UNIVERSITÀ DEGLI STUDI DI TRIESTE

Prof. Ing. Raffaele Campanella

E-mail: raffaele.campanella@yahoo.it

335 211609

INDUSTRIAL PLANTS II

Chapter two ï part 3

Maintenance of Industrial Plants

Maintenance Policies

DOUBLE DEGREE MASTER IN

ñPRODUCTION ENGINEERING AND MANAGEMENTò

CAMPUS OF PORDENONE

UNIVERSITY OF TRIESTE

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BRIEF HISTORY OF MAINTENANCE

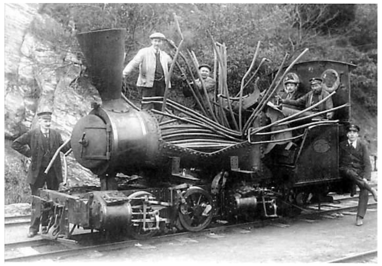
Very simple machines

More complex machines

Steam

Mechanical industry

Chemical Industry



Electrical Industry

1750 1775 1800 1825 1850 1875 1900

CORRECTIVE MAINTENANCE

PREVENTIVE MAINTENANCE

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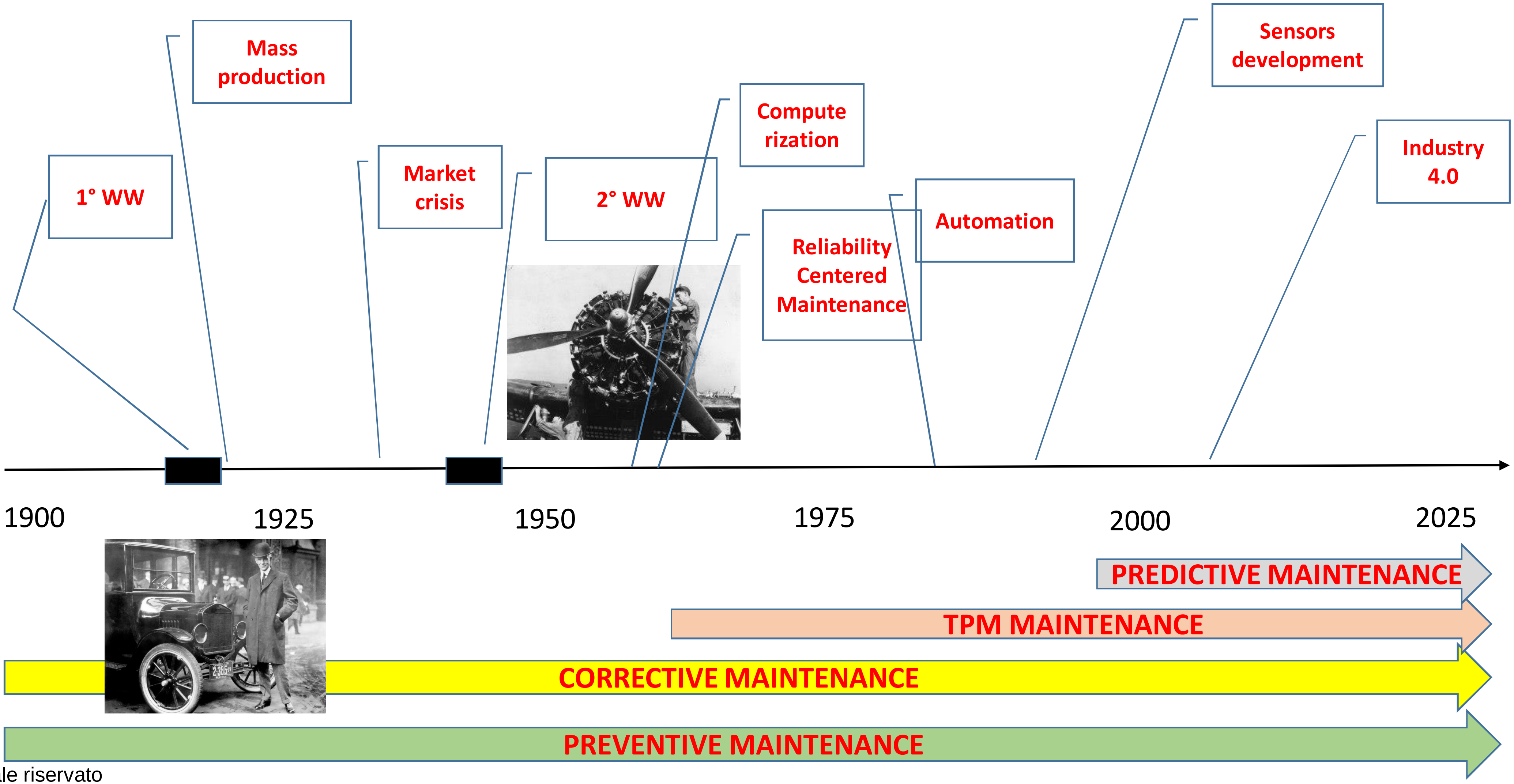
BRIEF HISTORY OF MAINTENANCE



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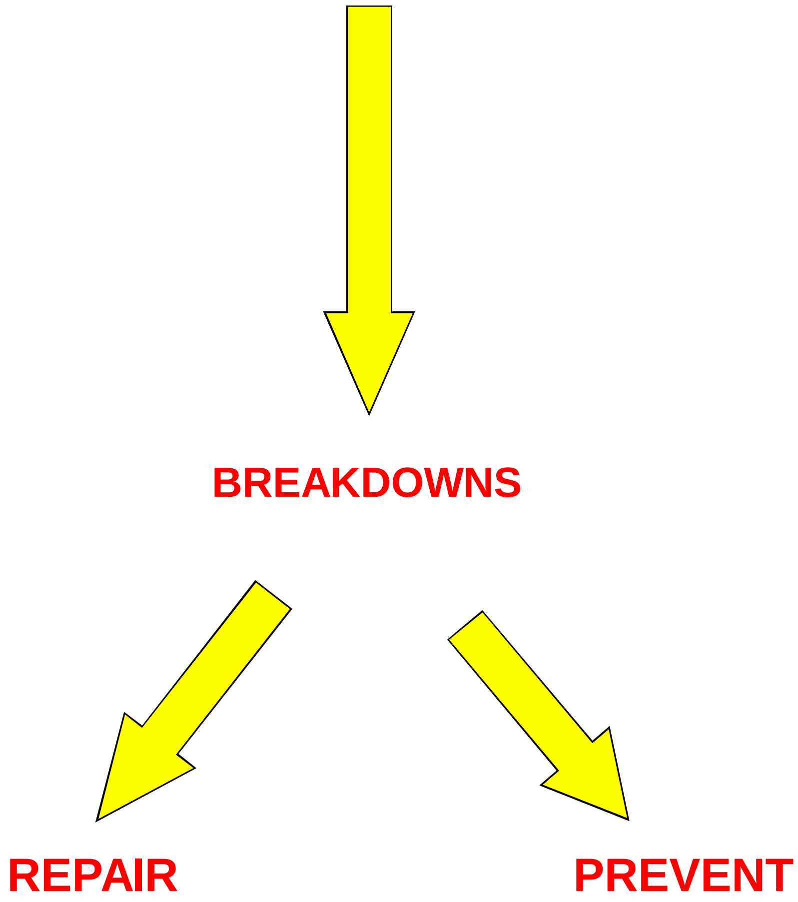
MAINTENANCE MISSION



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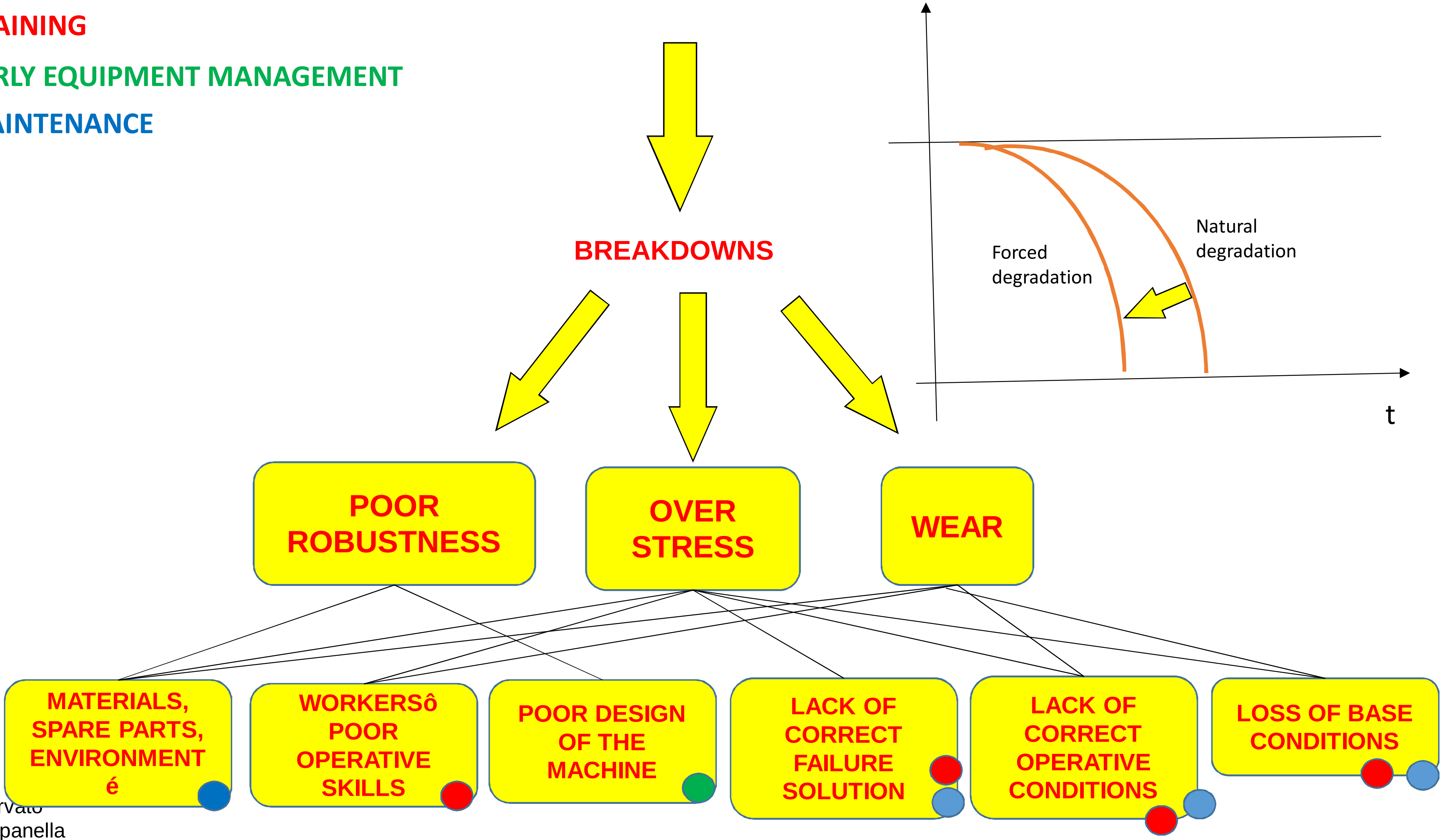
MAINTENANCE MISSION

TRAINING

EARLY EQUIPMENT MANAGEMENT

MAINTENANCE



MAINTENANCE POLICIES

CORRECTIVE

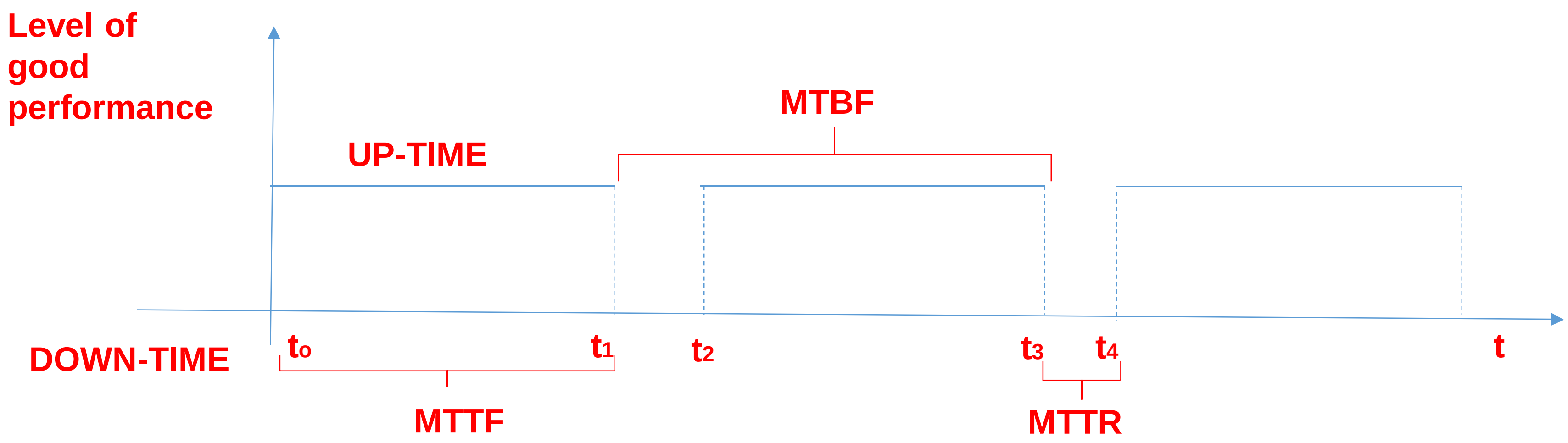
PREVENTIVE

TOTAL PRODUCTIVE MAINTENANCE

PREDICTIVE

CORRECTIVE MAINTENANCE

- The maintenance activity is carried out only when the unit reaches a state of critical deterioration such as to interrupt functionality.
- If the system has two operating states (faulty and functioning), this type of maintenance is performed only when the fault state occurs..
- The costs associated with using the system over a useful life span are function of the probabilities of state transition. C_{cm} = f(”Å)



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CORRECTIVE MAINTENANCE

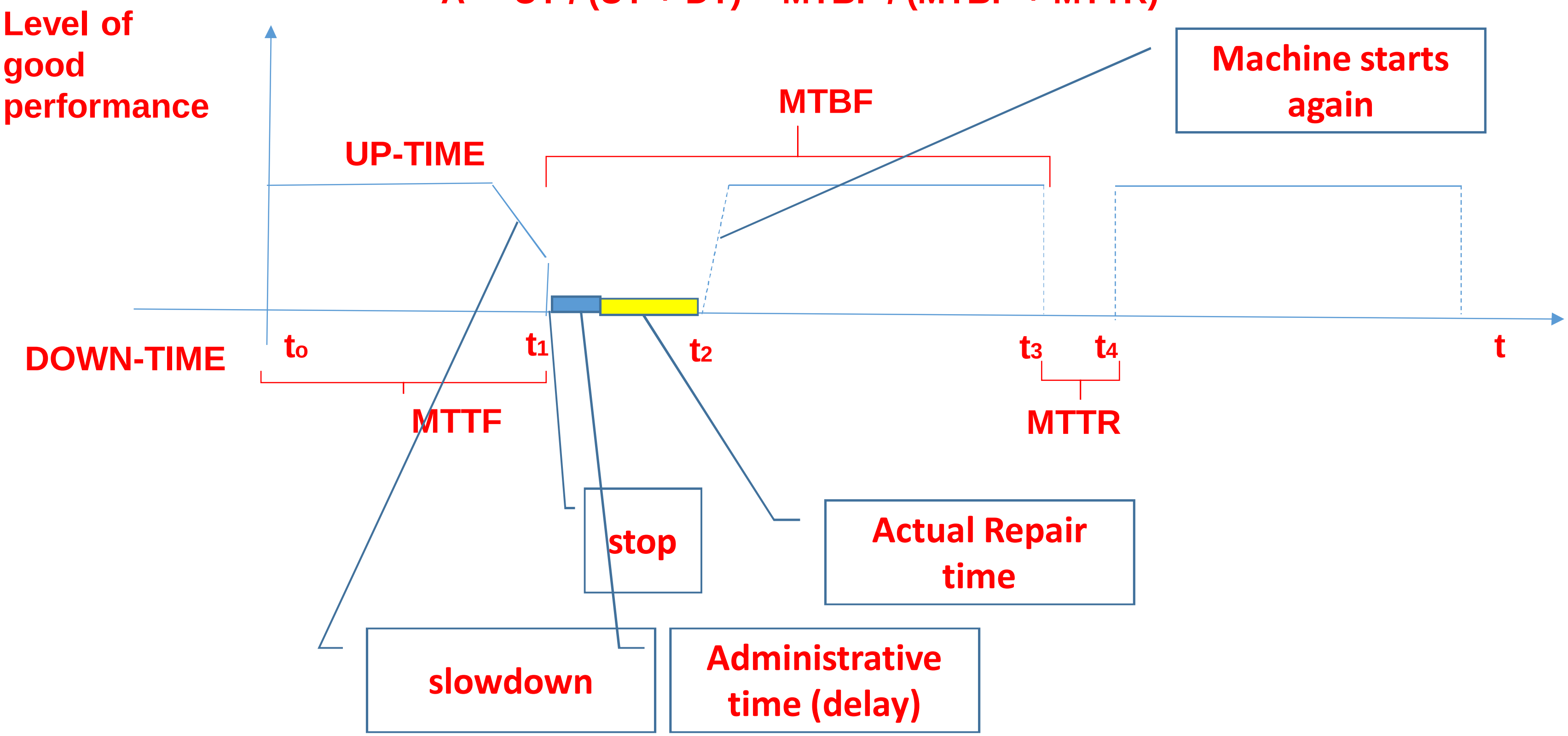
- We suppose to have a batch of all the same elements, subject to wear, with a probability distribution of normal or Gaussian type failure, which is characterized by an average time between $MTBF_0$ faults and a σ_0 dispersion.
- If only the non-functioning elements are replaced (most of the breakages will occur around $MTBF_0$), the new devices, while mixing with the previous ones, belong to another lot with higher $MTBF_1$ and higher dispersion σ_1.
- Subsequently, some surviving devices of both the first and second generation fail, a third generation must be introduced which will transform the previous batch into one with a higher $MTBF_2$ and higher σ_2, and so on and on.

$$MTBF_0 < MTBF_1 < MTBF_2$$

$$\sigma_0 < \sigma_1 < \sigma_2$$

CORRECTIVE MAINTENANCE

A = UT / (UT + DT) = MTBF / (MTBF + MTTR)



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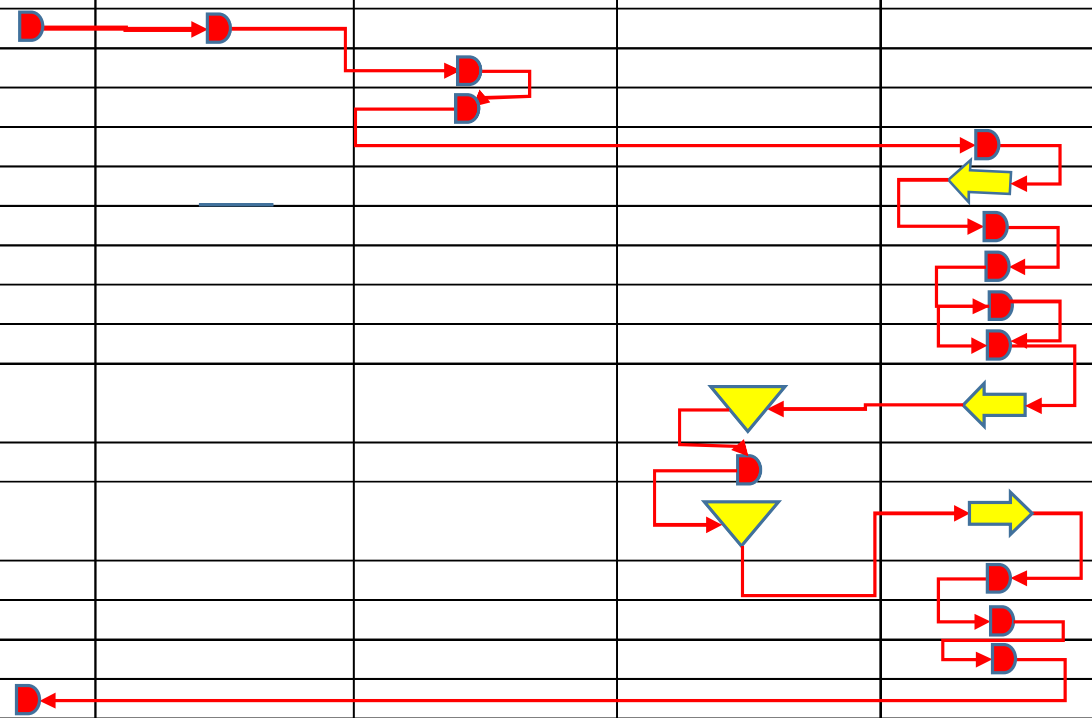
CORRECTIVE MAINTENANCE

PROCEDURE

Work instructions		Workflow					
	Activity	Operator	Workshop supervisor	Maintenance Planning Dept.	Spare Part Warehouse	Maintenance technician	
1	Breakdown						
2	warning n. 1						
3	warning n. 2						
4	Priority evaluation						
5	Decision to repair						
6	to the machine						
7	Failure analisys						
9	Root cause						
10	Disassembly						
11	Part removal						
12	Movement to spare part Warehouse						
13	spare part pick-up						
14	Movement from spare part Warehouse						
15	Part replacement						
16	Assembly						
17	Testing						



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CORRECTIVE MAINTENANCE

WHEN IS IT SUITABLE TO USE CORRECTIVE MAINTENANCE?

Mainly when:

1) **System and its components have a decreasing failure rate, like in the infant mortality phase (defects of design, manufacture, assembly, start-up or operation)**

2) **the failures are easily repairable and the machine stop does not provoke sensible damage to the general output of the production operations**

3) **There are the possibility to duplicate the machines inside the same process. In this way, if one machine stops, its role in the production process can be done by another asset.**

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CORRECTIVE MAINTENANCE

WHEN IS IT SUITABLE TO USE CORRECTIVE MAINTENANCE?

Possible negative points:

1) **Loss of profit for medium/long time stops due to machines breakdowns**

2) **Problems to organize an alternative material flow in case of breakdowns**

3) **The cumulative repair costs could become high because the failure or bad performance of a component for a long time can damage some more component of the machine.**

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CORRECTIVE MAINTENANCE

Summary

OBJECTIVES	TOOLS	PARAMETERS	TRENDS
REDUCTION OF FAILURE TIME (STOP OF THE MACHINE)	INTERVENTION SPEED	MEAN TIME OF INTERVENTION	↓
	DIAGNOSYS SPEED		
	ACTION SPEED	MEAN TIME TO REPAIR	↓
	SPARE PARTS AVAILABILITY		
REDUCTION OF FAILURE FREQUENCY	MODIFICATIONS	MEAN TIME BETWEEN FAILURE	↑
	IMPROVEMENT		
	TRAINING		
REDUCTION OF FAILURE COSTS	PLANT FLEXIBILITY	TOTAL COST OF MAINTENANCE	↓
	REDUNDANT SYSTEMS		
	FINISHED PRODUCTS INVENTORIES		

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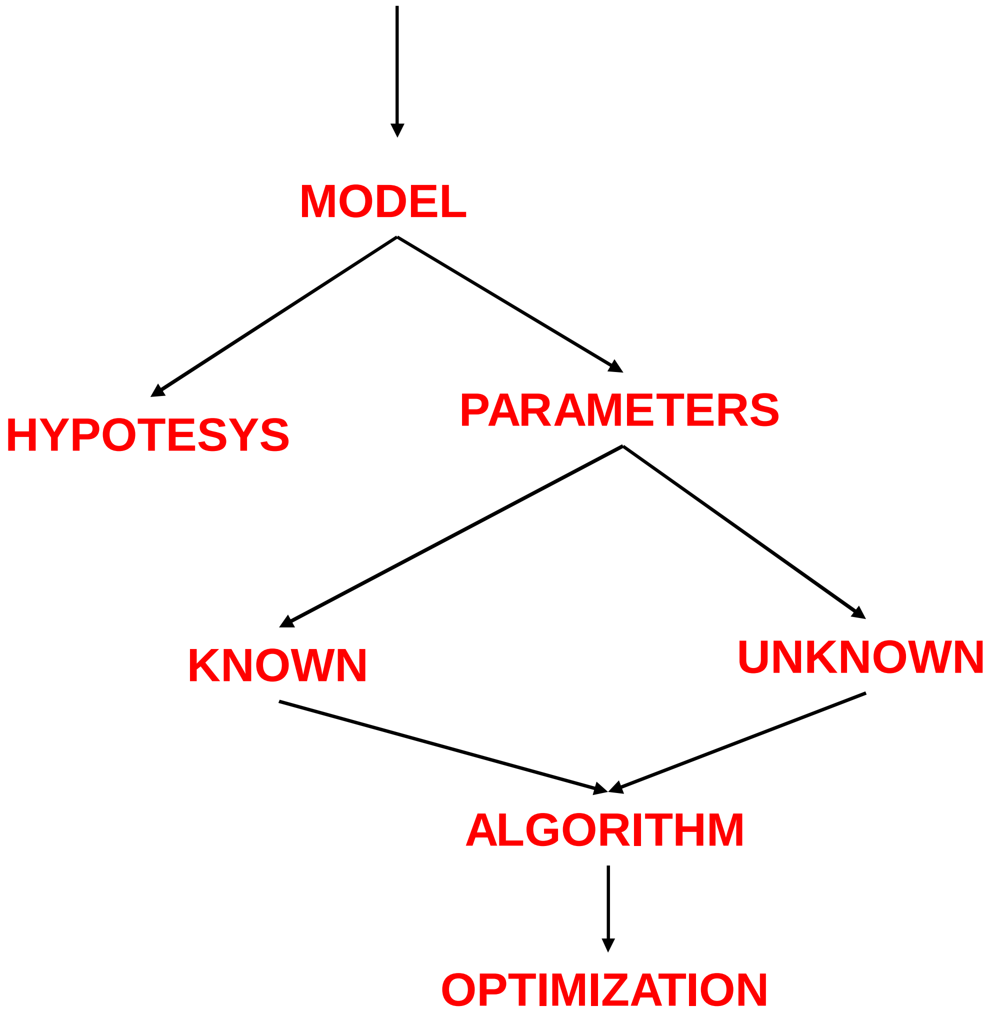
PREVENTIVE MAINTENANCE

- TIME
  - CONSTANT DATE
  - CONSTANT AGE
- LEVEL OF RELIABILITY
- PREDICTIVE
- AUTONOMOUS MAINTENANCE (TPM)

MAINTENANCE STRATEGIY



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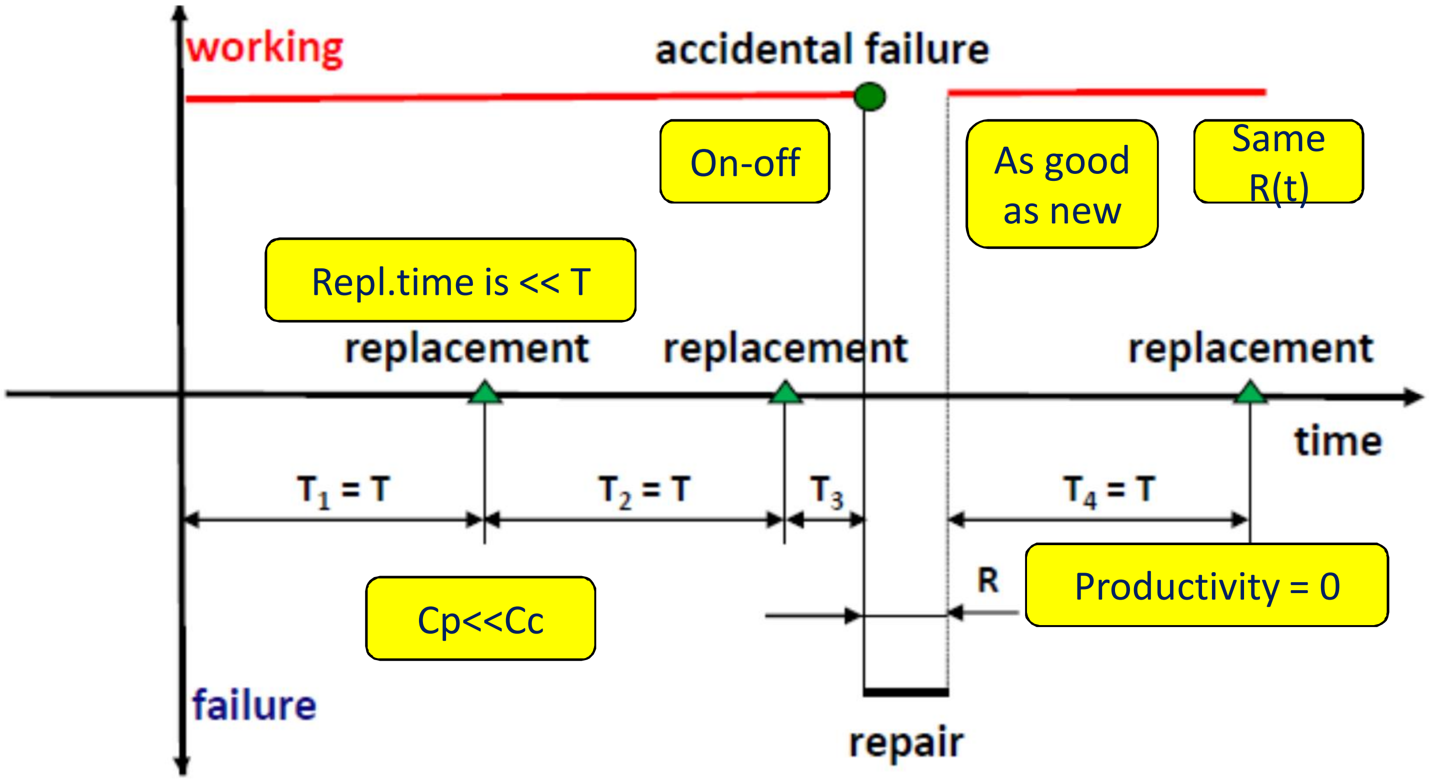
PREVENTIVE MAINTENANCE

AT CONSTANT AGE



In constant age preventive maintenance, the replacement operation takes place after the component or system has reached a certain operating time T (preventive replacement age) or before that age in case of failure (Corrective Maintenance).

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PREVENTIVE MAINTENANCE

- Preventive maintenance is scheduled in order to limit the casual behavior of the system.
- The level of system reliability varies over time according to a certain distribution of probability and with a predetermined frequency and by this activity the system is brought back to a better state of functionality because we assume (classical theory) that the preventive maintenance brings the state of the system back to a "good as new" condition.
- In other words, we assume that all the properties of the system are restored as new, that is, to restore the original distribution of probability of failure. Possible actions may be the replacement of components before the failure. The aim is to reduce the probability of failure with an associated cost recovery over the useful life of the system.

PREVENTIVE MAINTENANCE

AT CONSTANT AGE

It is assumed that the following hypotheses will be satisfied:

- Å The average preventive maintenance time of the system is very short compared with the average time to failure and therefore can be neglected
- Å Regardless of the maintenance policy, failures will occur according to a certain distribution function.
- Å The equipment can be considered "as good as new" after the intervention of corrective / preventive maintenance
- Å The period T must be chosen so that within T there can be at most one failure only.
- Å The cost of preventive maintenance must be less than the cost of maintenance corrective, because otherwise a preventive action would be useless.
- Å Once restored / replaced, the entity always follows the same law of reliability R (T) while, when the failure occurs, productivity is 0
- Å The state of the component or system does not present the possibility of a progressive decline in its performance, but only considers the two extreme states (functioning or broken)

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PREVENTIVE MAINTENANCE

AT CONSTANT AGE

Letôs suppose that:

$N_c(t)$ = number of failures in the interval (0, t);

$N_p(t)$ = number of preventive maintenance interventions in the interval (0, t);

C_c = cost of a corrective maintenance intervention (emergency intervention) ú/intervention, which takes into account both the replacement cost and the ones provokes by the the unit stop;

C_p = cost of a preventive maintenance intervention with replacement of the unit without the event of failure) ú/intervention;

T = Preventive Maintenance Time Cycle).T [1, □□ □□]

□□ □□ = Maximum Preventive Maintenance Time Cycle, where the unit is operating without failure

□* = Optimal Period of Preventive Maintenance optimizing the pertinent Maintenance cost

□□□ □(□) = Expected Cost Maintenance Per Period

□□□ □* (□) = optimal Expected Cost Maintenance Per Period

□(□) = Function of Density of Probability of failure

□(□) = Unreliability at time T(Cumulative probability of failure □(□))

□(□) = Reliability at T time (1 ī □(□))

□ (□)= Expected time of maintenance cycle if we do corrective maintenance due to a failure within 0 and T

□ □□□ (□) = Mean time between maintenance

PREVENTIVE MAINTENANCE

AT CONSTANT AGE

Therefore we use the model to determine the optimal time T* that minimizes the maintenance costs □□□ □* (□). The mean time before maintenance cycle when T varies can be calculated as follows:

$$\square\ \square\square\square\ (\square) = \square(\square) * \square + \square(\square) * \square\ (\square)$$

Where:

R (T): represents the probability that age T is reached without the occurrence of a fault and therefore represents the probability of carrying out a regular preventive replacement

F (T): represents the probability that age T is not reached and therefore the probability of carry out corrective maintenance

T: Time of the maintenance cycle if preventive maintenance is performed

M(T): Expected time of maintenance cycle if we are forced to perform corrective maintenance due to a failure in the interval (0, T]

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PREVENTIVE MAINTENANCE

AT CONSTANT AGE

$$\square\ \square\square\square\ (\square) = \square(\square) * \square + \square(\square) * \square\ (\square)$$

Let's calculate the value of $\square\ (\square)$

$$\square\ (\square) = \int_0^{\square} \square * \square(\square)\square\square / [1 - \square(\square)]$$

And, substituting M(T), we get

$$\square\ \square\square\square\ (\square) = \square(\square) * \square + \int_0^{\square} \square * \square(\square)\square t$$

Where the integrals are between 0 and T

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PREVENTIVE MAINTENANCE

AT CONSTANT AGE

After defining MTBM(T), we have to define the cost function ECMP(T) Expected Cost Maintenance Per Period.

□□∗ □(□) + □□ ∗ □(□)

□□□ □(□) = ----------------------------

□ □□□ (□)

That is, ECMP(T) will be the cost of corrective maintenance multiplied by the probability of the failure occurs before T, added to the cost of preventive maintenance by the probability that the entity survives until time T. The whole is divided by the expected duration of the cycle of maintenance.

Then for each T [1, Tmax], MTBM (T) and the pertinent ECMP (T) are calculated, and as in the case of preventive maintenance on a constant date, the optimum age T * which minimizes the ECMP*(T*) is found.

The ECMP (T) function should be a convex function, which first decreases to T * and then increases to Tmax. In case it is a function monotone decreasing of ECMP (T), the meaning is that we do not need any preventive maintenance but corrective maintenance because it is more convenient in terms of costs

That is, there will be a cost of corrective maintenance multiplied by the probability of the failure occurs before T, plus the cost of preventive maintenance by the probability that the en

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PREVENTIVE MAINTENANCE

AT CONSTANT AGE

□□□ □(□) = [□□∗ □(□) + □□ ∗ □(□)] / □ □□□ (□)

Consider a component of a system having a failure probability density f(t) uniformly distributed between 0 and 8 weeks:

$$f(t) = \begin{cases} \frac{1}{8} & (0 \leq t \leq 8) \\ 0 & \text{otherwise} \end{cases}$$

Furthermore, the costs of intervention are known:

- estimate: C_p = 10 kú/intervention

- on failure: C_c = 50 kú/intervention

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PREVENTIVE MAINTENANCE

AT CONSTANT AGE

□□□ □(□) = □□∗ □(□) + □□∗ □(□) / □ □□□ (□)

Consider a component of a system having a failure probability density f(t) uniformly distributed between 0 and 8 weeks:

Note the expression of f(t) we get:

$$f(t) = \begin{cases} \frac{1}{8} & (0 \leq t \leq 8) \\ 0 & \text{otherwise} \end{cases}$$

- **probability of failure**

$$F(t) = \begin{cases} \int_0^t \frac{1}{8}\, dt = \frac{1}{8}\, t & (0 \leq t \leq 8) \\ 1 & t > 8 \end{cases}$$

- **reliability**

$$\mathrm{R}(t) = 1 - F(t) = \begin{cases} 1 - \frac{1}{8}\, t & (0 \leq t \leq 8) \\ 0 & t > 8 \end{cases}$$

- **Failure rate**

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\frac{1}{8}}{1-\frac{1}{8}t} = \frac{1}{8-t}$$

PREVENTIVE MAINTENANCE

AT CONSTANT AGE

□□□ □(□) = [□□∗ □(□) + □□ ∗ □(□)] / □ □□□ (□)

□

□ □□□ (□) = □(□) ∗ □ + Ú□∗ □(□)□t

0

□

= {□□ ∗ *R(T)* + □□∗ [1 - □(□)]} / □(□) ∗ □ + Ú□∗ □(□)□t

0

□

= [10 ∗ (1 ï 1/8 * *T*) + 50 ∗ 1/8 *T]/ (1 ï 1/8 * *T*) ∗ □ + Ú□1/8 □t

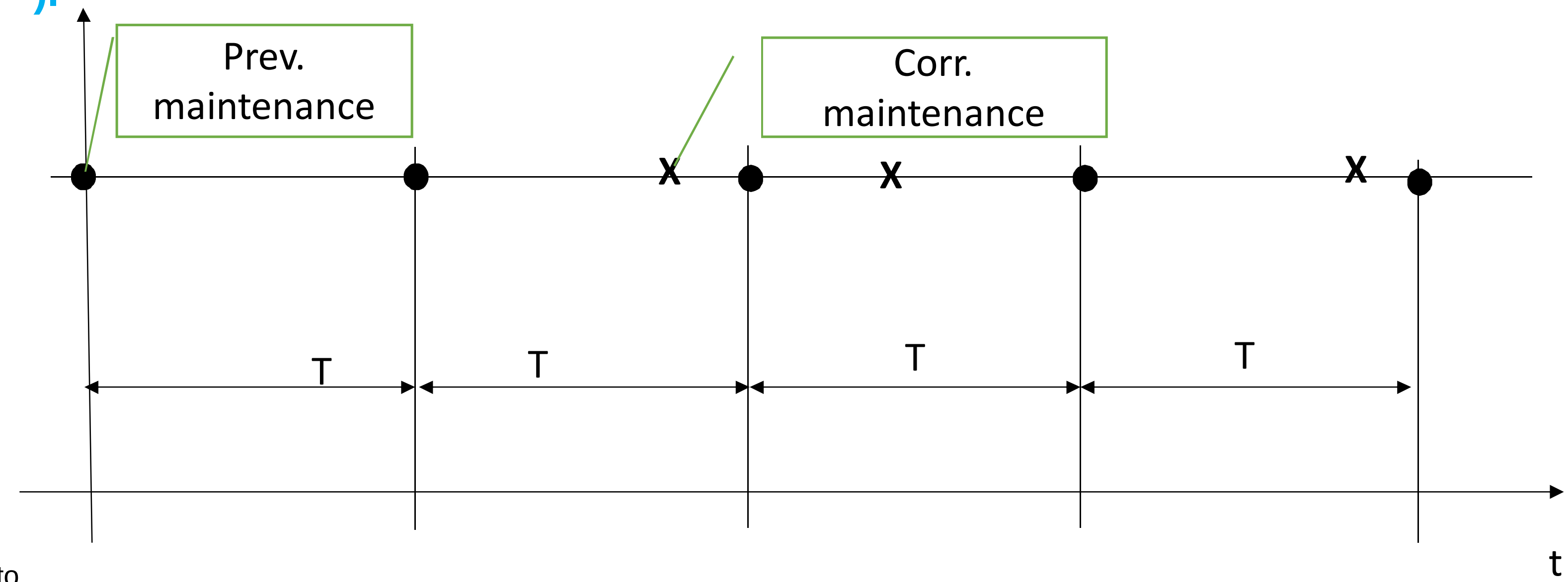
0

t_n	1	2	3	4	5	6	7	8
□□□ □(□)	16	11,43	10,26	10	10,18	10,67	11,43	12,50

PREVENTIVE MAINTENANCE

AT CONSTANT DATE

If we decide to implement a constant date preventive maintenance strategy, the system will be subjected to preventive maintenance every period T, and corrective maintenance every time a failure occurs within the interval T, as shown in the figure below. This maintenance policy consists of the systematic replacement of the component or system at a pre-established deadline, regardless of the age of the same, or at the time of its failure This model determines the optimal T* interval of preventive intervention that minimizes the maintenance cost (ECMP *).



PREVENTIVE MAINTENANCE

AT CONSTANT DATE

We give for granted the following assumptions:

- **The average preventive maintenance time is very short compared to the average failure time and therefore can be neglected.**

- **The equipment can be considered "as good as new" after corrective / preventive maintenance**

- **The period T must be chosen so that within T a single fault can occur at most.**

- **The cost of preventive maintenance must be less than the cost of corrective maintenance, because otherwise a preventive action would be useless.**

- **Once restored / replaced, the entity always follows the same law of reliability R (T)**

- **Only two states are considered (functioning or broken) and when the failure occurs, productivity is 0**

- **Availability of continuous information on the status of the component or system;**

PREVENTIVE MAINTENANCE

AT CONSTANT DATE

Letôs suppose that:

H(t) = Expected number of failures in the interval (0, t);

C_c = cost of a corrective maintenance intervention (emergency intervention) ú/intervention, which takes into account both the replacement cost and the ones provokes by the the unit stop;

C_p = cost of a preventive maintenance intervention with replacement of the part) ú/intervention;

T = Preventive Maintenance Time Cycle).T [1, □□ □□]

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□* = Optimal Period of preventive Maintenance optimizing the pertinent Maintenance cost

□□□ □(□) = Expected Cost Maintenance Per Period

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□(□) = Function of Density of Probability of failure

□(□) = Unreliability at time T(Cumulative probability of failure □(□))

□(□) = Reliability at T time (1 ī □(□))

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PREVENTIVE MAINTENANCE

AT CONSTANT DATE

First of all, we need to define a function that determines the **expected cost for each maintenance interval T**:

□□□ □ (□) = [□□ + □□ ∗ □ (□)] / □

That is, the expected cost for period T can be determined as the cost of preventive maintenance, added to the cost of corrective maintenance for the **number of failures that occurred in the interval (0, T].**
Once the cost function has been described, the following step is to determine the expected number of failures in the cyclic maintenance period T as follows:

□ (□) = Σ (i=0 to T-1) [1 + □ (□ − □ − 1)] ∗ ∫ (□ to □+1) □ (□) □□

PREVENTIVE MAINTENANCE

AT CONSTANT DATE

Therefore for each period T   [1, Tmax], the expected number of failures H (T) is calculated, and knowing the costs □□ and □□ it is possible to calculate the expected maintenance cost for each ECMP maintenance cycle (T). The optimal period T *, corresponds to the period where the ECMP (T) is minimum.

In general the ECMP (T) depends on the costs □□ and □□ and also on the probability density function □ (□). Once all ECMPs have been computed for T   [1, Tmax], the function should be a convex function, which first decreases to T * and then increases to Tmax.

In the event of a monotonous decreasing function, the model foresees that no preventive maintenance is necessary but corrective maintenance is more convenient in terms of costs.

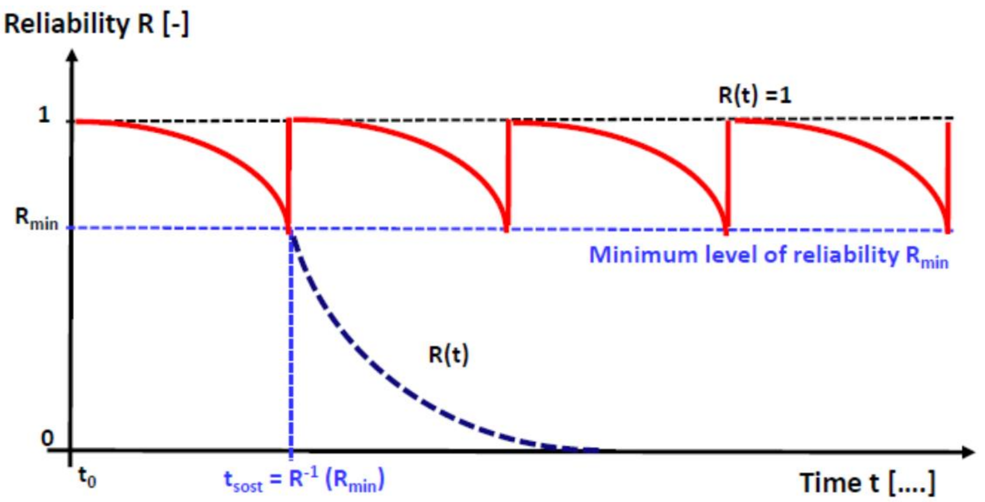
PREVENTIVE MAINTENANCE

AT A DETERMINED LEVEL OF RELIABILITY

In this policy, maintenance activities are carried out when the probability of breakdowns falls below a predetermined level.

The periods of preventive replacement are determined starting from the cumulative distribution of probability of failure.

This maintenance policy is mainly aimed at ensuring high levels of reliability, as well as the safety of the system used (figure)



PREVENTIVE MAINTENANCE

AT A DETERMINED LEVEL OF RELIABILITY

This maintenance is applied to those components where reliability and safety are predominant with respect to the economic criteria.

If the system consists of a batch of equal components, characterized by a normal or Gaussian type of density of probability of failure f(t), a maximum value of the probability of failure is established a priori and, consequently, a minimum reliability value not to be overcome.

Once this limit has been reached and, consequently, the optimal intervention interval has been determined, the whole lot is replaced with an identical one.

If the characteristics of the lots do not change as they are replaced, the intervention interval is defined by the systematic analysis on the probability density.

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PREVENTIVE MAINTENANCE

AT A DETERMINED LEVEL OF RELIABILITY

This maintenance strategy implies the possibility to act deeply in the design of the machine in order to improve the adherence to the Customerôs needs and minimize the quality problems.
Many times they are caused by the misuse done by the Customers because the performances are not according the expectations.

QUALITY FUNCTION DESIGN, FMEA and FTA are the most used techniques to act preventively on the technical specifications of the products

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QUALITY FUNCTION DEPLOYMENT

- **Late 1960s: Shigero Mizuno ï Yoji Akao first development**
- **First large scale application - Bridgestone (fishbone)**
- **1970 Kobe Shipyards ï House of Quality**
- **1970s ï Japanese Car manufacturers and other industries**
- **1985 ï first applications in the USA**
- **1990s ï large application in the USA and first applications in Europe**

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QUALITY FUNCTION DEPLOYMENT

OVERALL OBJECTIVE

The purpose of QUALITY FUNCTION DEPLOYMENT is to develop a quality assurance method that would design customer satisfaction into a product *before* it is manufactured.

Before QFD, quality control methods were primarily aimed at fixing a problem during or after manufacturing.

In other words: *The voice of the customer translated into the voice of the engineer since the beginning of the product development.*

QUALITY FUNCTION DEPLOYMENT

OBJECTIVES

ÅDEFINE THE RIGHT PRODUCT TECHNICAL CHARACTERISTICS
Å GUARANTEE THE COHERENCE BETWEEN NEEDS AND TECHICAL CHARACTERISTICS
Å BENCHMARK THE COMPETITION
Å FOCUS ON THE FIRST PHASE OF PRODUCT DEVELOPMENT
Å INCREASE THE PRODUCT INFORMATION LEVEL
ÅGUARANTEE THE COHERENCE BETWEEN THE DESIGN AND PRODUCTION
Å KEEP THE INFORMATION ON STRUCTURED AND FORMAL DOCUMENTS

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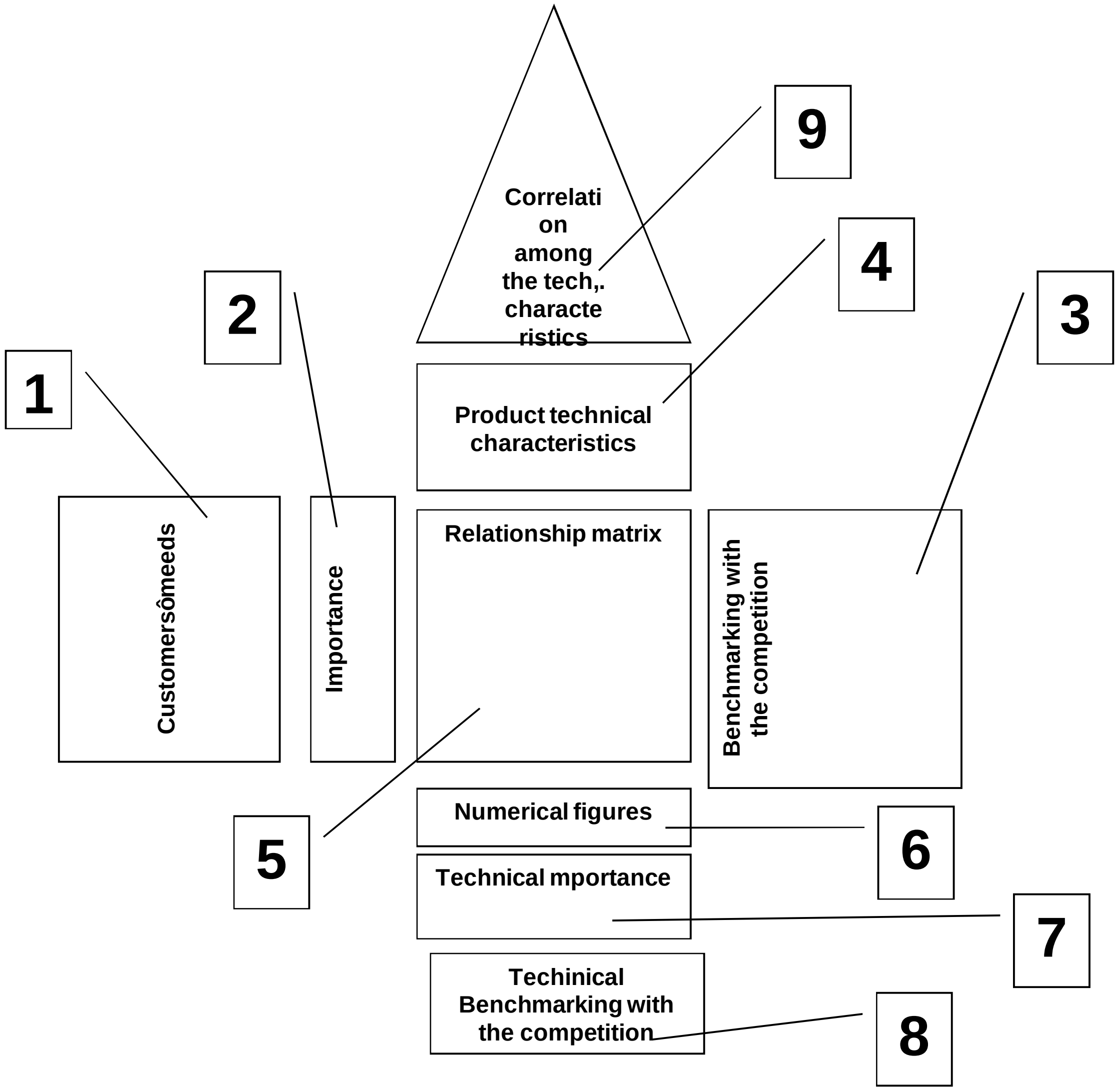
QUALITY FUNCTION DEPLOYMENT
RISKS

- Å UNCOHERENCE
- Å COMPLEXITY
- Å MANY DETAILS
- Å CORRELATION DIFFICULTIES
- ÅTIME EXPENDITURE

QUALITY FUNCTION DEPLOYMENT
HOUSE OF QUALITY



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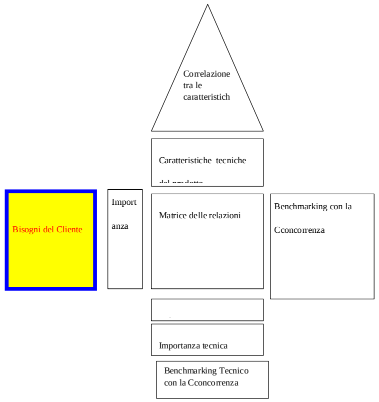
QUALITY FUNCTION DEPLOYMENT
STEP N. 1

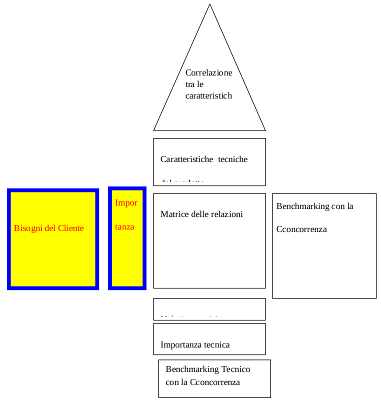
CAR SAFETY BELTS

NEEDS	PERFORMA S	PROTECT THE PASSENGERS
		EASY TO USE
	CONFORT	MINIMAL PRESSURE AFTER FASTENING
		NO HEAT ON THE BREAST
	AESTHETIC	REMAIN CLEAN
		COHERENT WITH INTERNAL AESTHETIC

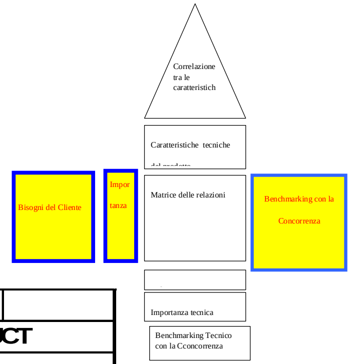


QUALITY FUNCTION DEPLOYMENT
STEP N. 2

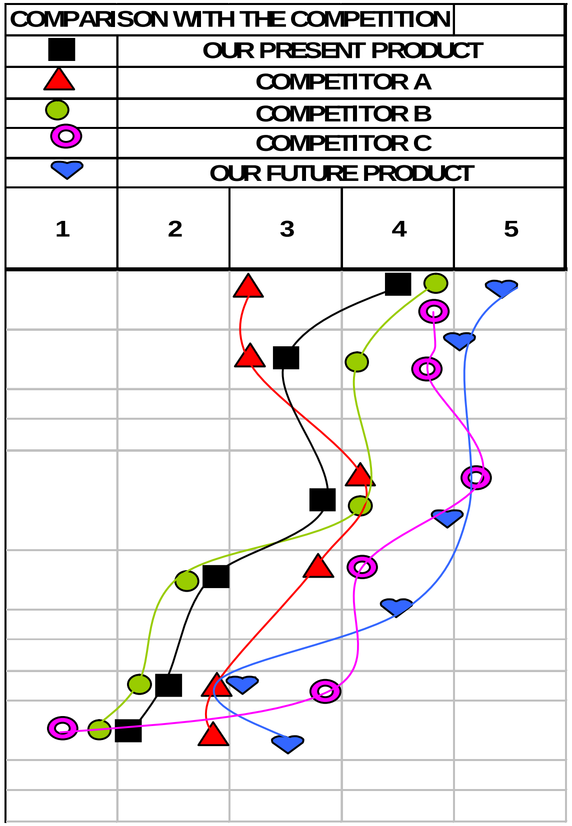
			IMPORTAN
NEEDS	PERFORMANCES	PROTECT THE PASSENGERS	10
		EASY TO USE	8
	CONFORT	MINIMAL PRESSURE AFTER FASTENING	7
		NO HEAT ON THE BREAST	5
	AESTHETIC	REMAIN CLEAN	5
		COHERENT WITH INTERNAL AESTHETIC	6



QUALITY FUNCTION DEPLOYMENT
STEP N. 3

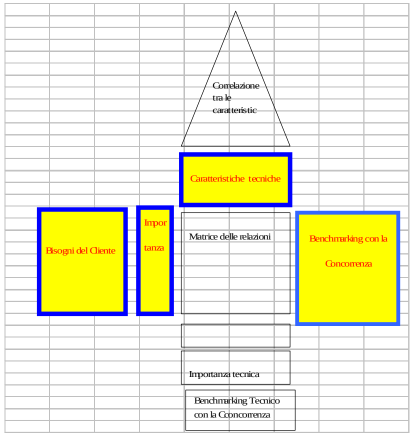


			IMPORTA
NEEDS	PERFORM ES	PROTECT THE PASSENGERS	10
		EASY TO USE	8
	CONFORT	MINIMAL PRESSURE AFTER FASTENING	7
		NO HEAT ON THE BREAST	5
	AESTHETIC	REMAIN CLEAN	5
		COHERENT WITH INTERNAL AESTHETIC	6



QUALITY FUNCTION DEPLOYMENT

STEP N. 4



TECHNICAL CHARACTERISTICS								
MAXIMUM FORC RETENTION	GEOMETRY OF BELT	TENSION FORCE	EXTRACTION FO	CLAMPING FOR	THERMAL INSUL	FIXING POSITION	STAIN RESISTA	MATERIAL COL

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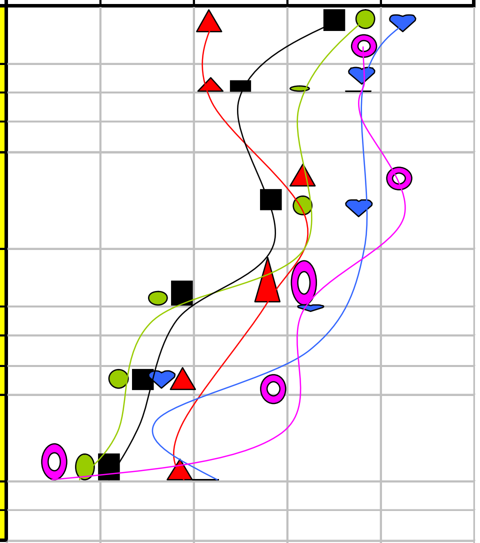
QUALITY FUNCTION DEPLOYMENT
STEP N. 5

			IMPORTANC	MAXIMUM FORCE OF RETENTIOI	GEOMETRY THE BELT	TENSION FORCE	EXTRACTIO FORCE	CLAMPING FORCE	THERMAL INSULATIOI	FIXING POSITION	STAIN RESISTANC	MATERIAL COLOUR
NEEDS	PERFORMAI ES	PROTECT THE PASSENGERS	10	9	3	3				3		
		EASY TO USE	8		1		9	9		3		
	CONFORT	MINIMAL PRESSURE AFTER FASTENED	7		3	9				3		
		NO ADDITIONAL HEAT	5			3			9	1		
	ESTETICA	KEEP CLEAN	5		1					3	9	1
		COHERENT WITH THE INTERNAL AESTHETIC	6		1					3		3

Symbol	Legend
■	OUR PRESENT PRODUCT
▲	COMPETITOR A
●	COMPETITOR B
○	COMPETITOR C
♥	OUR FUTURE PRODUCT

1	2	3	4	5



Materiale riservato
Raffaele Campanella

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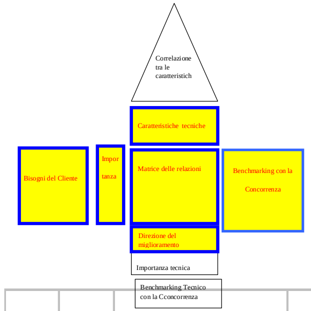
STEP N. 6

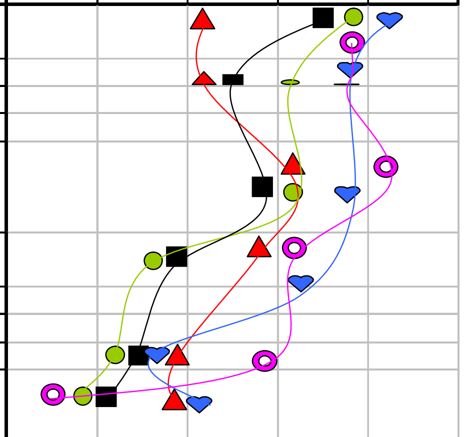


				TECHNICAL CHARACTERISTICS								
			IMPORTANCE	MAXIMUM FORCE RETENTION	GEOMETRY OF TI BELT	TENSION FORCE	EXTRACTION FOR	CLAMPING FORC	THERMAL INSULAT	FIXING POSITION	STAIN RESISTANC	MATERIAL COLOU
NEEDS	PERFORMANCES	PROTECT THE PASSENGERS	10	9	3	3				3		
		EASY TO USE	8		1		9	9		3		
	CONFORT	MINIMAL PRESSURE AFTER FASTENED	7		3	9				3		
		NO ADDITIONAL HEAT	5			3			9	1		
	ESTETICA	KEEP CLEAN	5		1					3	9	1
		COHERENT WITH THE INTERNAL AESTHETIC	6		1					3		3
IMPROVEMENT DIRECTION				⬆	=	⬇	⬇	⬇	⬇	=	⬆	=

COMPARISON WITH COMPETITION

■	OUR PRESENT PRODUCT
▲	COMPETITOR A
●	COMPETITOR B
○	COMPETITOR C
♥	OUR FUTURE PRODUCT

1 2 3 4 5



Materiale riservato
Raffaele Campanella

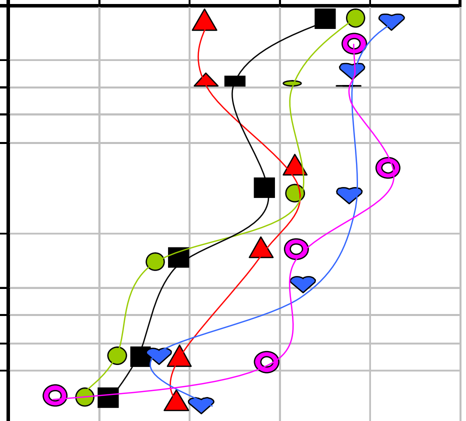
STEP N. 7

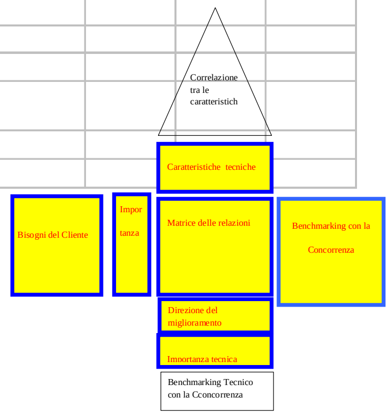
NEEDS			IMPORTANCE	MAXIMUM FORCE RETENTION	GEOMETRY OF T BELT	TENSION FORCE	EXTRACTION FOR	CLAMPING FORC	THERMAL INSULAT	FIXING POSITION	STAIN RESISTANC	MATERIAL COLO
				TECHNICAL CHARACTERISTICS								
NEEDS	PERFORMA ES	PROTECT THE PASSENGERS	10	9	3	3				3		
		EASY TO USE	8		1		9	9		3		
	CONFORT	MINIMAL PRESSU AFTER FASTENED	7		3	9				3		
		NO ADDITIONAL HEAT	5			3			9	1		
	ESTETICA	KEEP CLEAN	5		1					3	9	1
		COHERENT WITH THE INTERNAL AESTHETIC	6		1					3		3
IMPROVEMENT DIRECTION				⬆	=	⬇	⬇	⬇	⬇	=	⬆	=
TECHNICAL IMPORTANCE				90	70	108	72	72	45	113	45	23
RANKING				3	5	2	4	4	6	1	6	7

COMPARISON WITH COMPETITION

- ■ OUR PRESENT PRODUCT
- ▲ COMPETITOR A
- ● COMPETITOR B
- ○ COMPETITOR C
- ♥ OUR FUTURE PRODUCT

1	2	3	4	5





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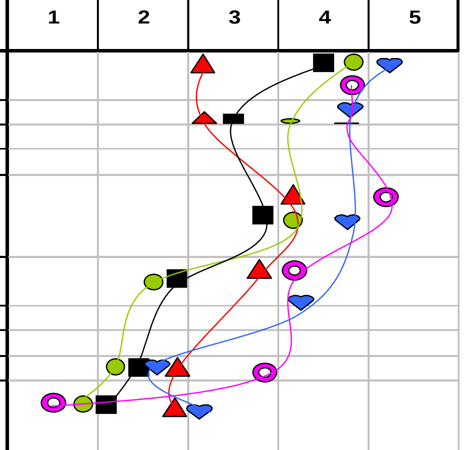
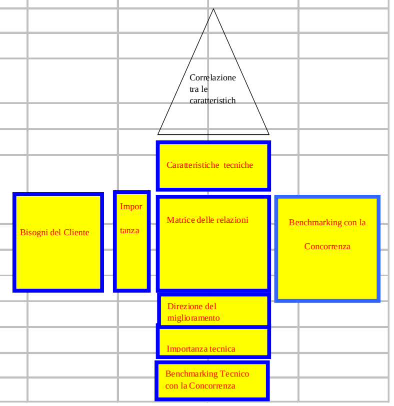
STEP N. 8

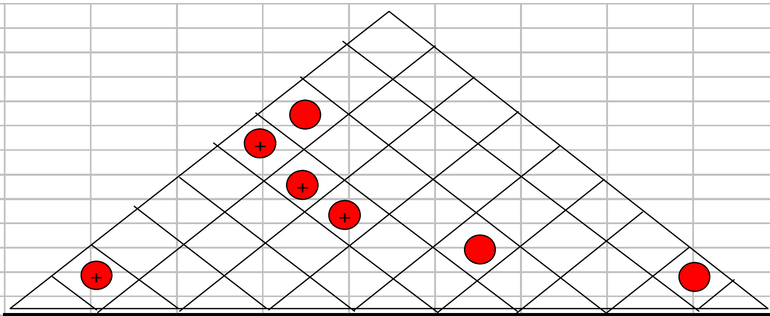
		IMPORTANCE	TECHNICAL CHARACTERISTICS: MAXIMUM FORC RETENTION	GEOMETRY OF BELT	TENSION FORCE	EXTRACTION F	CLAMPING FOR	THERMAL INSUL	FIXING POSITIO	STAIN RESISTA	MATERIAL COL
NEEDS – PERFORMANCES	PROTECT THE PASSENGERS	10	9	3	3				3		
	EASY TO USE	8		1		9	9		3		
NEEDS – CONFORT	MINIMAL PRESSUL AFTER FASTENED	7		3	9				3		
	NO ADDITIONAL HEAT	5			3			9	1		
NEEDS – ESTETICA	KEEP CLEAN	5		1					3	9	1
	COHERENT WITH THE INTERNAL AESTHETIC	6		1					3		3
IMPROVEMENT DIRECTION			⬆	=	⬇	⬇	⬇	⬇	=	⬆	=
TECHNICAL IMPORTANCE			90	70	108	72	72	45	113	45	23
RANKING			3	5	2	4	4	6	1	6	7
BENCHMARKING COMPETITION / MEASUREMENT UNITS			N	mm	N	N	N	CLASS	POS. A/B/C	CLASS	COLOR MATCHING
OUR PRESENT PRODUCT			7340	2X50	4,3	10	5	R19	A	34C	Y
COMPETITOR A			7150	1,5X55	3,9	9	4	R12	B	29C	Y
COMPETITOR B			7200	1,75X45	3,5	7,4	2	R16	A	35C	Y
COMPETITOR C			7430	1,3X50	4,3	11	5	R20	C	36C	Y
OUR FUTURE PRODUCT			7340	1,3X50	2,5	7	2	R12	A	30C	Y

COMPARISON WITH COMPETITION

- ■ OUR PRESENT PRODUCT
- ▲ COMPETITOR A
- ● COMPETITOR B
- ◎ COMPETITOR C
- ♥ OUR FUTURE PRODUCT







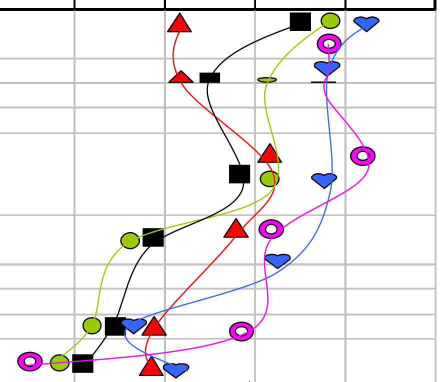
STEP N. 9

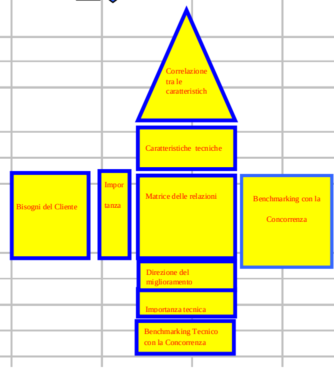
NEEDS			IMPORTANCE	MAXIMUM FORC RETENTION	GEOMETRY OF BELT	TENSION FORCE	EXTRACTION FO	CLAMPING FOR	THERMAL INSUL	FIXING POSITION	STAIN RESISTA	MATERIAL COL
NEEDS	PERFORMANCES	PROTECT THE PASSENGERS	10	9	3	3				3		
		EASY TO USE	8		1		9	9		3		
	CONFORT	MINIMAL PRESSUL AFTER FASTENED	7		3	9				3		
		NO ADDITIONAL HEAT	5			3			9	1		
	ESTETICA	KEEP CLEAN	5		1					3	9	1
		COHERENT WITH THE INTERNAL AESTHETIC	6		1					3		3
IMPROVEMENT DIRECTION				⬆	=	⬇	⬇	⬇	⬇	=	⬆	=
TECHNICAL IMPORTANCE				90	70	108	72	72	45	113	45	23
RANKING				3	5	2	4	4	6	1	6	7
BENCHMARKING COMPETITION (MEASUREMENT UNITS)				N	mm	N	N	N	CLASS	POS. A/B/C	CLASS	COLOR MATCHING
OUR PRESENT PRODUCT				7340	2X50	4,3	10	5	R19	A	34C	Y
COMPETITOR A				7150	1,5X55	3,9	9	4	R12	B	29C	Y
COMPETITOR B				7200	1,75X45	3,5	7,4	2	R16	A	35C	Y
COMPETITOR C				7430	1,3X50	4,3	11	5	R20	C	36C	Y
OUR FUTURE PRODUCT				7340	1,3X50	3,5	7	2	R12	A	[illegible]	Y

COMPARISON WITH COMPETITION

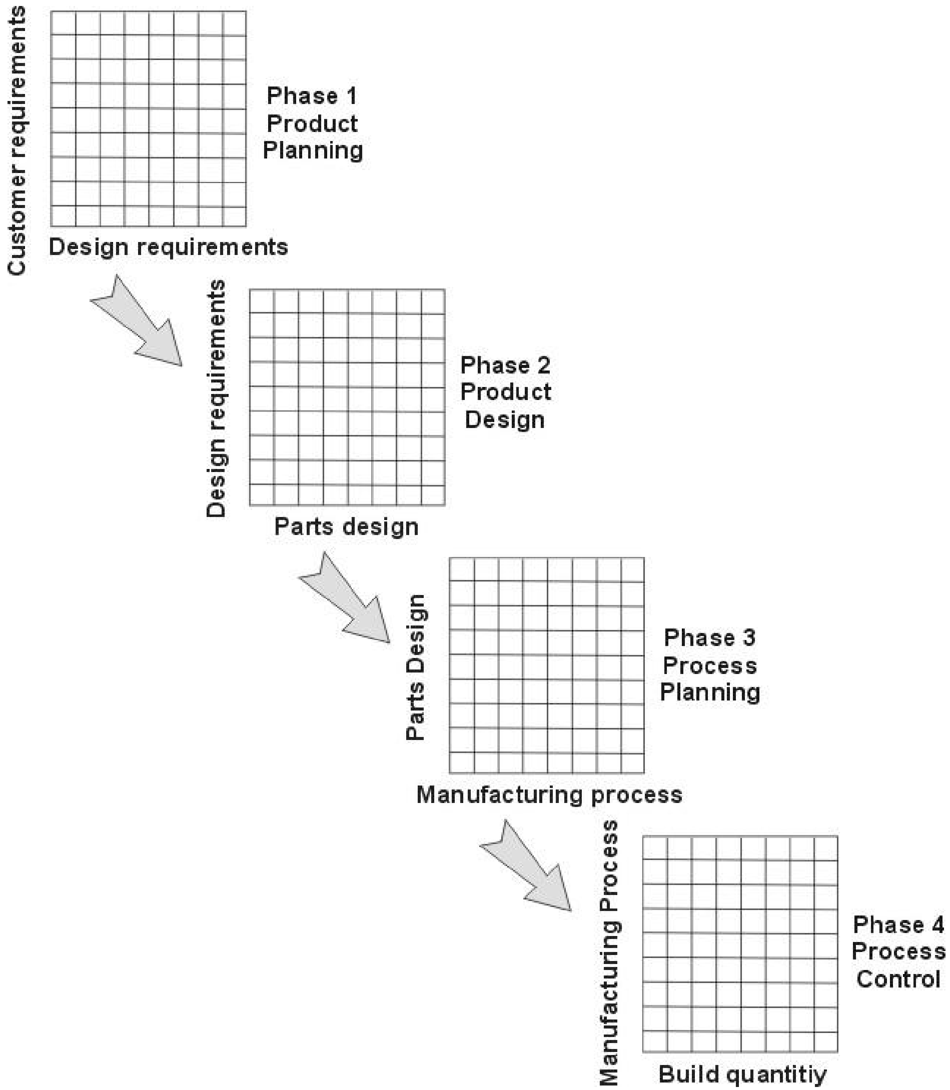
Symbol	
■	OUR PRESENT PRODUCT
▲	COMPETITOR A
●	COMPETITOR B
○	COMPETITOR C
♥	OUR FUTURE PRODUCT

1 2 3 4 5

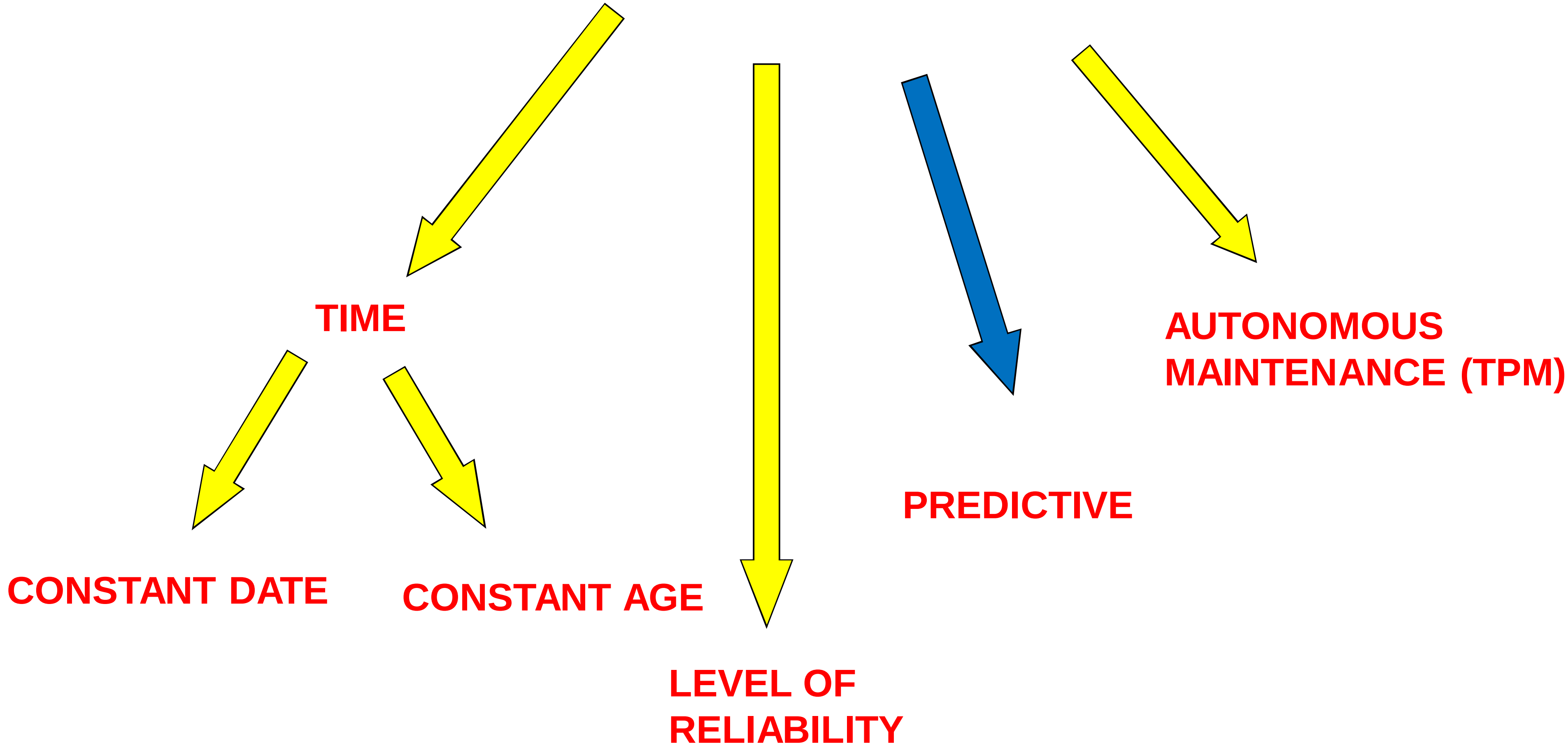




Each of the phases in the product development uses a QFD matrix to translate customer requirements from initial planning stages through production control



PREVENTIVE MAINTENANCE



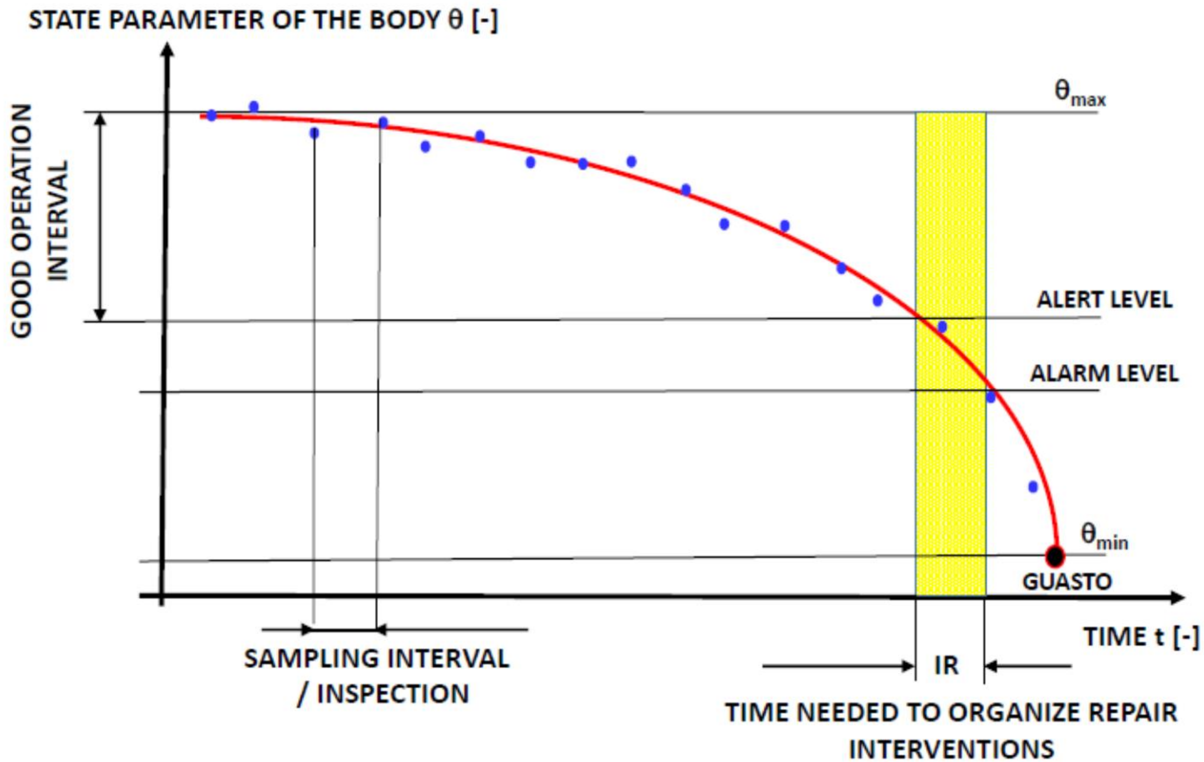
PREVENTIVE MAINTENANCE

PREDICTIVE MAINTENANCE

Predictive maintenance is based on inspections and measurement in the system, after setting the performance levels, in order to establish the level of deterioration.

Predictive maintenance is carried out when the critical level is reached. This not excludes that accidental failures can occur between one inspection and the next.

It depends strongly on the accuracy of measurements of parameters related to the unit's operating states, trying to predict the time of the fault occurrence.



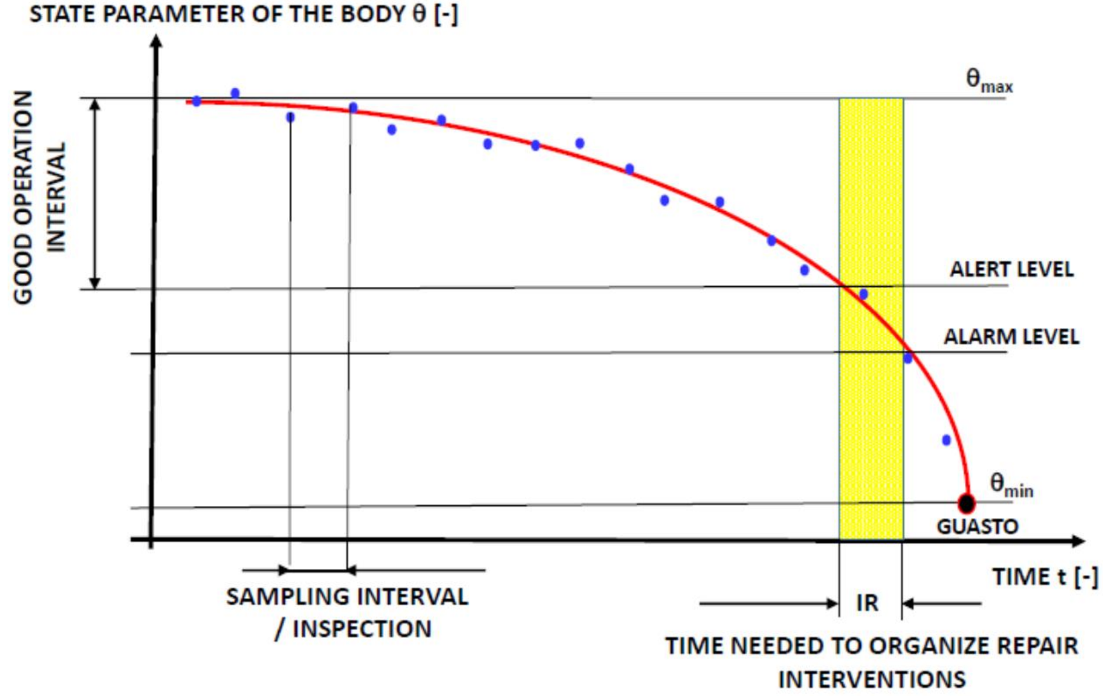
PREVENTIVE MAINTENANCE

PREDICTIVE MAINTENANCE

Predictive maintenance is also called ñon conditionò or ñcondition basedò maintenance which provides for the real-time programming of maintenance interventions according to the conditions of the unit and the requirements to be respected, allowing to avoid unexpected downtime or catastrophic chain reactions, improving the overall reliability of the system at a reduced cost.

This is possible using the non-destructive techniques to test the selected components or systems

It depends strongly on the accuracy of measurements of parameters related to the unit's operating states, trying to predict the time of the fault occurrence.



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PREVENTIVE MAINTENANCE

PREDICTIVE MAINTENANCE

This maintenance policy is mainly suitable for the systems with high hourly cost of operations, with complex and technologically advanced systems, where a plant shutdown would do particularly expensive.

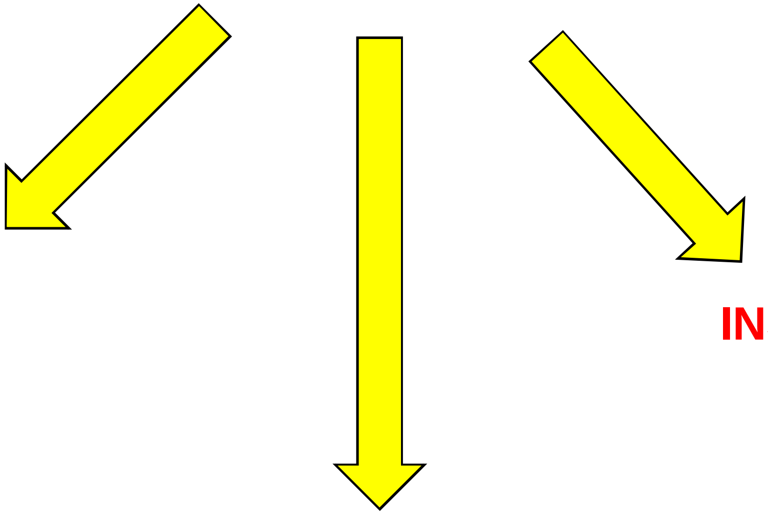
In predictive maintenance the intervention is no longer linked to the time of operation, but to the actual conditions of the component and the reliability of the system.

It combines the advantages of corrective and preventive policies; it constitutes an action done before the fault, supported by a high knowledge of the structure and the real state of the individual components of the machine or system, identifying important parameters to be measured during operation, and the pertinent tolerances ranges.

PREVENTIVE MAINTENANCE

PREDICTIVE MAINTENANCE

TECHNOLOGIES



SENSORS

INSTRUMENTS

VISUAL OBSERVATION

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PREVENTIVE MAINTENANCE

PREDICTIVE MAINTENANCE

Method	Tool	Application
Visual	Endoscope Optical fibers Strobe Penetrant liquids Thermographic paints Fluorescent liquids	Internal parts of machines accessible through small inspection holes Identical to the previous one, more flexible tool Belts, joints, gears, each part in relative movement Superficial cracks Surface and condensate drains temperature Surface cracks, in particular for light alloys
Temperature	Instant thermometer Infrared thermometer Infrared thermography	Bearings, condensate drains, all cases of rapid measurement Surface temperature, flame Refractory condition, insulating coatings, HV lines, gas pipes, hydraulic systems, heat losses, cleanliness of the exchangers
Noises/ultrasound	Stethoscope Sound Level Meter Ultrasound Emissione acustica	Audible band amplifier, mechanical noise Noise measurement in environments, machine Search for leaks of fluids under pressure, vacuum, compressor valves, piston rings, chains Crack propagation and other structural defects
Vibrations	Vibrometer Analyzer Phase indicator Real time Monitor Spn Acoustic emission	Total vibration measurement Frequency analysis for diagnosis of facts Analyzer accessories for balancing Frequency analyzer for analysis of transients and complex cases Continuous measurement and control with alarm and lockout Specification for rolling bearings Condition of rolling bearings
Non destructive tests	X-ray γ-rays Ultrasound Eddy currents	Thicknesses, corrosions, cracks, inclusions, blowholes, emissions Identical to the previous one Identical to the previous one Surface and skin defects, condition of the heat exchanger pipes
Wear particles	Magnetic plugs Automatic counters Absorption and emission spectrophotometry Ferroprapphy	Identification of magnetic parts, their shape Counting of wear particles and their size Damper metal particle quantification of the metal present Quantification of particles according to their size
Lubricating oils	Lubrisensor Owner Tbn Setaflash	Coarse determination of a lubricant Determination of the Total basic number to evaluate the influence of the sulfur content in diesel oils Determination of the presence of pollutants (diesel, water) in the lubricant
Others	Spark gap Gas Chromatography Mobil elektronik compression tester	Dielectric constant of transformer oils Titration of gases present in transformer oils to trace the state of insulating materials Diagnosis of Otto and Diesel engine status

PREVENTIVE MAINTENANCE

PREDICTIVE MAINTENANCE

- VIBRATIONS MONITORING
- THERMOGRAPHY
- VISUAL INSPECTION
- TRIBOLOGY
- PROCESS PARAMETERS
- OTHER NON-DESTRUCTING TESTING TECHNIQUES

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PREDICTIVE MAINTENANCE

VIBRATIONS MONITORING AND ANALYSIS

Vibrations monitoring and analysis are two of the most useful tool for predicting incipient mechanical, electrical and process-related problems within plant equipment, machinery, and continous-process sytems.

Therefore they are also the most often-used predictive maintenance technologies.

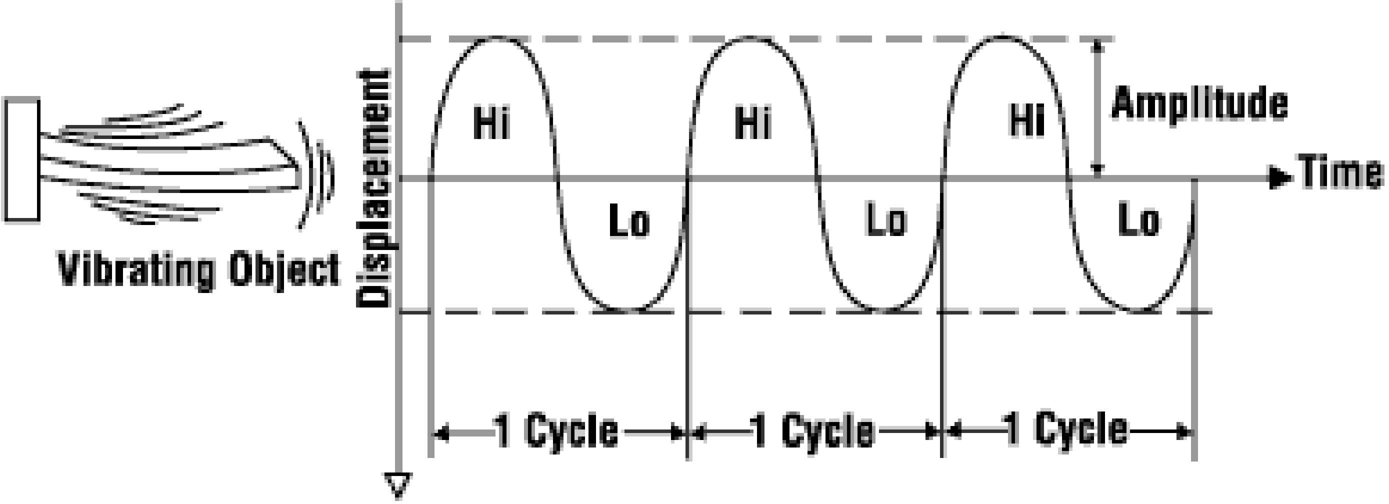
They are not used alone but in conjunction with other process-related measurements, such as flow, pressure, temperatureé

Vibrations monitoring and analysis can be used in many alternative applications such as:

- Accepting testing/Installation testing
- Quality Control
- Loose part detenction
- Abnormal noise control
- Leak detenction

PREDICTIVE MAINTENANCE

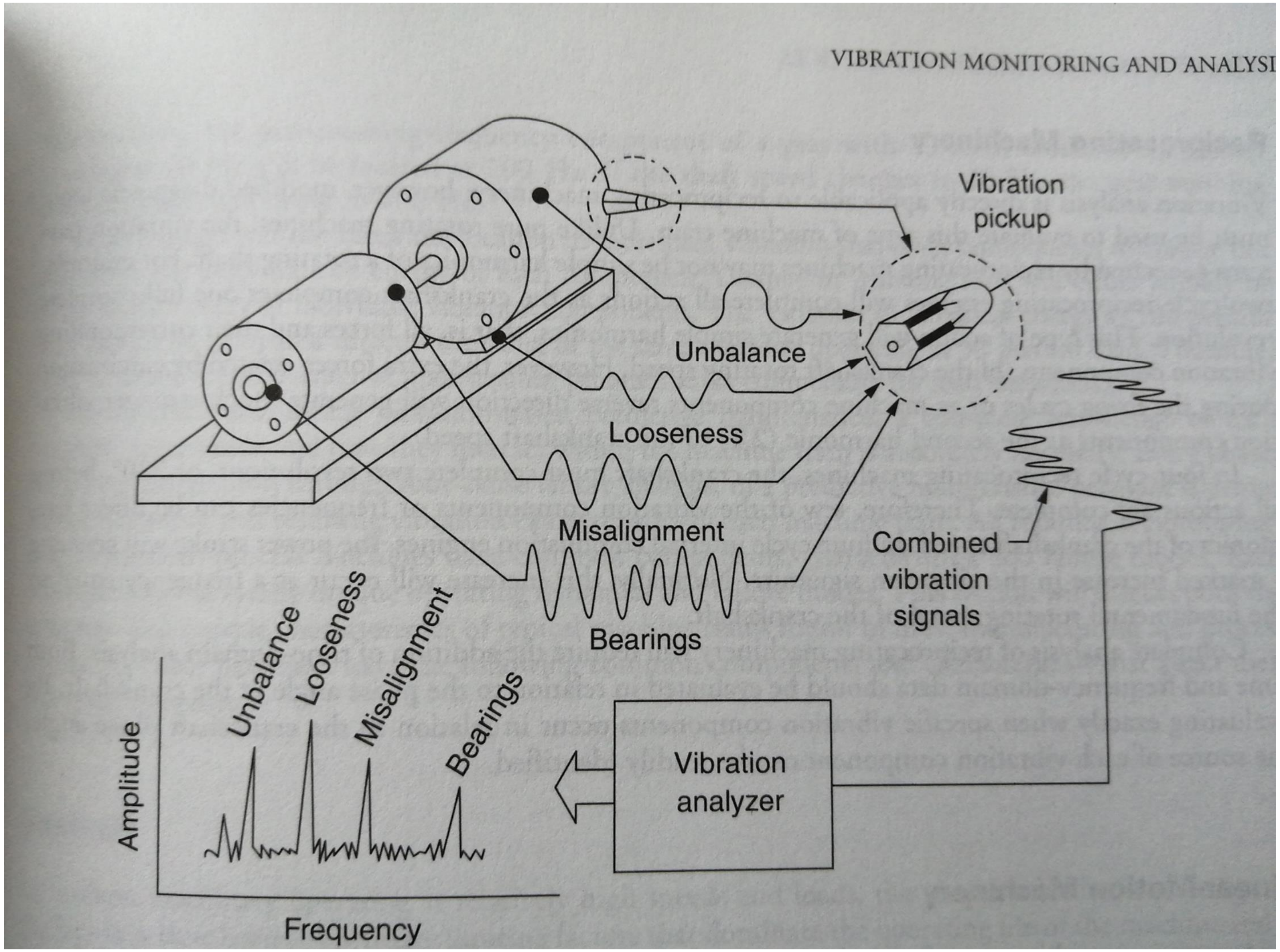
VIBRATIONS MONITORING AND ANALYSIS



- **DISPLACEMENT** : The actual change in position of an object from a fixed referencepoint is expressed as displacement
- **AMPLITUDE**: Amplitude is the distance from the stationary position to the extreme position on either side. The intensity of vibration depends on amplitude.
- **FREQUENCY**: The time rate of change of displacement is velocity (energy generated by vibrations)
- **ACCELERATION**: Acceleration is a measure of how quickly speed changes with time. The speed of a vibrating object varies from zero to a maximum during each cycle of vibration. (force generated by vibrations)
- **PHASE**: It is used to define the relationship of harmonic vibration components. Changes of phase can bringto resonance.
- **RESONANCE**: Every object tends to vibrate at one particular frequency called the natural frequency. The measure of natural frequency depends on the composition of the object, its size, structure, weight and shape.

PREDICTIVE MAINTENANCE

VIBRATIONS MONITORING AND ANALYSIS



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PREDICTIVE MAINTENANCE

THERMOGRAPHY

- **Thermography is the process of using an instrument designed to monitor the emission of infrared energy to look for abnormally hot or cold areas on a component operating under normal conditions. It is a viable nondestructive evaluation technique for the characterization of corrosion in metallic materials and is the simplest of all thermal inspection techniques.**

- **Thermography is the simplest method for predictive maintenance and it is widely used in industry. It can practically be used in all the processes for the detection of**
    - **Mechanical problems**
    - **Electrical problems**
    - **Corrosion/erosion damage in plants operating at elevated temperatures.**
    - **Fouling or internal plugging of piping systems**
    - **Quality problems of refractory materials.**
    - **Components faiures**
    - **Load problems**
    - **………….**

PREDICTIVE MAINTENANCE

TRIBOLOGY

TRIBOLOGY is the study of friction, wear, lubrication, fatigue and, more generally, the science of interacting surfaces in relative motion.
Several tribology techniques can be used for predictive maintenance:

- **Lubricating oil analysis**
  - **Viscosity**
  - **Contamination**
  - **Fuel dilution**
  - **Solid content**
  - **Fuel soot**
  - **Oxidation**
  - **Nitration**
  - **Control of Acidity and Basicity**
  - **Particle count**
- **Spectrographic analysis for oil analysis and part analysis**
- **Ferrography for oil analysis and worn part analysis**
- **Wear particle analysis due to several types of problems due to wear (Rubbing, Cutting, Rolling fatigue…**
- **…..**

PREDICTIVE MAINTENANCE

OTHER NON-DESTRUCTING TESTING TECHNIQUES

As a part od a predictive maintenance program, ultrasonic instruments are used mainly for the following applications:

- Airborne noise analysis
- Leak detention
- Material testing

All the electromechanical equipment produce a broad range of vibration and therefore sound. The high-frequency ultrasonic components of these sounds are extremely short-wave in nature. A short wave signal tends to be fairly directional and localized, which allows to separate these signal from background noise and to lacalise the source.
Further applications are link to:

- The electrical circuits status, because ultrasounds detect ionization produced by arcing, tracking, corona effect…, while infrared is better to locate overheating due to too high corrents;
- As a condition based lubrication because a ultrasound noise exceeding a certain limit is a signal of lubrication need.

PREDICTIVE MAINTENANCE

HYPOTESYS/CONDITIONS

The system must be inspectable during operation

The state of the machine or its component is known only due to the results of the inspections, except for the condition ñout of serviceò

The system evolves from conditions of perfect functionality to those of out of service through several intermediate stages characterized by the progressive worsening of some parameters

The function of distribution of failure is known and the inspection cost C_i must be lower than both the corrective investment cost C_c and the planned preventive intervention cost C_p.

$C_i < C_c$ ï C_p

and:

$C_i < C_c < C_p$

INSPECTION

NO ACTION

SCHEDULED MAINTENANCE

EMERGENCY MAINT.

PREDICTIVE MAINTENANCE

WHAT IS NECESSARY

Identify the parameters to identify the conditions of the machine

Identify the limit values of the parameters

Tolerate the performance values until resorting to a scheduled intervention

Choose the right methods and techniques for detecting these parameters

Identify the time frequency for the inspections

Carry out a scheduled maintenance intervention (repair/replacement) on pertinent components and carry out emergency interventions on them because otherwise the stop is caused

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PREDICTIVE MAINTENANCE

FREQUENCY OF PERIODIC INSPECTION

DIFFICULTY FACTORS

complexity of the systems

many elementary units/components /parts

failure rate for each component/system

economic point of view (few or many inspections?)

technical-operational problems, mixed to an economic problem

PREDICTIVE MAINTENANCE

FREQUENCY OF PERIODIC INSPECTION
DIFFICULTY FACTORS

- **In fact, as the time interval between two subsequent inspections decreases (increase in inspection frequency), the control of the state of the component or system increases and the reliability as well.**
- **As the inspection frequency increases, the cost resulting from accidental breakdowns decreases, however leading to higher direct inspection costs.**
- **The problem that arises is then to determine the optimal inspection frequency, such as to minimize the sum of the inspection costs and those associated with the out of operation of the machinery.**

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PREDICTIVE MAINTENANCE

SIMPLIFIED MODELS FOR FREQUENCY OF PERIODIC INSPECTION DEFINITION

Systems with components subject to random faults

Systems with components subject to wear-out phenomena

This is sequence of inspection intervals $t_1, t_2, ..., t_n$ where the function of distribution of the failure times between two successive inspections remain constant over time. Under this assumption the intervals are

$$t_i = i \cdot t \text{ with } i = 1, 2, ..., n$$

therefore sufficient to know t to determine the complete sequence of inspection times.

PREDICTIVE MAINTENANCE

Systems with components subject to random faults

The optimal inspection frequency, in the case of accidental failures, can be determined with an approximate method: this can be obtained by minimizing the cost function, which can be expressed as:

$$C = C_i \cdot f + C_c \cdot p + C_p \cdot (1-p)$$

where:

C_i = cost of an inspection that is supposed to be constant;

C_c = overall cost of the failure maintenance intervention;

C_p = overall cost of the preventive intervention;

f = average number of inspections up to and including maintenance;

p = conditional probability of failure between two successive inspections which is considered constant and can be expressed by the ratio:

$$p = \frac{F(t_i) - F(t_{i-1})}{R(t_{i-1})}$$

with: $F(t_i)$ = cumulative probability of failure at time t_i; $R(t_i)$ = reliability at the time t_i.

PREDICTIVE MAINTENANCE

Systems with components subject to random faults

The probability that the fault occurs in the inspection interval (i, i+1) can be expressed by the relation between the probability that the fault did not occur before and the probability that the fault occurs at the i-th inspection, that is:

$$(1 - p)^{i-1} \cdot p$$

The average number of inspections until failure can be expressed by the report:

$$f = \sum_{i=1}^{\infty} i \cdot (1-p)^{i-1} \cdot p = \frac{1}{p}$$

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PREDICTIVE MAINTENANCE

Systems with components subject to random faults

$$C = C_i \cdot f + C_c \cdot p + C_p \cdot (1-p)$$

Substituting in the cost function, we obtain:

$$\frac{C_i}{p} + C_c \cdot p + C_p \cdot (1 - p)$$

and, minimizing it, that is, deriving it with respect to p and equaling it to zero, we obtain:

$$-\frac{C_i}{p^2} + C_c - C_p = 0$$

from which:

$$p = \sqrt{\frac{C_i}{(C_c - C_p)}}$$

PREDICTIVE MAINTENANCE

Systems with components subject to random faults

For λ constant, applying an exponential type of system fault law, we have:

$$\frac{t}{MTBF} = -\ln(1-p)$$

from which the optimal inspection interval can be obtained by knowing the overall costs and the average time between failures (MTBF).
By means of a simple data processing program or the use of suitable tables (see next slide), it is possible to determine the optimal inspection frequency and therefore from the sequence of inspection times.

PREDICTIVE MAINTENANCE

Systems with components subject to random faults

Table for calculating the optimal inspection frequency in the event of accidental failures

$$p = \sqrt{\frac{C_i}{(C_c - C_p)}}$$

$$\frac{t}{MTBF} = -\ln(1-p)$$

$C_i/(C_c-C_p)$	p	t_i/MTBF
0,001	0,03162	0,03213
0,002	0,04472	0,04575
0,003	0,05477	0,05632
0,004	0,06324	0,06532
0,005	0,07071	0,07343
0,006	0,07745	0,08061
0,007	0,08366	0,08737
0,008	0,08944	0,09369
0,009	0,94861	0,09967
0,010	0,10000	0,10536
0,020	0,14142	0,15247
0,030	0,17340	0,19019
0,040	0,20000	0,22314
0,050	0,22360	0,25308
0,060	0,24425	0,28097
0,070	0,26437	0,30729
0,080	0,28284	0,33245
0,090	0,30000	0,33667
0,100	0,31672	0,38011
0,200	0,44721	0,59277
0,300	0,54772	0,79545
0,400	0,63245	1,00089
0,500	0,70710	1,22729
0,600	0,77459	1,48983
0,700	0,83666	1,81192
0,800	0,89442	2,24828
0,900	0,94868	2,96967

PREDICTIVE MAINTENANCE

Systems with components subject to random faults

Example

If the inspection cost on a machine is 1000 ú, an emergency intervention cost of ú 20,000, a preventive intervention cost of ú 15.000 with a mean time before failure MTBF of 200 hours, you will have:

$$\frac{C_i}{(C_c - C_p)} = \frac{1000}{20000 - 15000} = \frac{1.000}{5000} = 0,2$$

for which we will obtain:

$$\frac{t}{MTBF} = 0,59277 \quad and \quad t_1 = 0,59277 \cdot 200 = 118,5 \cong 119 \; hours$$

PREDICTIVE MAINTENANCE

Systems with components subject to random faults

Example:

The sequence of inspection times, taking into account that the component fails after 450 hours and is changed, is as follows:

t_1 = 119 hours
t_2 = 238hours
t_3 = 357 hours
t_g = 450 hours (failure)
t_4 = 569 hours
t_5 = 688 hours

and so you go until a new fault occurs or until the inspection gives results such as to recommend the scheduled intervention.

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PREDICTIVE MAINTENANCE

Systems with components subject to wear failure

Conditional probability of failure increase over time

the intervals between two next inspections are different and decrease over time.

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PREDICTIVE MAINTENANCE

Systems with components subject to wear failure

The determination of the inspection time sequence ti (i = 1, 2, ..., n) is carried out when are known:

- **the value of the ratio between the inspection cost Ci and the difference between the overall costs of the maintenance intervention at fault Cc and the preventive one Cp**

Ci/(Cc-Cp)

- **the values of p, the probability of failure between an inspection and the next one**
- **the values of the normalized variable time Ui expressed by the ratio**

$$U_i = \frac{(t_i - MTBF)}{\sqrt{FTV}}$$

where:

MTBF = mean time before failure;

FTV = variance of the distribution of the failure times related to the machine

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PREDICTIVE MAINTENANCE

Systems with components subject to wear failure

$$U_i = \frac{(t_i - MTBF)}{\sqrt{FTV}}$$

These values were obtained as a function of the ratio

$$C_i/(C_c - C_p)$$

as shown in the table and allowing to get the sequence of inspection times according to the relationship:

$$t_i = U_i \cdot \sqrt{FTV} + MTBF$$

PREDICTIVE MAINTENANCE

Systems with components subject to wear failure

Calculation of the optimal inspection times for components subject to wear

$C_i/(C_c-C_p)$	p	U_1	U_2	U_3	U_4	U_5	U_6	U_7
0,001	0,03162	-1,80	-1,54	-1,39	-1,15	-1,04	-0,93	-0,84
0,002	0,04472	-1,70	-1,36	-1,13	-0,97	-0,80	-0,71	-0,66
0,003	0,05477	-1,60	-1,25	-1,01	-0,84	-0,69	--0,56	-0,45
0,004	0,06324	-1,53	-1,16	-0,92	-0,74	-0,59	-0,46	-0,34
0,005	0,07071	-1,47	-1,10	-0,85	-0,66	-0,50	-0,37	-0,25
0,006	0,07746	-1,42	-1,04	-0,79	-0,60	-0,44	-0,30	-0,17
0,007	0,08367	-1,38	-0,99	-0,74	-0,54	-0,37	-0,23	-0,11
0,008	0,08944	-1,34	-0,95	-0,69	-0,49	-0,32	-0,17	-0,05
0,009	0,09487	-1,31	-0,91	-0,65	-0,45	-0,27	-0,12	+0,01
0,010	0,10000	-1,24	-0,88	-0,60	-0,40	-0,23	-0,07	+0,06
0,020	0,14142	-1,08	-0,63	--0,34	-0,11	+0,08	+0,26	+0,40
0,030	0,17321	-0,94	-0,48	-0,19	+0,08	+0,29	+0,47	+0,63
0,040	0,20000	-0,84	-0,36	-0,03	+0,23	+0,45	+0,64	+0,81
0,050	0,22361	-0,76	-0,26	+0,08	+0,35	+0,58	+0,78	+0,95
0,060	0,24495	-0,69	-0,18	+0,17	+0,45	+0,69	+0,90	+1,08
0,070	0,26458	-0,63	-0,10	+0,26	+0,54	+0,79	+1,00	+1,19
0,080	0,28284	-0,57	-0,04	+0,34	+0,63	+0,88	+1,10	+1,30
0,090	0,30000	-0,52	+0,03	+0,41	+0,71	+0,96	+1,19	+1,39
0,100	0,31623	-0,48	+0,08	+0,47	+0,78	+1,04	+1,27	+1,48
0,200	0,44721	-0,13	+0,51	+0,96	+1,30	+1,63	+1,90	+2,15
0,300	0,54772	+0,12	+0,83	+1,30	+1,73	+2,08	+2,38	+2,66
0,400	0,63246	+0,34	+1,10	+1,65	+2,09	+2,47	+2,81	+3,10
0,500	0,70711	+0,55	+1,37	+1,95	+2,44	+2,85	+3,22	+3,59
0,600	0,77460	+0,76	+1,64	+2,27	+2,80	+3,14	+3,64	+4,02
0,700	0,83666	+0,98	+2,00	+2,62	+3,19	+3,68	+4,12	+4,39
0,800	0,89443	+1,25	+2,28	+3,04	+3,66	+4,20	+4,65	+4,78
0,900	0,94868	+1,63	+2,79	+3,56	+4,26	+4,80	+4,91	+4,99

PREDICTIVE MAINTENANCE

Systems with components subject to wear failure

Example:

- **We have a machine subject to wear failures, characterized by a function of failure time distribution having MTBF = 5,000 hours and FTV = 1,000 hours.**
- **We want to apply a predictive maintenance policy,, which entails an inspection cost of 1,000 ú, a cost of the emergency intervention of ú 20,000 and the preventive intervention of ú 18,000.**
- **It is possible to calculate the ratio value from the above table:**

$$\frac{C_i}{(C_c - C_p)} = \frac{1.000}{(20.000 - 18.000)} = \frac{1.000}{2.000} = 0,5$$

$$U_1 = +0,55 \quad U_2 = +1,37 \quad U_3 = +1,95 \quad U_4 = +2,44$$

$$U_5 = +2,85 \quad U_6 = +3,22 \quad U_7 = +3,59$$

PREDICTIVE MAINTENANCE

Systems with components subject to wear failure

Example:

Known from U_1 to U_7, the consequent inspection times are determined and, if a preventive intervention is foreseen at time t_4, we have:

$$t_1 = U_1 \cdot \sqrt{FTV} + MTBF = 0{,}55 \cdot \sqrt{1.000} + 5.000 = 5.017\ hours$$
$$t_2 = U_2 \cdot \sqrt{FTV} + MTBF = 1{,}37 \cdot \sqrt{1.000} + 5.000 = 5.043\ hours$$
$$t_3 = U_3 \cdot \sqrt{FTV} + MTBF = 1{,}95 \cdot \sqrt{1.000} + 5.000 = 5.062\ hours$$
$$t_4 = U_4 \cdot \sqrt{FTV} + MTBF = 2{,}44 \cdot \sqrt{1.000} + 5.000 = 5.077\ hours$$
$$t_5 = t_4 + U_1 \cdot \sqrt{FTV} + MTBF = 5.077 + 0{,}55 \cdot \sqrt{1.000} + 5.000 = 10.094\ hours$$
$$t_6 = t_4 + U_2 \cdot \sqrt{FTV} + MTBF = 5.077 + 1{,}37 \cdot \sqrt{1.000} + 5.000 = 10.120\ hours$$

thus continuing until a fault arises or until the inspection gives results such that the scheduled intervention is recommended.

PREDICTIVE MAINTENANCE

Other systems

Other authors have proposed models to support the determination of the optimal inspection frequency which are reported:

a) Inspection scheduling model for single machine

If there is a component of a system, whose status is identifiable by monitoring appropriate indicators, if a fault is repaired with a maintenance intervention, the component returns to a good state.

It is therefore necessary to determine the optimal scheduling of the inspection interventions such as to minimize the cost per unit of time associated with the inspection, corrective maintenance and the consequent non-identification of the fault.

PREDICTIVE MAINTENANCE

Other systems

b) profit maximization model (breakeven inspection)

The aim of the model is to establish the optimal periodic inspection interval by maximizing the profit function, where:

p = the profit per unit of time associated with the operation of the machine

T the duration of the operating cycle (time interval in which the inspection is carried out until a break can be detected manifested in an instant t, with t < T)

P(T) = the expected profit for the operating cycle

$P_1(T)$ = the profit related to an operating cycle without failure,

$P_2(T)$ = the profit related to an operating cycle with failure,

UP(T) = the total profit per unit of time

F(t) = the probability of failure,

the following cost relations associated with an operating cycle can be written:

$$P_1(T) = p \cdot T - C_i \qquad P_2(T) = \frac{\int_0^T p \cdot t \cdot f(t)\, dt}{F(T)} - C_i - C_r$$

PREDICTIVE MAINTENANCE

Other systems

b) profit maximization model (breakeven inspection)

Also in this case the component must be as good as new in the face of a maintenance intervention.

$$P_1(T) = p \cdot T - C_i \qquad P_2(T) = \frac{\int_0^T p \cdot t \cdot f(t)\, dt}{F(T)} - C_i - C_r$$

The expected profit over a cycle is:

$$P(T) = P_1(T) \cdot R(T) + P_2(T) \cdot F(T)$$

$$P(T) = (p \cdot T - C_i) \cdot R(T) + \int_0^T p \cdot t \cdot f(t)\, dt - (C_i + C_r) \cdot F(T)$$

$$P(T) = (p \cdot T - C_i) \cdot R(T) - [1 - R(T)] \cdot (C_i + C_r) + p \int_0^T t \cdot f(t)\, dt$$

$$P(T) = p \int_0^T R(t) dt + C_r \cdot R(T) - C_i - C_r$$

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PREDICTIVE MAINTENANCE

Other systems

b) **profit maximization model (breakeven inspection)**
The unit profit to be maximized is:

$$UP(T) = \frac{p\int_0^T R(t)dt + C_r \cdot R(T) - C_i - C_r}{T}$$

That function with one variable can be solved deriving it and equalling it to zero.

PREDICTIVE MAINTENANCE

Other systems

b) profile maximization model (breakeven inspection)

Example:

Consider a component of a system having a failure probability density f(t) uniformly distributed between 0 and 8 weeks:

$$f(t) = \begin{cases} \frac{1}{8} & (0 \le t \le 8) \\ 0 & otherwise \end{cases}$$

Furthermore we know:

- **repair costs: C_r**
- **inspection costs: C_i**
- **profit per unit of time associated with the operation of the machine: p = ú/week**

PREDICTIVE MAINTENANCE

Other systems

b) profit maximization model (breakeven inspection)

Reliability is as follows:

$$R(t) = 1 - F(t) = \begin{cases} 1 - \frac{1}{8}\,t & (0 \le t \le 8) \\ 0 & t > 8 \end{cases}$$

The **unitary profit** is:

$$UP(T) = \frac{p\int_0^T R(t)dt + C_r \cdot R(T) - C_i - C_r}{T} = \frac{p\int_0^T \left[1 - \frac{1}{8}t\right]dt + C_r \cdot \left[1 - \frac{1}{8}T\right] - C_i - C_r}{T}$$

$$UP(T) = \frac{p \cdot \left(T - \frac{1}{8}T^2\right) - \frac{C_r}{8} \cdot T - C_i}{T} = \frac{p \cdot (8 \cdot T - T^2) - C_r \cdot T - 8 \cdot C_i}{10 \cdot T}$$

The values of the unitary profit when T changes are shown in the table, calculated by applying the exhaustive method:

T	1	2	3	4	5	6	7	8
UP(T)	800	2.000	1.667	1.200	680	133	-429	-1.000

Trend of UP(T) [€/week]

The optimal period in which to carry out the inspection visit is 2 weeks with a unit profit is ú 2,000;

INTERVENTION PLANS

PRODUCTIVE SYSTEM

- SIMPLE PRODUCTION ASSETS
- NON RIGIDLY CONNECTED
- OVER CAPACITY

OPERATIVE MANAGEMENT

- CORRECTIVE (60%)
- PREVENTIVE(20 %)
- PREDICTIVE(20%)

TECHNICAL MANAGEMENT

- PREVENTIVE/INSPECTIVE MAN.
- MANAGEMENT TOWARD TO EFFICACY OF QUICK INTERVENTION AND THE TECHNICAL MODIFICATIONS

PRODUCTIVE SYSTEM

- COMPLEX PRODUCTION ASSETS
- LIMITED CAPACITY

OPERATIVE MANAGEMENT

- CORRECTIVE (10%)
- PREVENTIVE(40 %)
- PREDICTIVE(50%)

TECHNICAL MANAGEMENT

- PREVENTIVE/INSPECTIVE MAN.
- SPARE PARTS MANAGEMENT
- TECHNICAL MODIFICATIONS

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PRODUCTIVE SYSTEM

- HIGH AUTOMATION
- LACK OF RESERVES
- RIGID INTERCONNECTION
- REDUCED STOCK

OPERATIVE MANAGEMENT

- CORRECTIVE (5%)
- PREVENTIVE(20 %)
- PREDICTIVE(50%)
- TPM (25 %)

TECHNICAL MANAGEMENT

- MONITORING OF ASSET EFFICIANCY
- DATA ANALYSIS FOR RELIABILITY
- DIAGNOSYS SYSTEMS
- STRATEGIES DEFINITION
- DEFINITION OF MAINTENANCE STANDARDS

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MAINTENANCE EVOLUTION