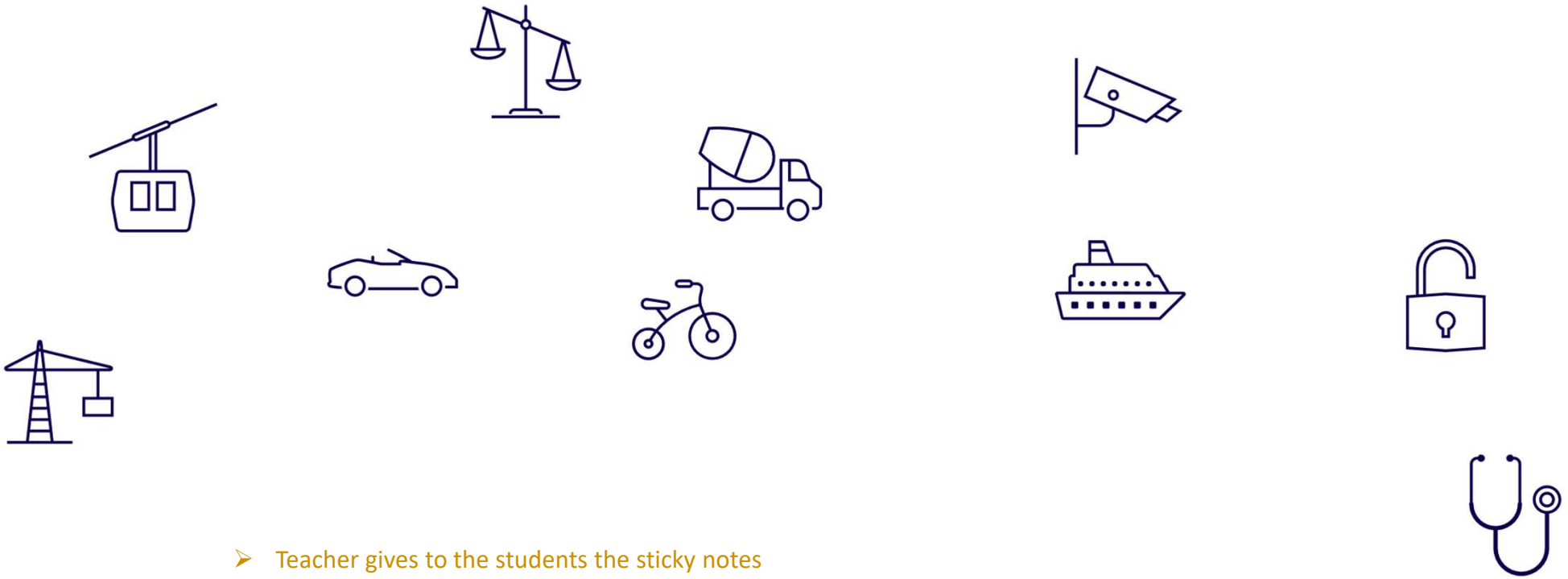
Metrological **traceability** - Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of *calibrations*, each contributing to the measurement *uncertainty*. *[source: VIM 3 clause 2.41]*

A basic tool for ensuring the *traceability* of a measurement is the *calibration*.

General requirements for the calibration laboratories - SR EN ISO/IEC 17025:2018

The Guide to the Expression of Uncertainty in Measurement gives a way to express uncertainty that allows the uncertainty in a calibration to be “carried over” into the uncertainty budget for subsequent measurements with the standard or instrument. It also allows us to compare two measurements of the same item and determine whether they agree, given their uncertainty.

Where we need Traceability?



- Teacher gives to the students the sticky notes
- Every student writes about applications for traceability and puts the Sticky notes on the flipchart
- Teacher discusses together with the students about the traceability in measurements.

Traceability- Callibration - Acreditation

Traceability may therefore require **calibration** of several attributes of the measuring equipment and not all of them may be in the unit of what we are measuring.

E.g., the the traceability of the calibration of the temperature sensor becomes a significant part of the uncertainty for the length measurement.

Using this logic, the information needed to prove that a measurement is traceable in the technical sense is a list of the significant uncertainty contributors for the measurement.

Accreditation is intended to provide this credibility. Accreditation is essentially a third party putting a seal of approval on the comparisons and the accompanying uncertainties that a calibration laboratory performs.

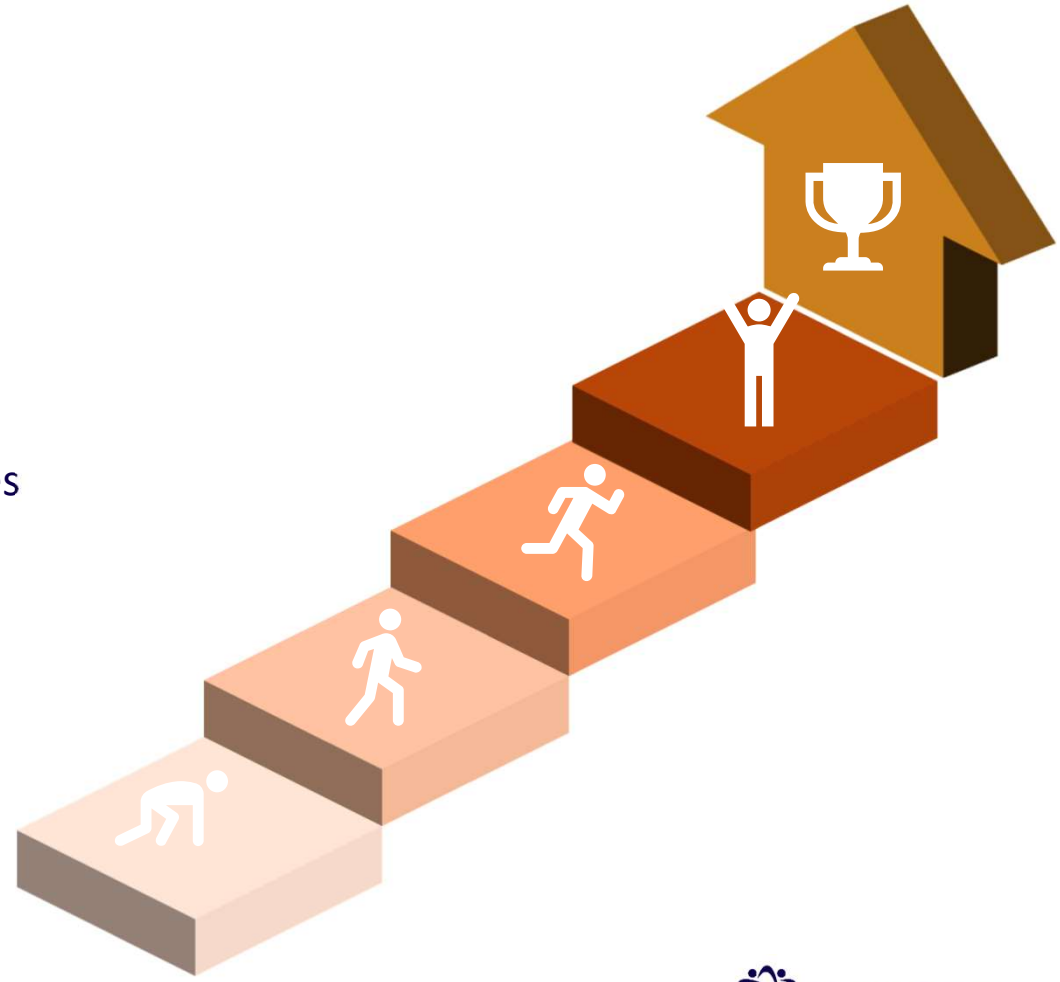
Traceability system

https://www.verifarma.com/what-is-traceability/

Conclusions

As a result, you know:

- ☑ What the measurement uncertainty is
- ☑ The classification and resources of uncertainties
- ☑ The calculation of the uncertanty of the measurements
- ☑ Calibration and traceability



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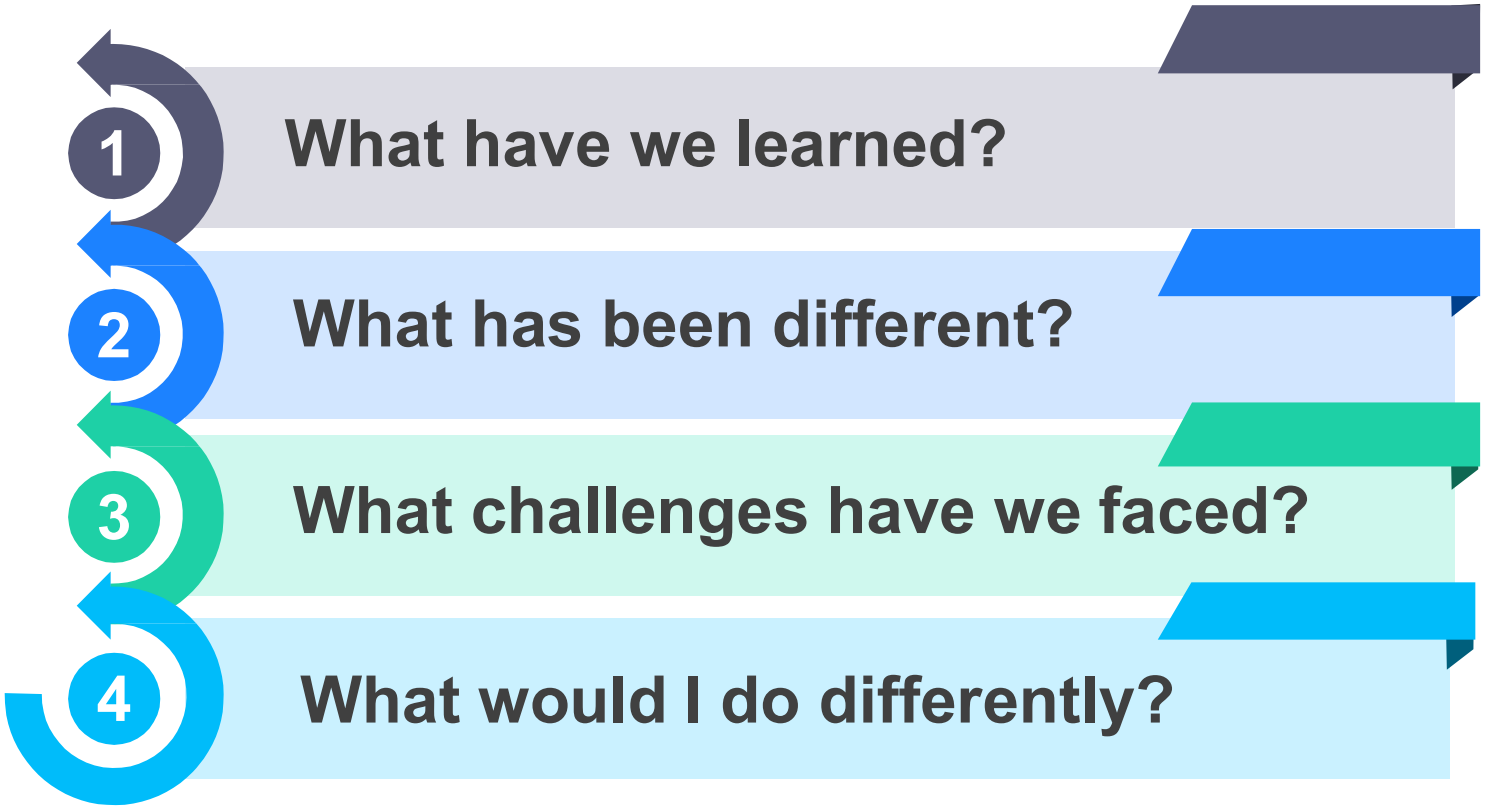
Feedback



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Thank you for your calibration despite some moments of uncertainty!

Assoc.prof. **Simona NOVEANU** PhD

- Email: simona.noveanu@mdm.utcluj.ro

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[1] Source: European Commission, Drinking water reporting requirements and synthesis reports, Link

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https://calibrationawareness.com/the-deeper-meaning-of-a-traceable-calibration-every-calibration-technician-must-understand?expand_article=1

https://www.youtube.com/watch?v=Lw2h_jjBHcU&ab_channel=MITOpenCourseWare

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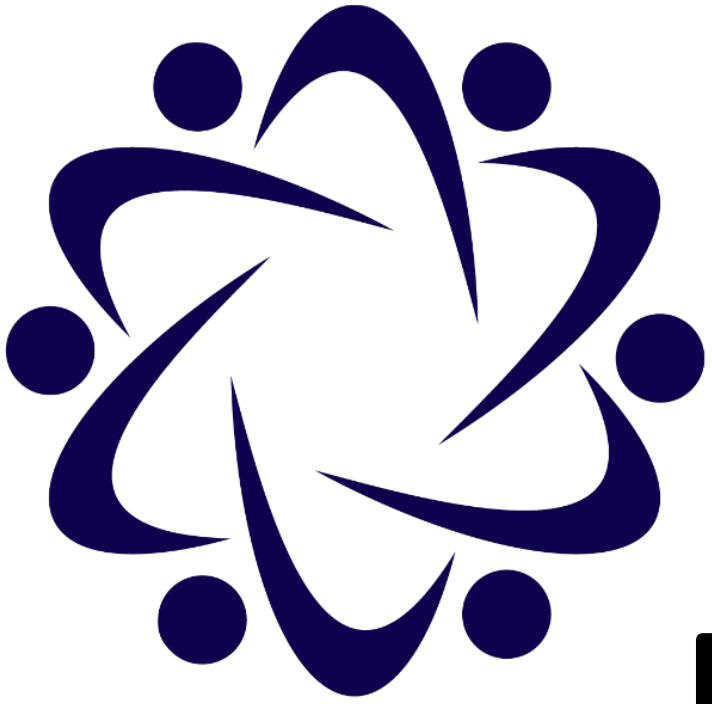
Thank you!

Kiitos!



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M3 – Development Techniques - FMEA

P1 – JAMK University of Applied Sciences

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Development Techniques

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Content

- © Open Source Six Sigma, LLC
- Managing the Measure Phase in a Lean Six Sigma Project (www.pluralsight.com)
- © Robert Bosch GmbH | Date 06.2012 Failure Mode and Effects Analysis (FMEA)

FMEA; Failure Mode and Effects Analysis

History of FMEA

- First used in the 1960's in the Aerospace industry during the Apollo Missions
- In 1974 the Navy developed MIL-STD-1629 regarding the use of FMEA
- In the late 1970's automotive applications driven by liability costs began to incorporate FMEA into the management of their processes
- Automotive Industry Action Group (AIAG) now maintains the FMEA standard for both Design and Process FMEA's

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Types of FMEA

System FMEA: Performed on a product or service product at the early concept/design evel when various modules all tie together. All the module level FMEA's tie together to form a system. As you go lower into a system more failure modes are considered.

- Example: Electrical system of a car, consists of the following modules: battery, wiring harness, lighting control module and alternator/regulator.
- System FMEA focuses on potential failure modes associated with the modules of a system caused by design

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Types of FMEA

Design DFMEA: Performed early in the design phase to analyze product fail modes before they are released to production. The purpose is to analyze how fail modes affect the system and minimize them. The severity rating of a fail mode MUST be carried into the Process PFMEA.

Process PFMEA: Performed in the early quality planning phase of manufacturing to analyze fail modes in manufacturing and transactional processes that may escape to the customer. The failure modes and the potential sources of defects are rated and corrective action taken based on a Pareto analysis ranking.

Equipment FMEA: used to analyze failure modes in the equipment used in a process to detect or make the part.

- Example: Test Equipment fail modes to detect open and short circuits

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Purpose of FMEA

- Improve the quality, reliability and safety of products.
- Increase customer satisfaction.
- Reduce product development time and cost.
- Document and track actions taken to reduce risk and improve the process.
- Focus on continuous problem prevention not problem solving.

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When Do I Need to Use FMEA?

- An FMEA should be used when teams need more detailed information about inputs and possible associated fail-points
- It offers some of the information that is offered by SIPOC, but it also provides evaluations of the inputs

Structuring Your FMEA Spreadsheet

To create a FMEA, open a spreadsheet with 15 columns

Structuring Your FMEA Spreadsheet

Equipment Information												Actions		Action Results					
System	Assembly	Component	Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Occur	CRT	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	New Sev	New Occ	New Det	New CRT	New RPN

Write down each failure mode and effects of the failure

Severity – On a scale of 1-10, rate the Severity of each failure (10 = most severe). See Severity table

Occurrence – Write down the potential causes, and on a scale of 1-10, rate the Occurrence of each failure (10 = most likely). See Occurrence table

Detection – Examine the current design, then, on a scale of 1-10, rate the Detectability of each failure (10 = least detectable). See Detection table

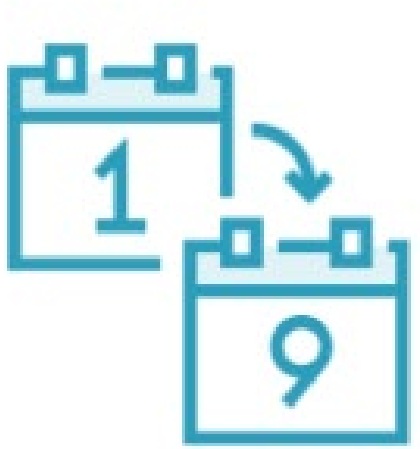
Risk Priority Number – The combined weighting of Severity, Occurrence, and Detection. **RPN** = Sev x Occur x Det

Response Plans and Tracking

Structuring Your FMEA Spreadsheet

Columns 1 - 9 are completed on the Measure phase

1. Process step
2. Potential failure
3. Potential failure effect
4. SEV
5. Potential cause of failure
6. OCC
7. Current monitor/control
8. DET
9. RPN



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Structuring Your FMEA Spreadsheet

Columns 10 - 15 are more appropriate for the **Improve Phase (DMAIC Process), but you can do it also in Measure Phase**

10. Recommended changes
11. Who and When?
12. Action completed
13. SEV
14. DET
15. RPN

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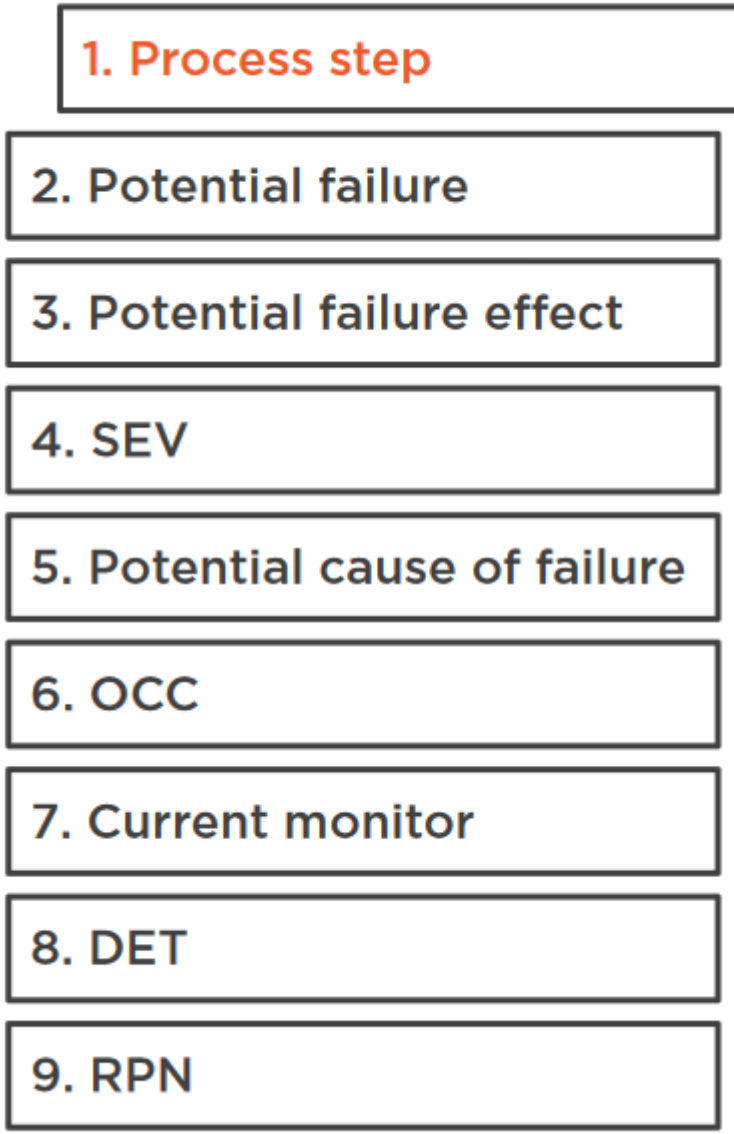
Filling Out Your Spreadsheet

Identify all possible process steps, activities, or inputs



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Filling Out Your Spreadsheet

Indicate what might go wrong for each process step

Potential Failure Modes refers to the mode in which the process could potentially fail. These are the defects caused by a C,P or N factor that could occur in the Process.

This information is obtained from **Historical Defect Data –> Do you have reliable data?**

1. Process step
2. Potential failure
3. Potential failure effect
4. SEV
5. Potential cause of failure
6. OCC
7. Current monitor
8. DET
9. RPN

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Filling Out Your Spreadsheet

Enter a short description of the impact of the failure on the customer

Potential Failure Effects is simply the effect of realizing the potential failure mode on the overall process. It focuses on the outputs of each step.

1. Process step
2. Potential failure
3. Potential failure effect
4. SEV
5. Potential cause of failure
6. OCC
7. Current monitor
8. DET
9. RPN

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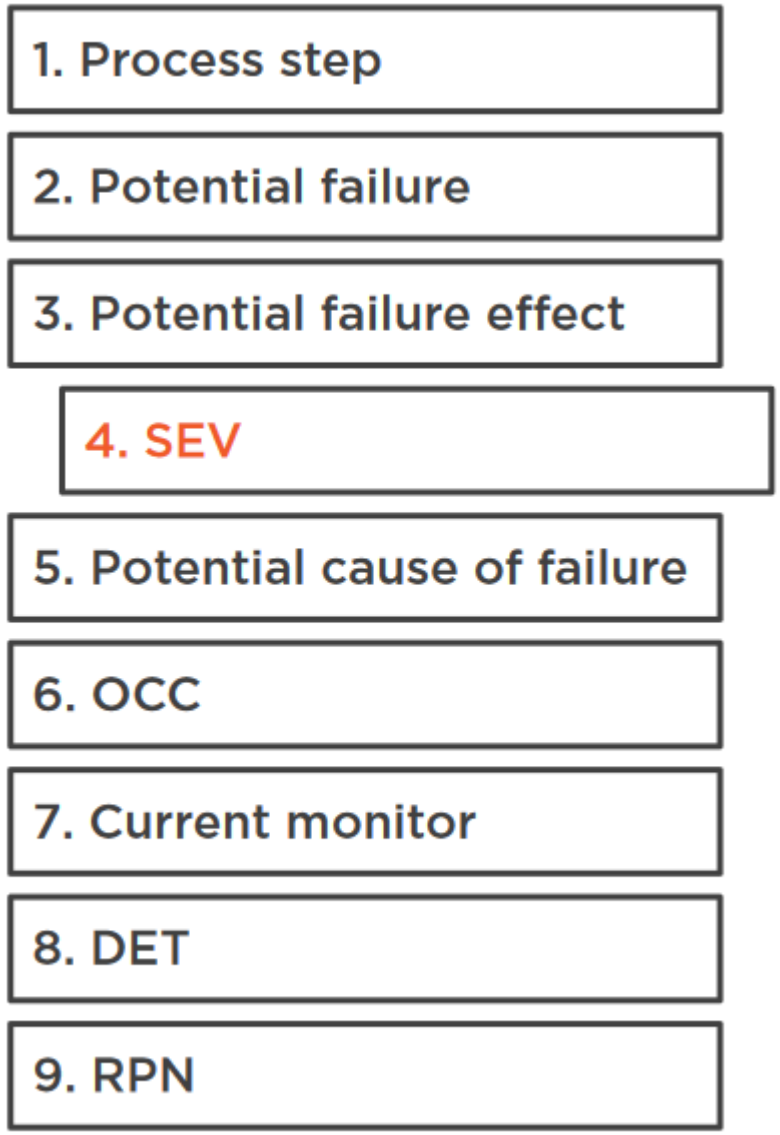
Filling Out Your Spreadsheet

Rate the severity of the possible failure from the previous columns
Rate it from 1 to 10

This ranking should be developed based on the team's knowledge of the
process in conjunction with the predetermined scale.
The measure of Severity is a financial measure of the impact to the business
of realizing a failure in the output.



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Ranking Severity

Effect	Criteria: Severity of Effect Defined	Ranking
Hazardous: Without Warning	May endanger the operator. Failure mode affects safe vehicle operation and/or involves non-compliance with government regulation. Failure will occur WITHOUT warning.	10
Hazardous: With Warning	May endanger the operator. Failure mode affects safe vehicle operation and/or involves non-compliance with government regulation. Failure will occur WITH warning.	9
Very High	Major disruption to the production line. 100% of the product may have to be scrapped. Vehicle/item inoperable, loss of primary function. Customers will be very dissatisfied.	8
High	Minor disruption to the production line. The product may have to be sorted and a portion (less than 100%) scrapped. Vehicle operable, but at a reduced level of performance. Customers will be dissatisfied.	7
Moderate	Minor disruption to the production line. A portion (less than 100%) may have to be scrapped (no sorting). Vehicle/item operable, but some comfort/convenience item(s) inoperable. Customers will experience discomfort.	6
Low	Minor disruption to the production line. 100% of product may have to be re-worked. Vehicle/item operable, but some comfort/convenience item(s) operable at a reduced level of performance. Customers will experience some dissatisfaction.	5
Very Low	Minor disruption to the production line. The product may have to be sorted and a portion (less than 100%) re-worked. Fit/finish/squeak/rattle item does not conform. Most customers will notice the defect.	4
Minor	Minor disruption to the production line. A portion (less than 100%) of the product may have to be re-worked online but out-of-station. Fit/finish/squeak/rattle item does not conform. Average customers will notice the defect.	3
Very Minor	Minor disruption to the production line. A portion (less than 100%) of the product may have to be re-worked online but in-station. Fit/finish/squeak/rattle item does not conform. Discriminating customers will notice the defect.	2
None	No effect.	1

** Potential Failure Mode and Effects Analysis (FMEA), Reference Manual, 2002. Pgs 29-45. Chrysler Corporation, Ford Motor Company, General Motors Corporation.*

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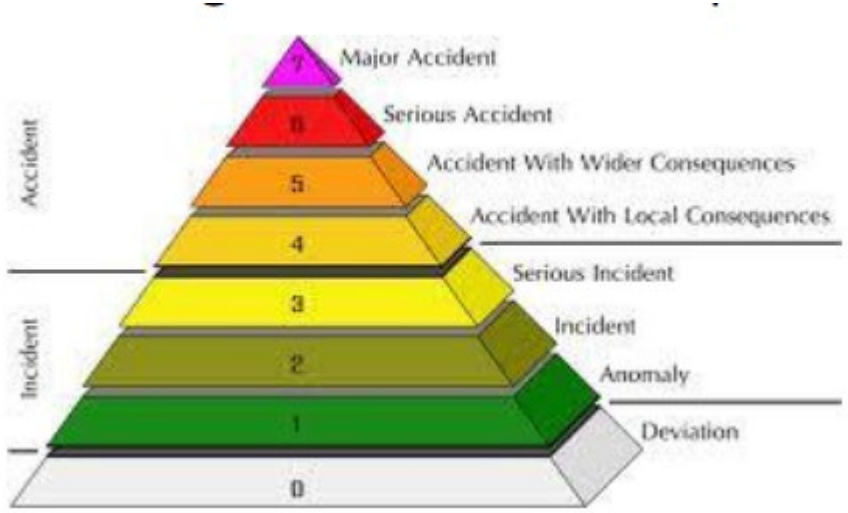
Applying Severity Ratings to Your Process

- The guidelines presented on the previous slide were developed for the auto industry.
- This was included only as a guideline....”actual results may vary” for your project.
- Your severity may be linked to impact on the business or impact on the next customer, etc.

You will need to define your own criteria…
and be consistent throughout your FMEA!!



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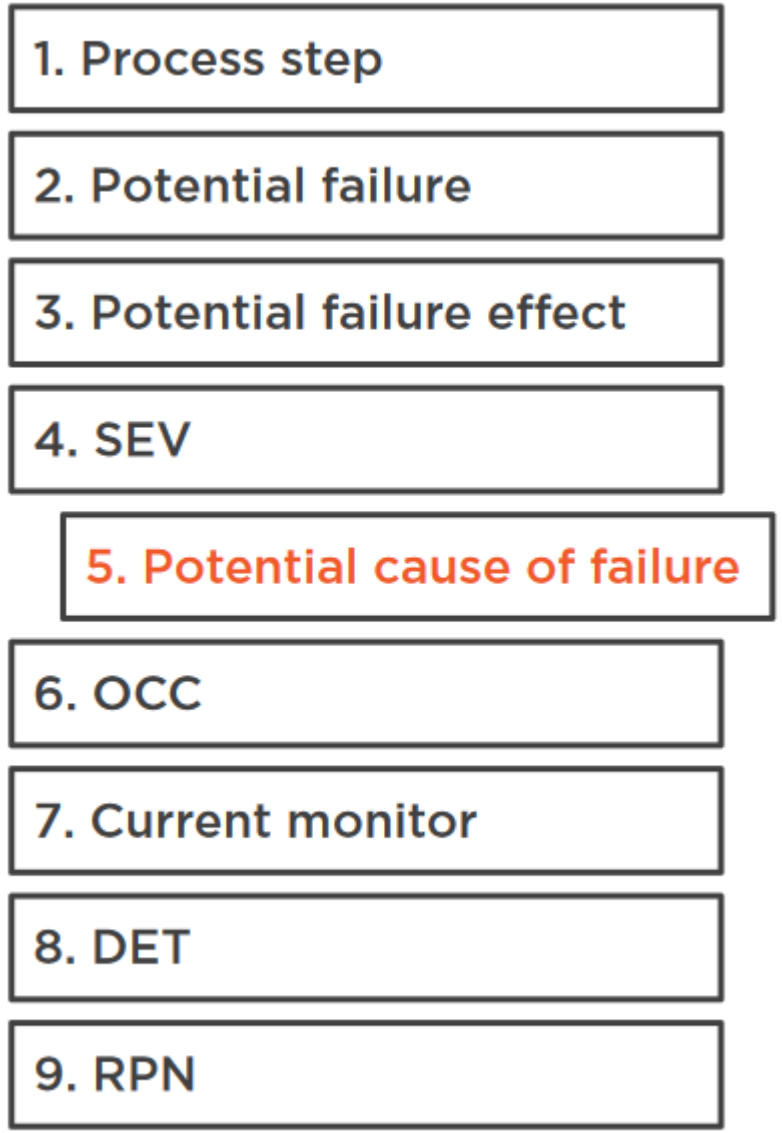
Filling Out Your Spreadsheet

Enter the potential reasons the specific failure might occur

Potential Causes of the Failure refers to how the failure could occur.
This information should be obtained from the Fishbone Diagram.

Fishbone Diagram =
Cause and Effect Diagram =
Ishikawa Diagram



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Cause and Effect Diagram

Products

- Measurement
- People
- Method
- Materials
- Equipment
- Environment

Transactional

- People
- Policy
- Procedure
- Place
- Measurement
- Environment

Categories for the legs of the diagram can use templates for products or transactional symptoms.

Or you can select the categories by process step or what you deem appropriate for the situation

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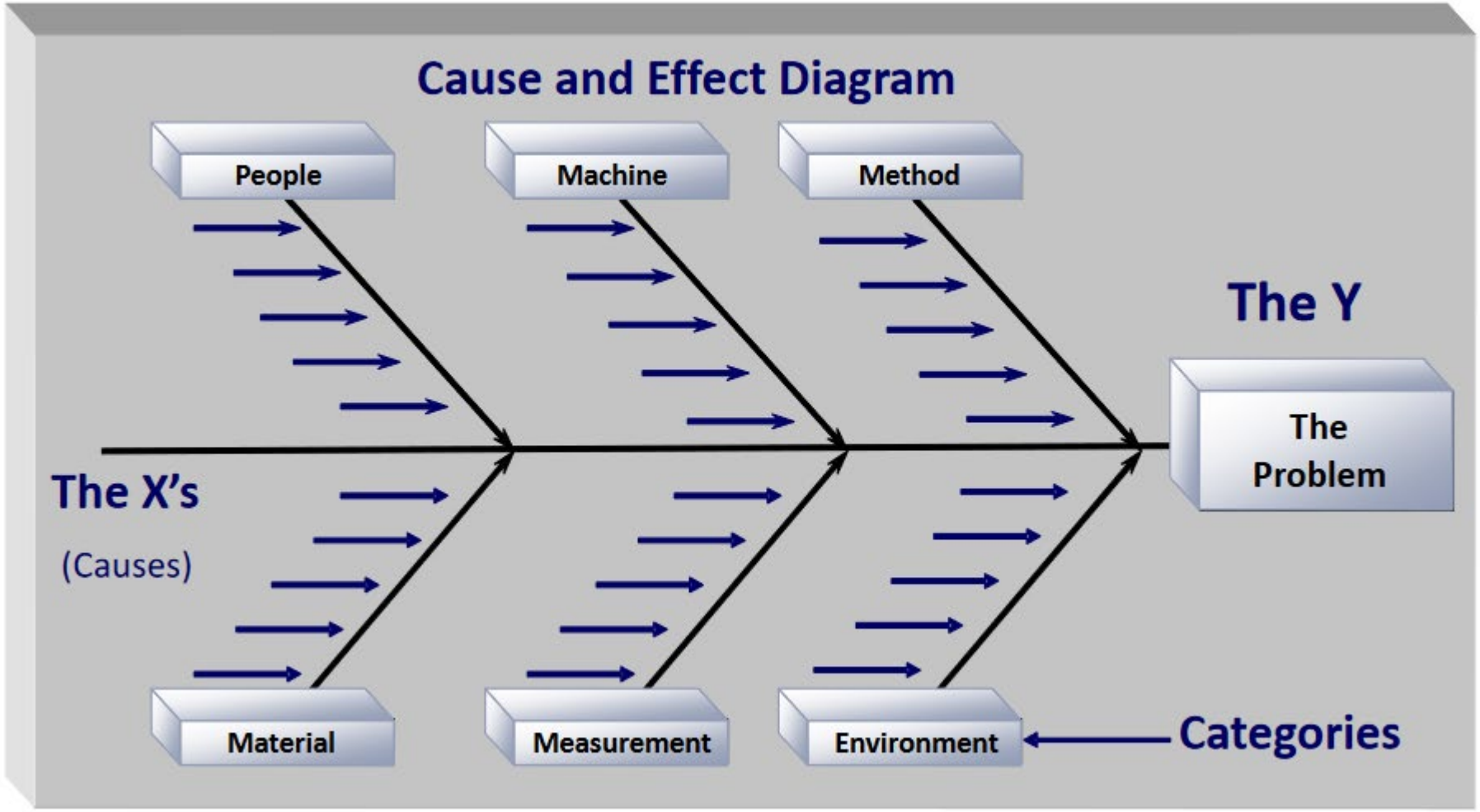
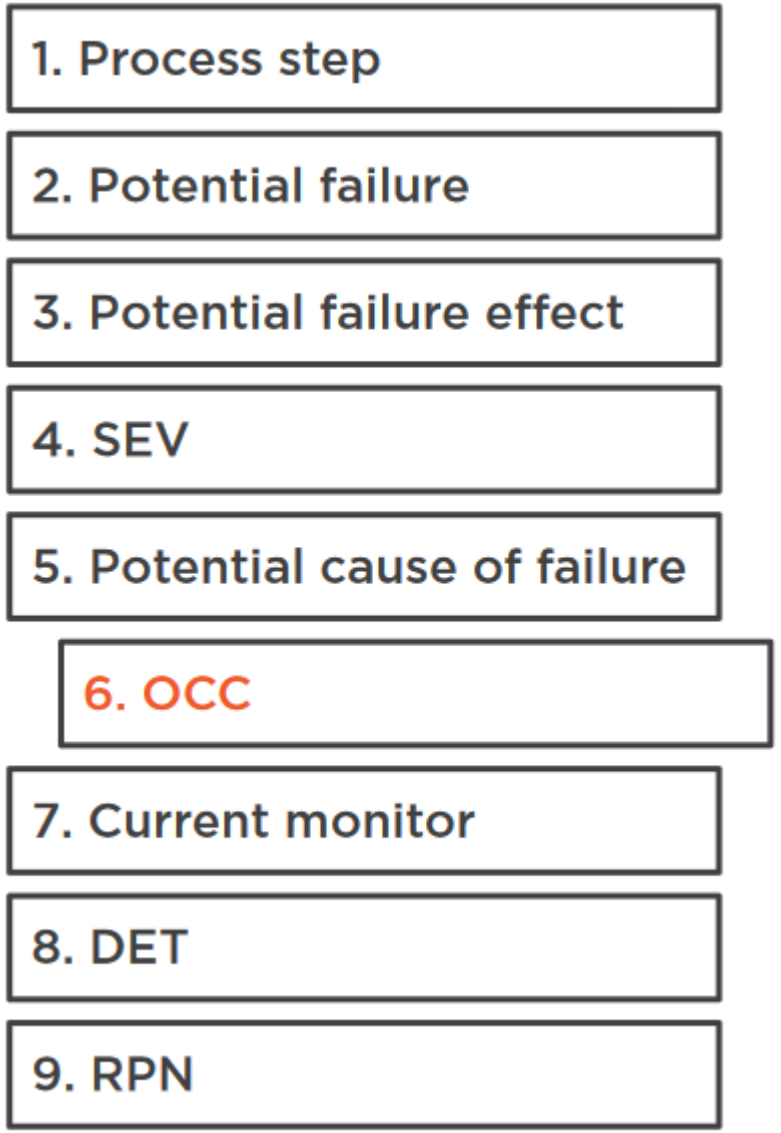
Cause and Effect Diagram



Occurrence “OCC”

Occurrence refers to how frequently the specified failure is projected to occur.



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Occurrence “OCC”

Probability of Failure	Possible Failure Rates	Cpk	Ranking
Very High: Failure is almost inevitable.	>= 1 in 2	< 0.33	10
	1 in 3	³ 0.33	9
High: Generally associated with processes similar to previous processes that have often failed.	1 in 8	³ 0.51	8
	1 in 20	³ 0.67	7
Moderate: Generally associated with processes similar to previous processes that have experienced occasional failures but not in major proportions.	1 in 80	³ 0.83	6
	1 in 400	³ 1.00	5
	1 in 2,000	³ 1.17	4
Low: Isolated failures associated with similar processes.	1 in 15,000	³ 1.33	3
Very Low: Only isolated failures associated with almost identical processes.	1 in 150,000	³ 1.5	2
Remote: Failure is unlikely. No failures ever associated with almost identical processes.	<= 1 in 1,500,000	³ 1.67	1

Potential Failure Mode and Effects Analysis (FMEA), Reference Manual, 2002. Pg. 35.. Chrysler Corporation, Ford Motor Company, General Motors Corporation.

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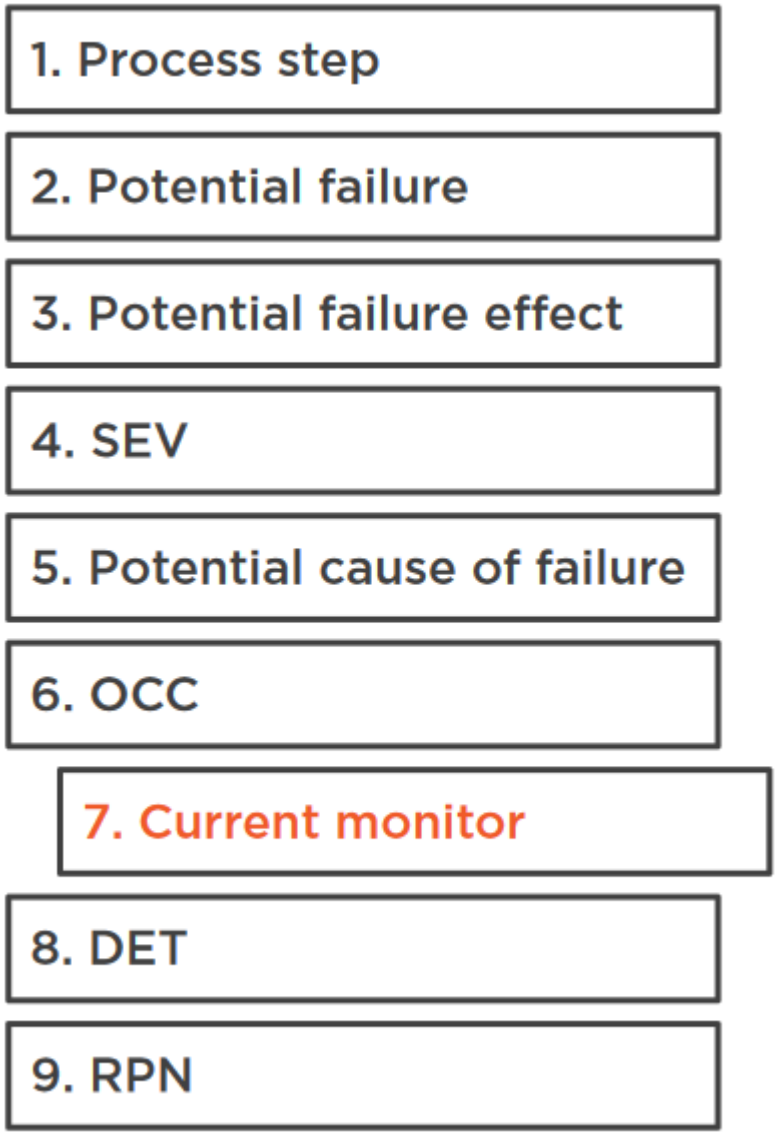
Current Process Controls

Create a short description of the current controls that are in place

Current Process Controls refers to the three types of controls that are in place
to prevent a failure in with the X's. The 3 types of controls are:

- SPC - (Statistical Process Control)
- Poke-Yoke – (Mistake Proofing)
- Detection after Failure – (Inspection)

Ask yourself "How do we control this defect?"



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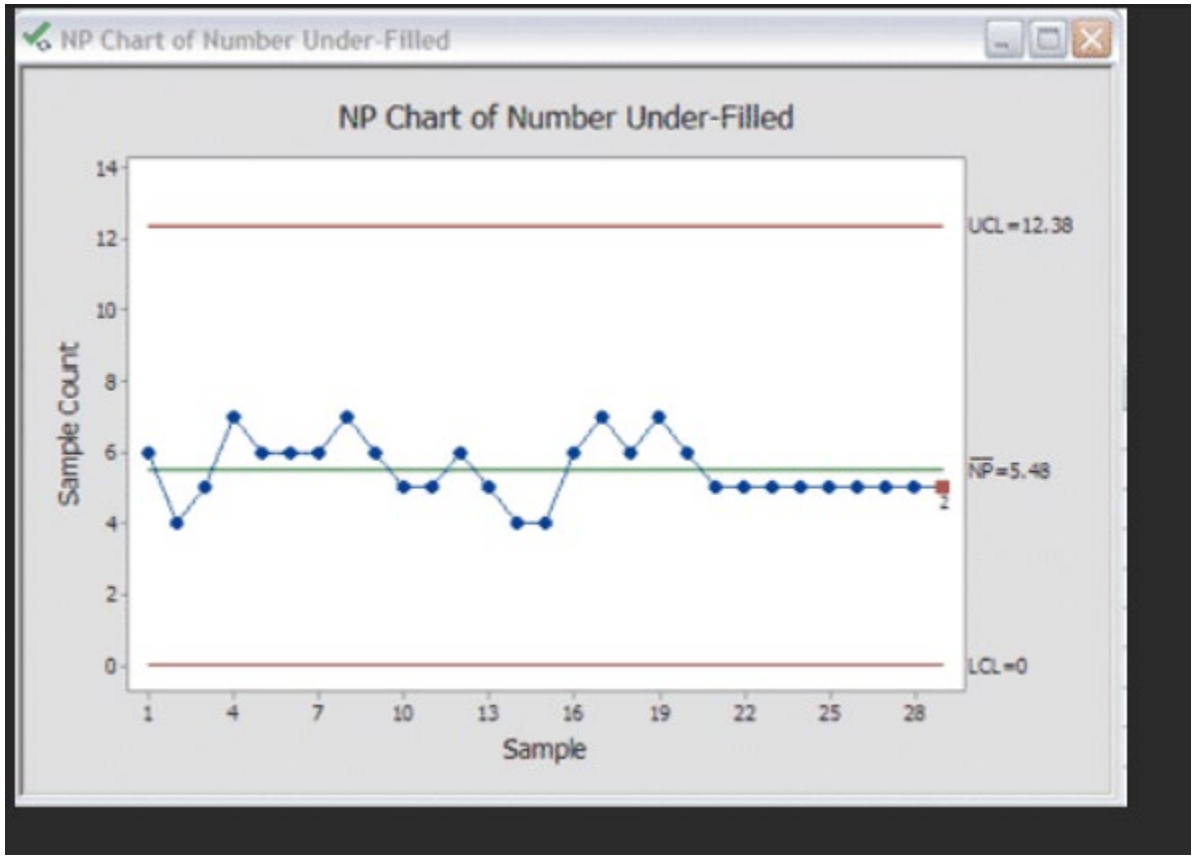
SPC - (Statistical Process Control)



Filling Out Your Spreadsheet

Rate the ability of the process or staff to detect failure if it does occur

Can be also customer! Can customer detect failure?

Rate detection between 1 and 10

1. Process step
2. Potential failure
3. Potential failure effect
4. SEV
5. Potential cause of failure
6. OCC
7. Current monitor
8. DET
9. RPN

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Filling Out Your Spreadsheet

Detection	Criteria: The likelihood that the existence of a defect will be detected by the test content before the product advances to the next or subsequent process	Ranking
Almost Impossible	Test content must detect < 80% of failures	10
Very Remote	Test content must detect 80% of failures	9
Remote	Test content must detect 82.5% of failures	8
Very Low	Test content must detect 85% of failures	7
Low	Test content must detect 87.5% of failures	6
Moderate	Test content must detect 90% of failures	5
Moderately High	Test content must detect 92.5% of failures	4
High	Test content must detect 95% of failures	3
Very High	Test content must detect 97.5% of failures	2
Almost Certain	Test content must detect 99.5% of failures	1

Potential Failure Mode and Effects Analysis (FMEA), AIAG Reference Manual, 2002 Pg. 35. Chrysler Corporation, Ford Motor Company, General Motors Corporation.

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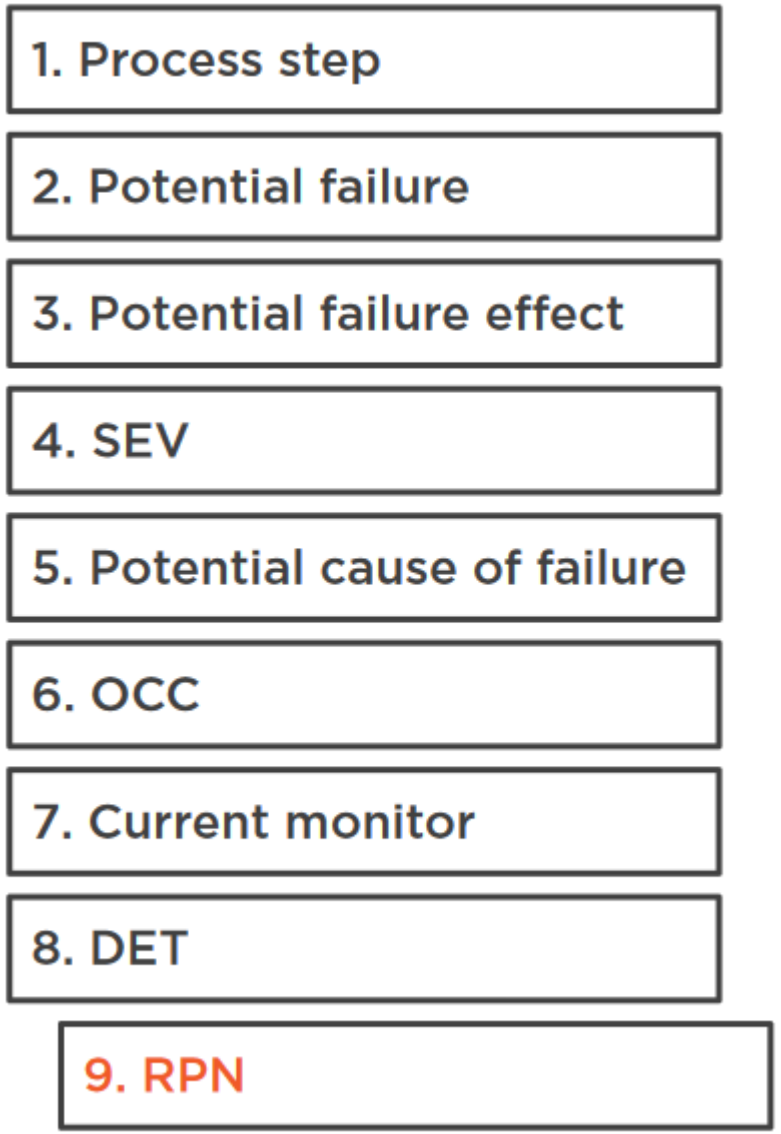
Risk priority number

Calculate the risk priority number

(SEV * OCC * DET) = RPN

→ What next?



Structuring Your FMEA Spreadsheet

Columns 10 - 15 are more appropriate for the **Improve Phase (DMAIC Process), but you can do it also in Measure Phase**

These columns are a type of **post FMEA**. Remember to update the FMEA throughout your project, this is what we call a **“Living Document”** as it changes throughout your project

10. Recommended changes
11. Who and When?
12. Action completed
13. SEV
14. DET
15. RPN

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Recommended changes

Recommended Actions refers to the activity for the prevention of a defect

During Analyze and Improve phases, the team would recommend:

- Changes
- Commended actions
- Who and When → **If you want something to happen properly, appoint a person or persons to make the changes**
- Rescore the process

If the RPN is higher or the same, then the change was not a good one and the team might need to try again

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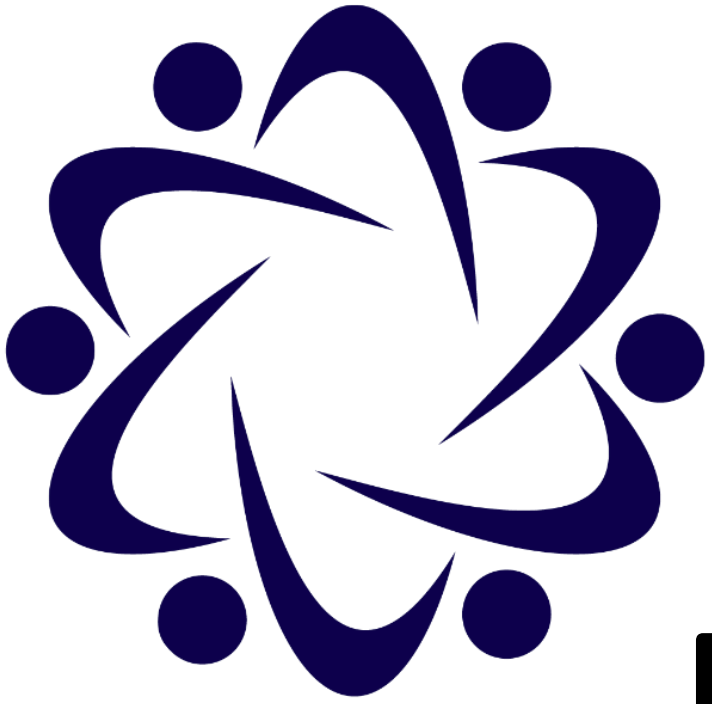
Thank you!

Kiitos!



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C4 – Quality assurance and applied methods

M4 – Development Techniques - LEAN

P1 – JAMK University of Applied Sciences

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Development Techniques

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Content

https://learntransformation.com/top-25-lean-tools/

LEAN Tools

LEAN Tools

Lean Concepts is an organized approach that identifies & eliminates all types of waste that don't add any value to the process during business transformation. The primary concept of Lean is to boost customer value while reducing waste. Further, Lean has several tools that we can apply to operations & projects. So, These techniques permit to map out the value stream, identify & remove waste, produce value to the customer, and lead organizational change.

These lean tools are utilize either solely or together. The benefits will notably increase, however, as we can use more techniques since they support & strengthen each other. So, Lean tools are organized & scientific methods for problem-solving.

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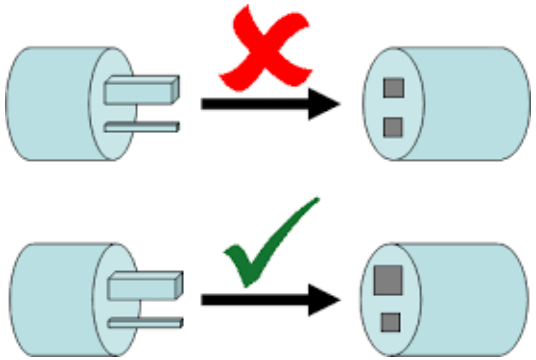
5S

5S is a Japanese lean tool that becomes evolved by Toyota as part of their lean manufacturing production system. 5S is an improvement tool for organizing & maintaining a disciplined, clean and productive workplace. It helps to create a better working environment, reduces waste while improving efficiency & quality. Further, 5S represents five simple practices that begin with the letter ‘S’ which are:

- Sort, setting in order,
- Shine,
- Standardize,
- Sustain.
- Furthermore, In Japanese, these are call as: seiri, seitan, serious, seiketsu, and shitsuke.

Poka – Yoke

Poke Yoke was developed by Toyota. It is a Japanese term that mean error prevention. Moreover, The idea of Poka Yoke is to prevent mistakes from becoming defects. In addition to this, This lean technique prevents an operator from making a blunder with the aid of using which includes preventive in-built responsiveness in the layout of product or manufacturing process.



The aim of this lean tool is to create a form of quality control that highlights defects automatically and in time takes humans out of the equation. We can apply it to most processes, but areas where it can prove vital include such as in situations where the customer can make an error, when a small error turns into a big error, or when at any point where an error will lead to major disruption.

Andon

Andon is another lean manufacturing tools that is a visual feedback system for the shop floor that suggests manufacturing status. It alerts whilst help is in need, and empowers operators to stop the production process if any defect they get in the product.

How does Andon help?

Ando utilizes an amalgam of light as well as sound to acting as a communication tool for the shop floor that brings instant attention to problems as they occur, updates production status.

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Kaizen

Kaizen is the Japanese word that means “continuous improvement” for quality transformation.

Generally, It involves 2 words: Kai means to change or improvement and zen means for betterment. So, It is an approach wherein employees work cooperatively proactively to reap regular, incremental enhancements within the production process.
Further, Kaizen includes the engagement of all employees, from upper management to assembly line workers, and we can use it to enhance every process in a supply chain, from purchasing to logistics.

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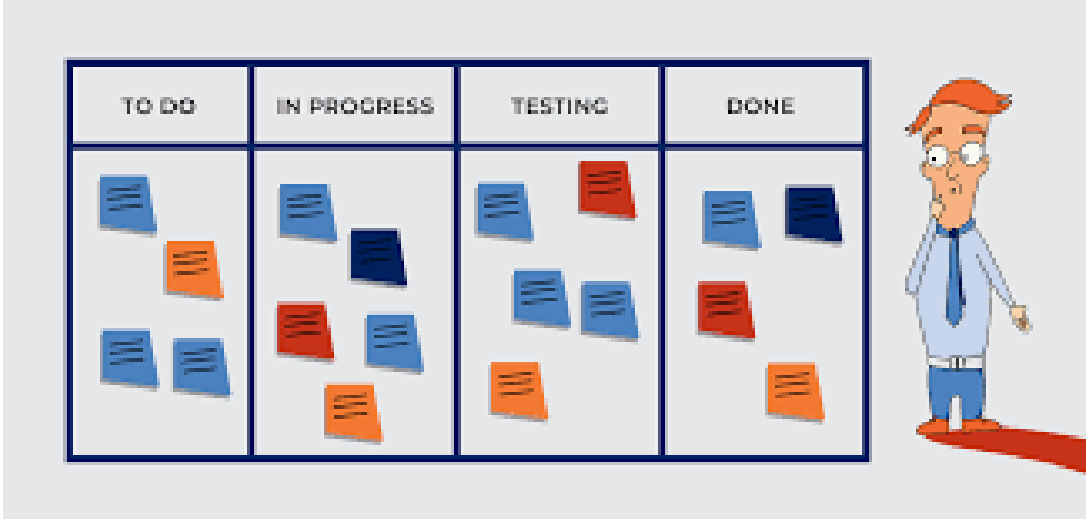
Kanban Pull System lean tools

Kanban is the Japanese word for “Sign Board” or “Billboard” in previous decades, manufacturing workers would fill out a signal card when a part was running low. Moreover, The signal card would be sent to a team that’s job was to order more of that part. With a Kanban pull system, a customer process signals a supplying process to produce a product or information. The lean technique of pull system refers to JIT (Just in Time) efficiency, where the product meets consumer demand, not exceeds it.



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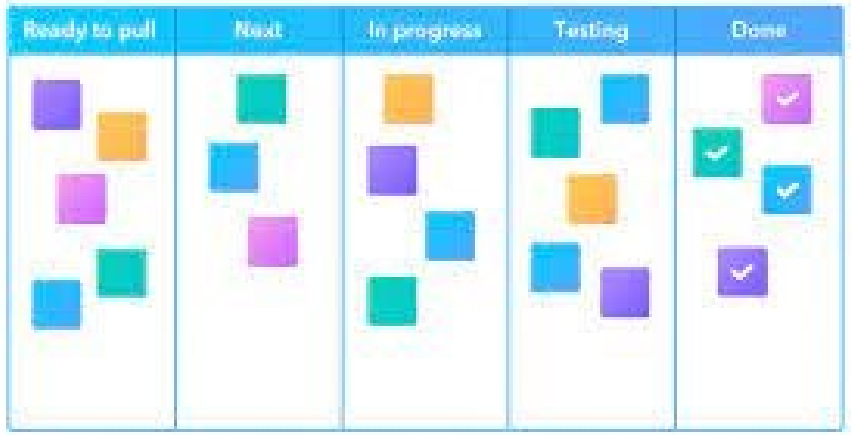
Kanban Pull System lean tools

The goal of Kanban is to decrease waste during the implementation of lean transformation. If parts are only bought when required, you are less probably to waste time, money, or space ordering unnecessary parts. This lean tool creates more efficient processes because the strategy is executed based on consumer demand. If there is a lot of demand for a product only then should you order more. If there isn't sufficient demand, companies can prevent unnecessary orders.



Gemba

Gemba refers to “the real place.” It means an actual place where the problem is found or the incident happens. In manufacturing, it mentions to shop floor. It also can be a construction site, sales floor, etc. So, The idea of lean manufacturing tool, Gemba is that management must go to shop floor to search & fix visible problems. Gemba argues that manufacturing problems, cannot be solved from an office. So, A problem solver’s team presence is necessary at Gemba.

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Heijunka lean tools

Heijunka is the Japanese term which means “leveling.” It levels the type & quantity of production, while decreasing batching in lean manufacturing process. Toyota utilized Heijunka to minimize batching & create a more efficient manufacturing process. It supports predictable & steady flow of small- batch manufacturing rather than larger production processes.

The objective of this specific lean manufacturing tool is to reduce capital costs, inventories, manpower & production time to a minimum. For instance, let say a mobile manufacturing company receives 1000 orders for mobiles every weak. 100 on Monday, 300 on Tuesday, 400 on Wednesday, 200 on Thursday. Rather than manufacturing 1000 mobiles in the starting of the weak or exact amount required each day, the company would produce 200 mobiles each day. By this the company can optimize the manufacturing operation & therefore create a more efficient process.

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Bottleneck Analysis

Bottleneck (or constraint) in a supply chain refers to the lean tool that takes the longest time in whole operations. Further, The word Bottleneck refers to the slowest member of a whole operation. That member can determine the speed of the entire group. Furthermore, The same goes for processes in manufacturing. So, If one part of a supply chain is unnecessarily slow, it can decrease the speed and efficiency of the complete manufacturing process. When managers find that the manufacturing process is taking too long. At this point, managers will try to determine exactly where the bottleneck is occurring.

The goal of Bottleneck Analysis is to determine the slowest parts of the lean manufacturing process and then solve how to speed them up. The process can be costly but will usually lead to increased efficiency & profits

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Standardized Work

Standardized Work is a lean tool used to record current best practices, improve the standard & makes sure that the new standard becomes a baseline for improvement. Furthermore, At its core, it is about ensuring your operations run as smoothly as possible. Standardized work is essential to reaching your ideal Takt Time.

Standardized Work improves 3 essential aspects of the manufacturing process:

- The pace at which products are produced in order to meet consumer demand.
- The operator's work sequence to produce products at that time rate.
- The standard inventory required to ensure a smooth manufacturing process.

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Visual Management

Visual Management is a communication lean technique that uses visual aids to convey messages swifter & more efficiently. Work instructions can often be clarified and far easier to understand when visual aids are involved. For example, if a worker must build a piece of furniture from multiple parts, it will often be better understood in a visual format. It is particularly useful for tasks that are difficult to explain with words alone.

The objectives of Visual Management are:

- Clarify waste.
- Display problems in a simpler way.
- Indicate your efficiency goals.
- Increase effective communication.

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Quick Changeover/ SMED

SMED is the Single Minute Exchange of Dies, which is a process of reducing changeover time by labeling machine elements as internal or external, after which changing the internal factors so that they may be modified externally at the same time as the machine remains operating.
For instance: A pit team at an automobile race is a good instance of Quick Changeover. The quicker a crew can a changeover, the better chance a racer has of winning. A slow changeover will often result in losing a race.

Benefits of Quick Changeover:

- Reduce the number of defects.
- Reduce inventory costs.
- Better chance of on-time delivery.

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Thank you!

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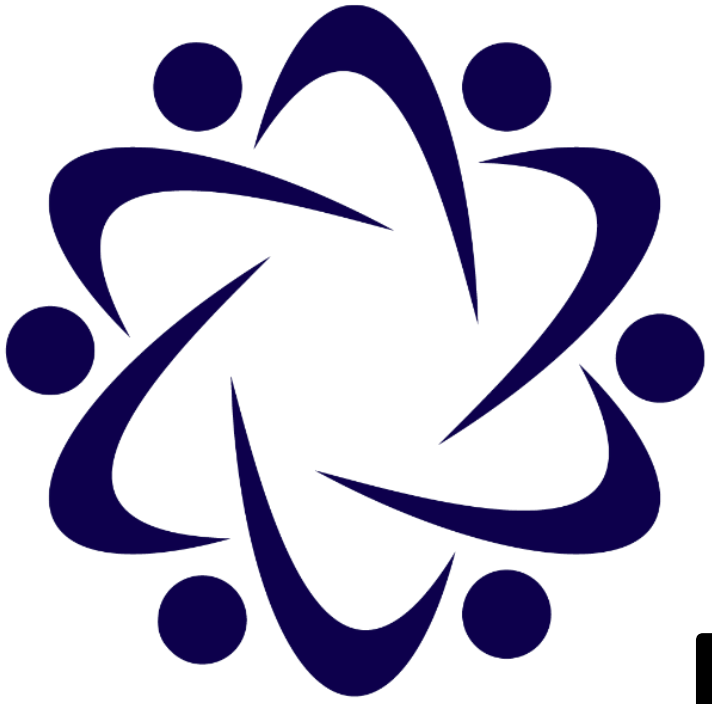

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C4 – Quality assurance and applied methods

M5 – The evolution of Six sigma

P2 – University of Jaén

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- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

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Integracion Sensorial y Robotica

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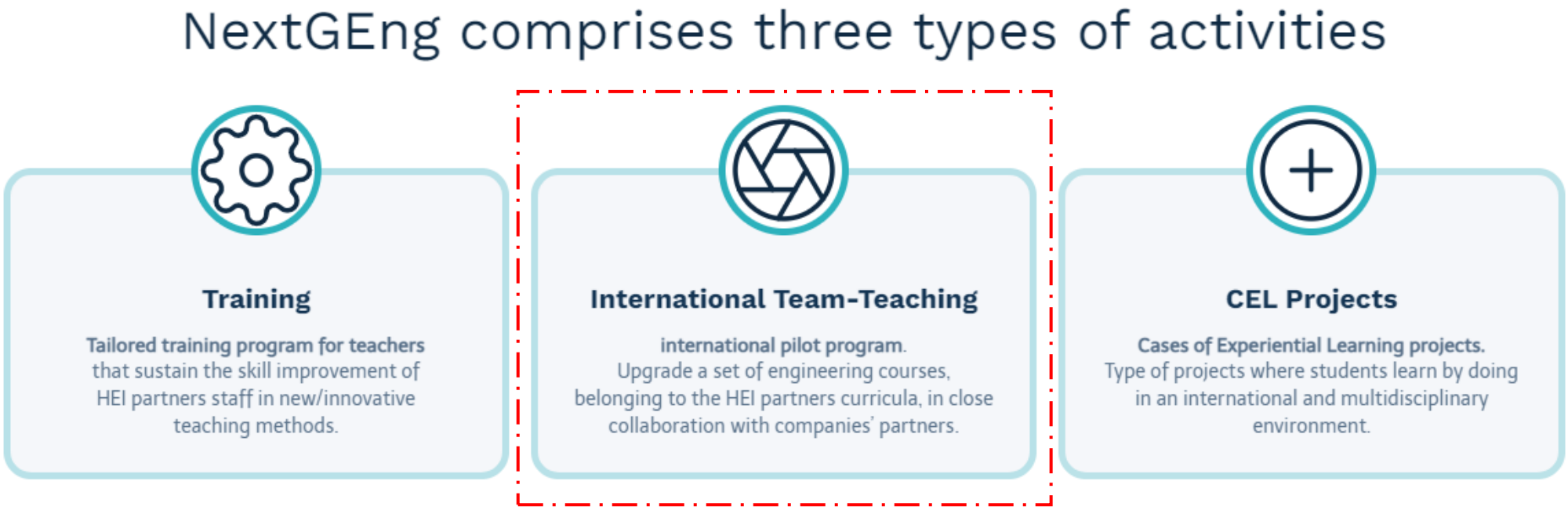
About NextGEng Project

- **NextGEng Project** aims to create new pedagogical models that promotes international team-teaching with the support of new learning materials for existing courses in the curricula



THE EVOLUTION OF SIX SIGMA

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THE EVOLUTION OF SIX SIGMA

Upon completion of this module, the student will be able to understand:

1) That "*Green Six Sigma*" is the adaptation of *Lean Six Sigma* and *FIT SIGMA* for climate change initiatives.
2) *FIT SIGMA* is a sustainable improvement programme, derived from *Lean Six Sigma*.
3) The "timeline" of the Quality Systems.

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Content

- Forward Green Six σ
- The 1st wave of operational excellence
- The 2nd wave of operational excellence
- The 3rd wave of operational excellence
- Six sigma performance level

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Forward Green Six Sigma

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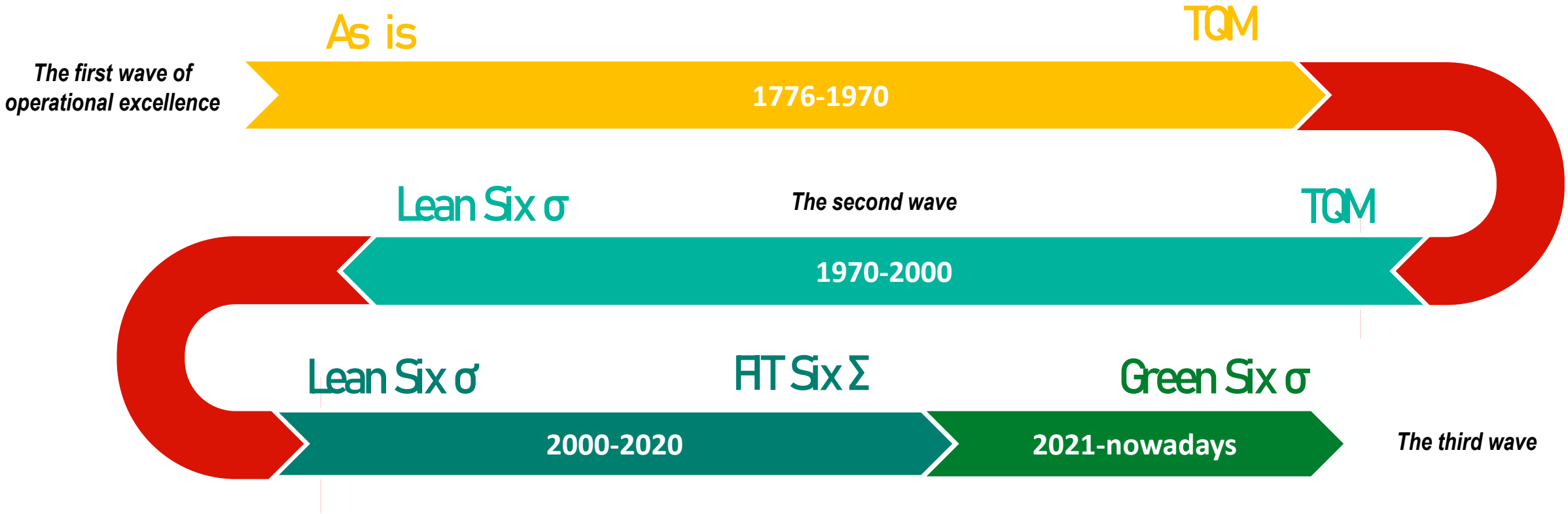
The evolution of Six Sigma.

Forward Green Six σ



The waves of operational excellence

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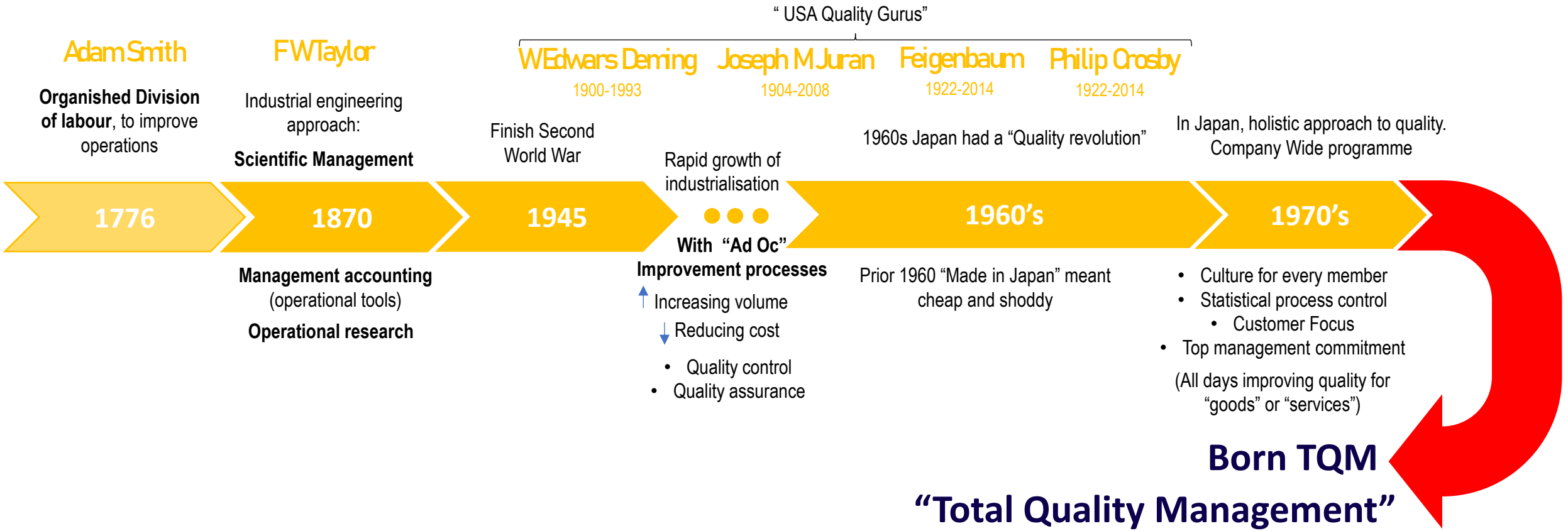
The evolution of Six Sigma.

The 1st wave of operational excellence

As is → TQM



Born TQM

"Total Quality Management"

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The evolution of Six Sigma.

The 1st wave of operational excellence

As is → TQM

(Summary)

- Culture for every members
- Statistical Process Control
- Customer Focus
- Top managemente commitmet
- Continuos education on quality for all
- Annual plan for quality improvement and cost reduction

(All days improving quality)

TQM

Japanes filled the GAPS in TQM

- JIT: Just in time
- TPM: Total Productive Maintenance
- BPR: Bussiness Process Reengineering
- MRPII: Manufacturing Resource Planning

LEAN Co.

1970's

Japaneses extended and customised, the occidental TENETS of QUALITY, with an integrated culture

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How Japanese filled the GAPS in TQM?

But before 2nd wave

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The elimination of waste.

The evolution of Six Sigma.

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The elimination of waste.

With two pillars:

1. **Automation with a "human touch"**
2. **Just in Time**

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Sakichi Toyoda

1867-1930

He was the founder of TOYOTA

The ability to prevent mistakes from happening again.

Solving the cause of the problem rather tan the actual mistake.

TOOLS for finding root causes:

1. Going to the Source
2. Cause and effect diagrams
3. The "5Whys" (asking questions five times)

He said: **"Automation YES, but with a human touch"**

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The evolution of Six Sigma.

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1912-1990

Who is said the founder of TPS system "Toyota Production System"

- 1949 Ohno visited the USA automotive industry
(but actually he liked the americans self services)

- He applied the "self service concepts" to the automotive industry,
and then invented **"Just in Time (JIT)": Materials flow like water**

- In 1959 deployed "Kamban method" (the basic tool for achieving JIT)

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The evolution of Six Sigma.

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Ohno

defined 7 types of waste:

1. Waste of overproduction
2. Waste of time on hand (waiting)
3. Waste in transportation
4. Waste of processing itself (processing too much)
5. Waste of stock on hand (inventory
6. Waste of movement
7. Waste of making defective products.

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The evolution of Six Sigma.

The 2nd wave of operational excellence

TQM→ Lean Six Sigma

TQM

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TQM: (has his origins in Japan)
Company Wide programme

1980

Japan manufactury dominance.
Because:
They had a sucessful application of **TQM**

TQM, seemed to be everywhere
(like a buzzword: **ISO 9000, EFQM**)

1980's

TQM, became a nacional priority in US

D. A Garvin, Managing Quality (New York: Free Press-1988)

A widely cited US study about durable goods like vehicles or Air Conditioning Systems; showed that those made in USA had a higher defect rate than those made by the worst japanese companies.

TQM failure: NOT define quality, only goodness

Bill Smith (engineer in MOTOROLA), began 6σ

The idea of inserting data based statistics for quality

In Statistical terms
σ = Variation from the mean
4σ 2,700 errors /1,000,000
6σ 3.4 errors /1,000,000

1990

LEAN ≡ TOYATAISM
Operational tools: Kamban, …

WOMACK
"The machine that changed the world"
(story of TOYOTA)

"Materials flow like water"

Supplier →Production →Costumer
(In response to a demand)

1990's

They had a sucessful application of **6σ**

GENERAL ELECTRIC
"The home of 6σ"

- With "problema-solving techniques": **DMAIC**
- With rigorous/structured training plan: **BELTS**

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The evolution of Six Sigma.

The 3rd wave of operational excellence

Lean 6σ → FIT 6Σ → Green 6σ

1990's

6σ
LEAN
} Common Goals { Elimination of waste
Improvement of process capability

Integration + **LEAN ENTERPRISE** (The industrial engineering tools)
6σ (The science of the "statistical processes")
= **LEAN sigma** (An operational excellence methodology to address the entire value delivery system)

Born Lean 6σ **The predictable Six Sigma precisions + the agility of Lean** ⇒ **better, faster, cheaper** business processes.

- Optimum flow value
- Cycle times are reducted
- Defects are eliminated

2000 Dot.com companies fall, The huge bubble bursts, Globalization , Climate change (Greenhouse gases, Temperature rising, ...)

Their earlier apparent success was not sustainable — The "old economy" is not sustainable.

2000-nowadays

2nd Mill. Changes comes quickly

The challenge for all businesses is to find the benefits of change
Avoid overall drops (experimented even by TQM companies)

2021-nowadays

Ron Basu (aportation in response to COP26 Glashgow Climate Pact)

To ENSURE the longer–term competitive advantages of Lean 6σ

⇒ **Additional features are embeded**

- Senior managemet → Formal review process / At regular intervals (like "operational planning")
- Periodic "Self-assessment" with a Structured Checklist
- Continous learning programme & Knowledge management
- Whole busines **LEAN 6σ programme**

Born FIT Σ

"Sustainable"
"Fit to purpose" (**FIT**)
Integration of a "Seamless organisation" (**Σ**)
TARGETS

Adaptation for Climate change initiatives

Green 6σ

S: Sustein (DMAICS)
To ensure environmental standards

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The 3rd wave of operational excellence

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The evolution of Six Sigma.

The 3rd wave of operational excellence

Lean 6σ → FIT 6Σ → Green 6σ

1990's

FIT Σ

With appropriate value-adding change programme

A sustainable continuous improvement programme.

(Programmes: Suitable for all types or size of organisations)

TOOLS for Green 6σ

Material flow accont

Carbon footprint tools

…

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Six Sigma performance level

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Six Sigma performance level

TQM often said: "We cannot measure the benefits, but if we did not have TQM, who know what losses might have occurred".

Six Sigma a statistical approach to quality.

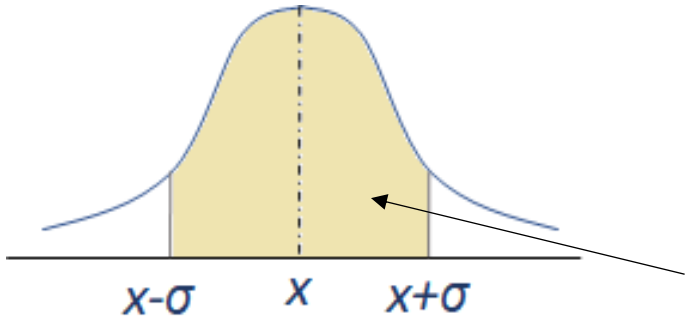
One of the *Key success factors* that difference *6σ* from *TQM*

"Effects quantified in tangible savings" (Not in TQM approach to quality)

Then is possible to measure COPQ (Cost of Poor Quality), with the *σ level* at which process performs.

- *6σ* level, COPQ < 1% cost/sales
- *3σ* level, COPQ ∈ [25%÷30%] cost/sales

Example: Results of tossing ten coins 100 times "Bell saphed" (symmetrical from midpoint)



Distribution curve (NORMAL)

- *x* : measure of central dispersion (*arithmetic mean,* mid point, average)
- σ: measure of variation (*Standard deviation from mean)*

The area under de curve, is PROBABILITY

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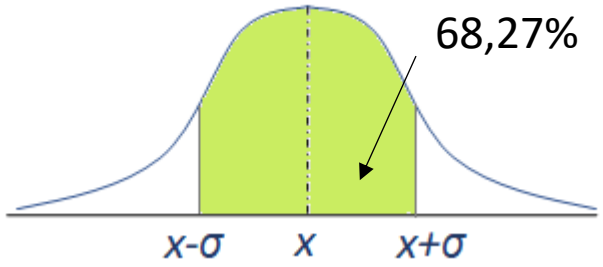
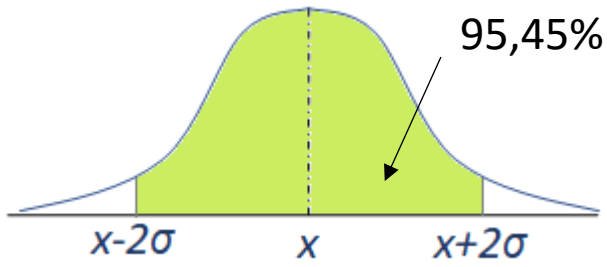
Six Sigma performance level

The higher the sigma ⇒ The fewer the defects.

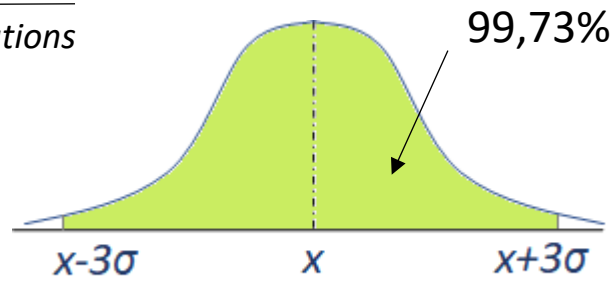


317,300 defects
1,000,000 realizations



45,500 defects
1,000,000 realizations

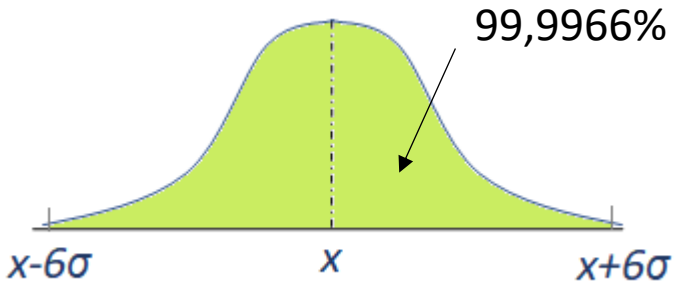
6σ ≅ 0 defects for any product/process/services in an organisation



This is aceptable by many organisations

2,700 defects
1,000,000 realizations

But: COPQ [25%÷30%] cost/sales



3,4 defects
1,000,000 realizations

6σ level, COPQ < 1% cost/sales

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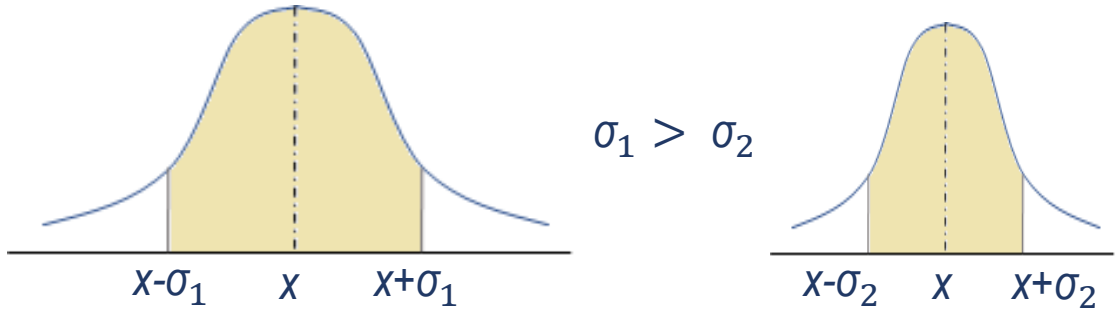
Six Sigma performance level

The powerful of "Lean Six Sigma"



"Six Sigma" works with the grothing of coeficient that multiplies σ

"Lean" works with the reduction of σ value.

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References

- The Green Six Sigma Handbook. **Ron Basu**. Editorial: Routledge. 2023
- Green Six Sigma. Ron Basu. Editorial: WILEY. 2022
- Operations Management. 14th Edition. **William. J Stevenson**. Editorial: Mc Graw Hill. 2021

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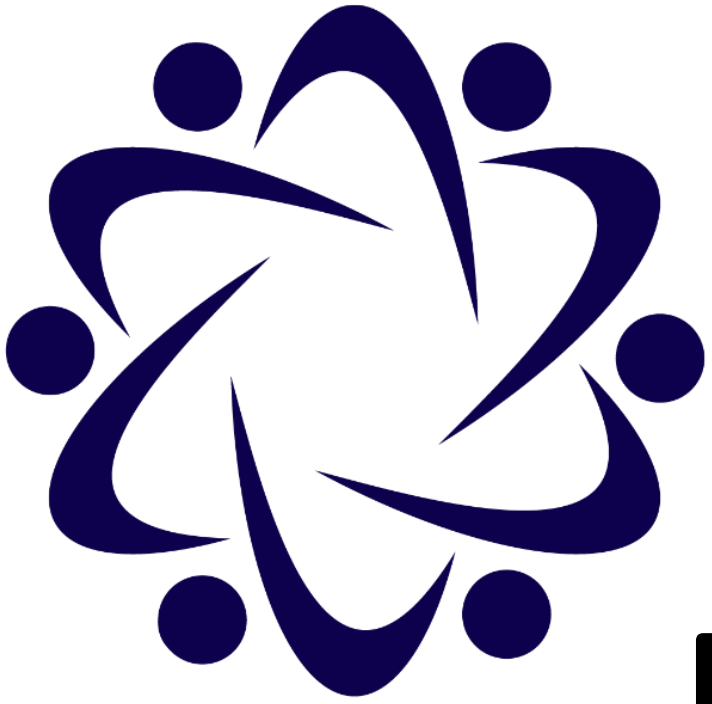
Thank you!

Kiitos!



Gracias!

Mulțumesc!

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C4 – Quality assurance and applied methods

M6 – Green Six Sigma

P2 – University of Jaén

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- Three-year Erasmus+ Cooperation Partnership project that started in October 2022
- International consortium consisting of 3 universities and 3 companies from European countries
- Project co-funded by the European Union and coordinated by Technical University of Cluj-Napoca, Romania

Technical University of Cluj-Napoca

Integracion Sensorial y Robotica

Jamk University of Applied Sciences

Valmet Technologies Oyj

University of Jaén

Rober Bosch SRL

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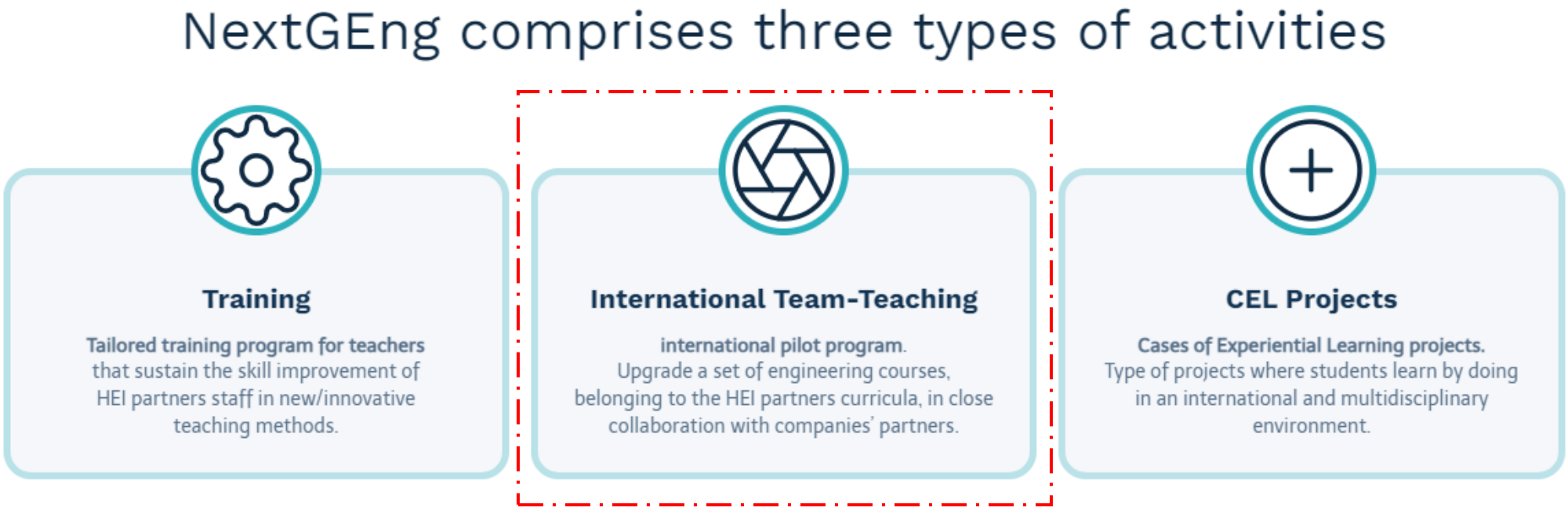

GREEN SIX SIGMA

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GREEN SIX SIGMA

Upon completion of this module, the student will be able to understand:

1) *DMAIC* is an essential project life cycle for Six Sigma
2) *DMAIC* improves an existing process, *DMAICS* improves and sustains a process; with an extra-phase: “Sustain”
3) The Sustain phase is the evolution towards GREN SIX SIGMA

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Content

- *Six Sigma* deployment Plan
- *Green Six Sigma* Projects with *DMAICS*
- *Green Six Sigma* TOOLS & TECHNIQUES
- *DMAICS* worked-Out Example (actual case)
- Examples of Green Six σ contributions.

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Six Sigma deployment plan

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Six Sigma deployment plan (DP)

Hierarchical structure of Six Sigma

- EXECUTIVE LEADERS *(Sponsors)*
- MASTER BLACK BELTS *(Champions)* M.B.B.
- BLACK BELTS *(Experts)* B.B.
- GREEN BELTS *(Agent advocates)* G.B.

Proven structured approach of Six Sigma.

TOP MANAGEMENT must have A TOTAL COMMITMENT:

- Establish 6 σ *"Leadership team"*
- Develop/Roll up a *"Deploy Plan"* (DP)
- Assign M.B.B. to identify/to own CRITICAL PROYECTS (CP)
- Provide support B.B. to make "breakthrough improvements" in CP
- Encourage G.B. to identify/implement "Jus do it" projects
- Set aggresive 6σ targets to *"Leadership team"*
- Continously EVALUATE (implementation & DP). To make CHANGE if necessary.

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Six Sigma deployment plan (DP)

1_ Business Alignment Planning

To assure 6σ projects align with Business strategy

- Preliminary projects selection (Projects having potentially savings $-1M or more).
- "Leadership" education programme (5 days) M.B.B. are selected/assigned to key projects
- M.B.B. instruction takes 3 to 4 weeks (DMAICS)
- Concurrently start → selection process for B.B.

2_ 1st Wave of Black Belts Training.

- It is a combination of { formal classroom education / Onsite Project work
- It is spread over 4 ÷5 months with (4 ÷5 weeks classroom work)
- External consultant and experienced trainers

3_ 2nd/3rd Wave of Green Belts Training.

- Master B. Belts (trained in house) are the teachers. 6÷7 weeks (5 days of formal classroom work)
- To get an awareness of 6 *σ* principles
- To learn apply the DMAIC/S cycle to support B.B. in "end-to-end projects".

*4*_ To deliver results + sustain culture.

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Six Sigma deployment plan (DP)

Six Sigma Academy Awards:

- Certification of Black Belt.

- Certification of Master Black Belt.

But, somepeople said/thought:

- Large manufacturing multinacional can have a huge Budget for consultants to train hundreds of Black Belts (High start-up cost)
- Aversion to sophisticated statistical techniques (some times in the Service Sector)

FIT Σ "fit for purpose"

An improvement programme suitable for all types or sizes of organisations

(light DP)

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Green Six Sigma Projects with DMAICS

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Green Six Sigma projects with DMAICS

¿What is DMAICS? A data driven life-cycle approach to Green Six Sigma projects.

An essential part of a Company's quality programme

Define: Identify by selecting and prioritising "the right Project"
If you don't know what the problem is, you cannot fix it.
What's wrong with the process?
Don't forget: "What's important to customers?".

Measure: It's better work with hard evidences rather than opinions.
How the bad the process is?
Pointers to locate where process issues are happening.

Analyse. To pinpoint the root causes of the problem.
First you need to develop hypotheses, then these are validated by analysis

Improve. First you need to propose ideas to remove the root causes.
Solutions are tested, and the ones that seem to work are implemented. (And results are measured)

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Green Six Sigma projects with DMAICS

¿What is DMAICS? A data driven life-cycle approach to Green Six Sigma projects.

An essential part of a Company's quality programme

Control. The improved process is monitored, to level the consolidation range.
It is also recommended to update the FMEA.
Control targets are: consolidate and sustain the results

Sustain: You need both:

- the longer-lasting stability of performance deliverables
- to ensure environmental standards

(The needs of present without compromising the future needs)

Then start again:

"We are what we repeatedly do. Excellence, then, is not an act but a habit" (Aristotle)

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Green Six Sigma TOOLS & TECHNIQUES

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These are instrumental to the success of a quality programme

- Tools and techniques can be effective in the right hands and can be dangerous in the wrong ones.
- Choose them for their purpose and apply them after a training programme.

QUANTITATIVE TECHNIQUES	QUALITATIVE TECHNIQUES
Q1: Failure Mode and Effects Analysis (FMEA) Q2: Statistical Process Control (SPC) Q3: Quality Function Deployment (QFD) Q4: Design of Experimentes (DOE) Q5: Design for Six Sigma (DFSS) Q6: Monte Carlo Technique (MCT) Q7: Inventive Problem-Solving (TRIZ) Q8: Measurement System Analysis (MSA)	R1: Benchmarking R2: Balanced Scorecard R3: European Foundation of Quality Management (EFQM) R4: Sales and operational planning (S&OP) R5: Knowledge management R6: Kanban R7: Activity-based costing (ABC) R8: Quality management systems (QMSs, ISO 9000) R9: Kaizen

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Green Six Sigma TOOLS & TECHNIQUES

DMAICS Phase	TOOLS & Techniques	
Define	D1: IPO: Input-Process-Output diagram D2: SIPOC: Supliers, Inputs, Process, Outputs, Customers diagram	D3: Flow Diagram D4: Critical to Quality (CTQ) Tree D5: Project Charter
Measure	M1: Check sheets M2: Histrograms M3: Run charts M4: Scatter Diagrams M5: Cause and Effect Diagrams M6: Pareto Charts	M7: Control Charts M8: Flow Process Charts M9: Process Capability Measurement Q2: SPC, Statistical Process Control R1: Benchmarking
Analyse	A1: Process mapping A2: Regression analysis A3: Resource utilisation and customer service (RU/CS) analysis A4: SWOT (strengths, weaknesses, opportunities, threats) analysis A5: PESTLE (política, economic, social, technical, legal, environmental) analysis A6: 5 whys A7: Interrelationship diagram A8: Overall equipment effectiveness (OEE) A9: Tree diagram M4, M5,M6,M7 I7: Brainstorming Q1: FMEA Q2: SPC Q4:DOE	

Green Six Sigma TOOLS & TECHNIQUES

DMAICS Phase	TOOLS & Techniques	
Improve	I1: Affinity diagram I2: Nominal group technique I3: Single minute Exchange of diez (SMED) I4: Five S's I5: Mistake proofing I6: Value stream mapping	I7: Brainstorming I8: Mind mapping Q1: FMEA (failure mode and effect analysis) Q3: QFD (quality function deployment) Q4: DOE (Design of experiments)
Control	C1: Gantt chart C2: Activity network diagram C3: Radar chart C4: PDCA (plan-do-check-act) cycle C5: Milestone tracker diagram C6: Earned value management (EVM)	 M7: Control Charts R2: Balanced Scorecard R3: EFQM, European Foundation of Quality Management R4: Sales and operations planning
Sustain	S1: Manual flow analysis diagram S2: Carbon footprint tool	R2: Balanced Scorecard R3: EFQM, European Foundation of Quality Management R4: Sales and operations planning R5: Knowledge management

DMAICS worked-out example (actual case)

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DMAICS worked-out example (actual case)

Dow Chemical, a large producer of plastics (polystyrene, polyurethane, polyethylene. etc)

They began usisng Sig Sixma in 1998. This particular example is about a subsidiary: FilmTech, a manufacturer of membranes to debug water.

Define: They were losing demand from coustomer.
Two criteria for membrane quality:

a) Flux of water in a given period
b) How much impurity is removed from the water

Measure: The quality tests were detecting batches out of standard which was delaying the delivery process. The shortfall greew up $500,000 per year.

Analyse: Statistical analysis was used to identify variables that affected membrane flux most significantly.
So was located a component, which concentration was a very important factor. The feeding of this component was failing one a day, during the replacing time. And empty containers were often not noticed.

DMAICS worked-out example (actual case)

Dow Chemical, a large producer of plastics (polystyrene, polyurethane, polyethylene. etc .

Improve: An unexpensive reservoir was added to fill the chemical while containers were exchanged.
And a level alarm was installed.
As a result, the standard deviation of the product out of spec was reduced from 14,5 % to only 2,2 %.
Then quality improved, and product was made available to customers faster.

Control: Trends in Fill Tech, was shown in a tabular way; after the Six Sigma study, they started using Excel charts. Since then the trends were checked easier.

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DMAICS worked-out example (actual case)

Dow Chemical, a large producer of plastics (polystyrene, polyurethane, polyethylene, etc .

Sustain: When the Project was going out “Sustain phase” didn´t exit.

What do yo think, could be done “to ensure environmental standards” ?

For example:

1_ To study the carbon footprint derived from the Project results.

2_ To study viable applications to reuse the membranes at the end life cycle.

3_ To ensure about emissions to air or water were in legal range.

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Another example of *Green Six σ* contributions

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Green six σ contributions

“The Hanford Site”

A LEAN APPROACH TO SUSTAINABLE CLIMATE CHANGE INITIATIVES

- “The Hanford Site”, was stablish in Washington State in 1943, to produce plutonium. The production reactors were shut down between 1964 and 1971.
- Many early safety procedures and waste disposal practices were inadequate, resulting in the release of significant amounts of radioactive materials into the air and the Columbia River, resulting in higher rates of cancer in the surrounding area.
- “Bechtel team” was the first major engineering and construction company to adopt Six Sigma. In 2021, USA Gobert contract them. They worked to map out failure modes and effect analysis. The application of Six Sigma, helped develop an improved process for regulatory compliance, and decreased the amount of time needed to process the plutonium wastes.

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Green six σ contributions

A LEAN APPROACH TO SUSTAINABLE CLIMATE CHANGE INITIATIVES

"Enviromental mangement dashboard to slash carbon footprint"

- In 2007, an important UK Bank (140,000 people, 30 countries), reduced its carbon footprint by 210,000 tonnes (36% of its total footprint).
- Focus on energy savings (by people, buildings equipment, …)
- The dashboard "Footprint Tracker" by Building Sustainability Ltd, helps all actors to be motivated to control their energy usage with digital lighting control system, rooftop photovoltaic cells and solar thermal panels for water heating.
- The organization demonstrated its environmental credentials and commitment to progressive technologies.
- Also validated the saying "you cannot manage what you cannot measure"

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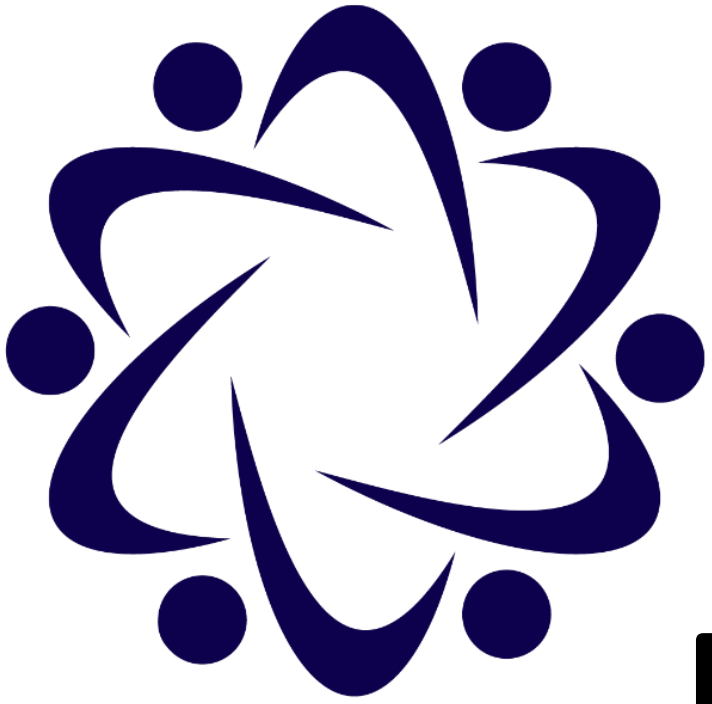
Thank you!

Kiitos!



Gracias!

Mulțumesc!

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