Giovedì, 18 Settembre, 2014
9:00 - 17:30
POLITECNICO di TORINO – DIMEAS – Sala FERRARI

Prognostic and Health Management in Aeronautics; **relations with Reliability** and examples on **Fuel System**

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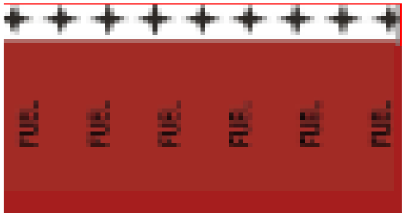
Un sentito ringraziamento all' ing. Davide FERRETTO, per il prezioso supporto

SUMMARY

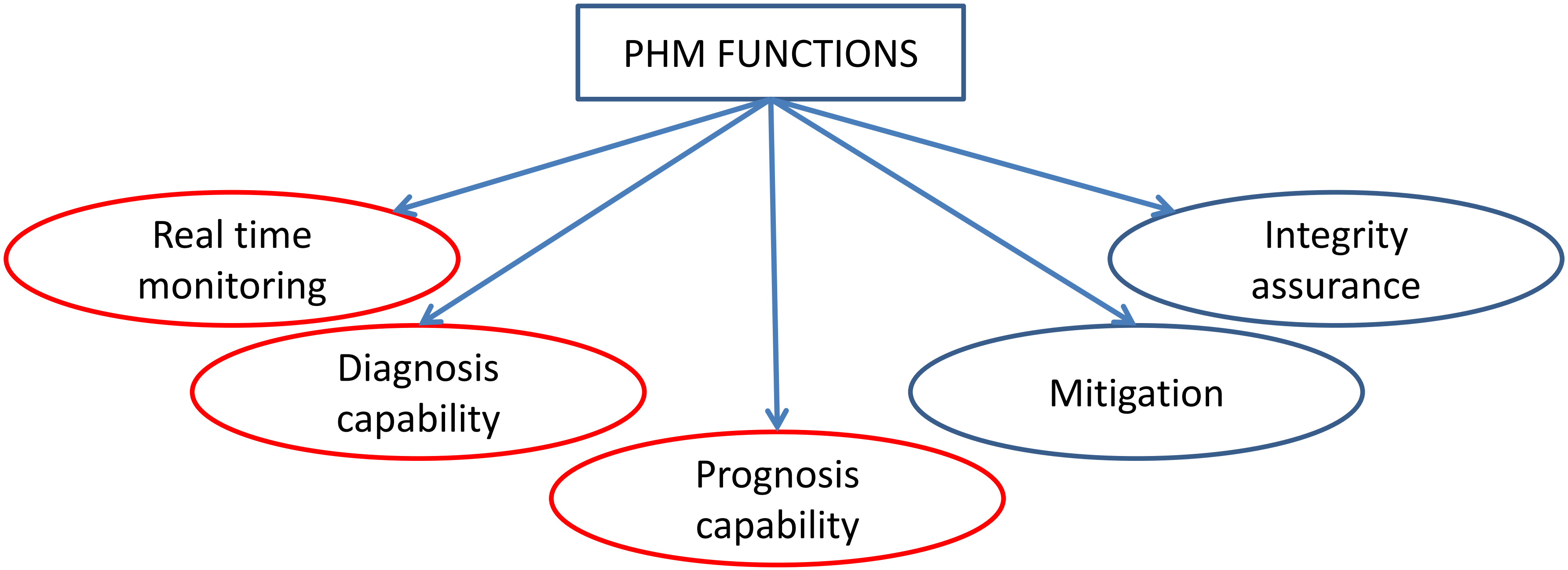
- Generalities (1-7)
- Reliability remind (8-14)
- Diagnosis (15-18)
- Prognosis (19 – 28)
- Examples on AC Fuel System (29-51)



Definitions

Prognostic and Health Monitoring (PHM) Concept:

The processes, techniques, and technologies used to design, analyze, build, verify, and operate a system to prevent faults and/or mitigate their effects



- **Real time monitoring**

  The action of detecting anomalies from adverse events throughout the aircraft in hardware and in software as soon as they appear.

- **Diagnosis capability**

  The action or process of identifying and determining the status of a component, or of a system, in particular its ability to perform its function(s), based on observed parameters or through the relevant evaluation methods.

- **Prognosis capability**

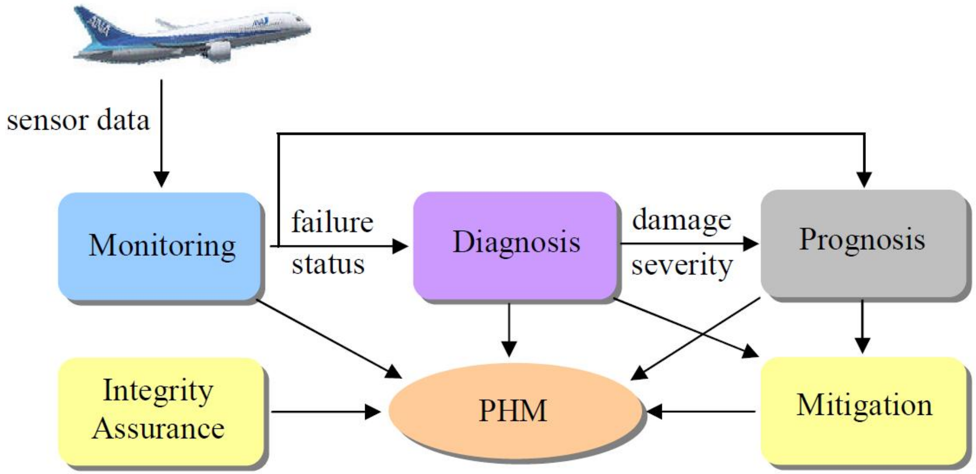
  The specific process of predictive diagnostics which includes either the prediction of the remaining useful life or determination of the time span of appropriate operation of a component or a system.

- **Mitigation**

  The action or process of minimizing the impact of adverse effects to ensure continued safe flight and/or landing of the aircraft

- **Integrity assurance**

  The process of assuring robustness and performance of tools, test beds and technologies used to build PHM environment



Main PHM benefits (potential or real)

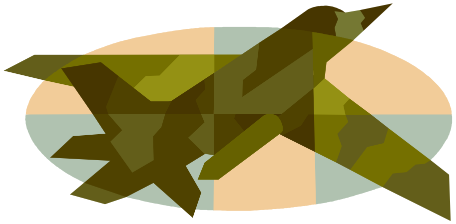
A new aircraft with PHM technology will have a strongly competitive capability in the future aviation market !

PHM Working process

ON BOARD PROCESS

- Real time monitoring
- Failure detection/diagnosis
- Consequences prediction/prognosis

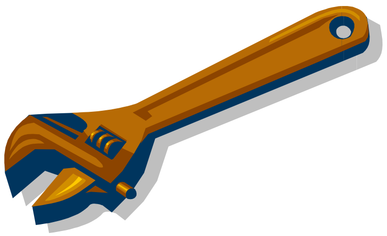
- Real time data relay to ground-based maintenance equipment



OFF BOARD PROCESS

- Maintenance activities preparation

- Data warehouse
- Postprocessing



PHM State-of-the-art

Aircraft Diagnostic and Maintenance System (ADAMS), by Honeywell

- Central maintenance computer
- Aircraft condition monitoring functions
- Built-In-Test functionality of various systems
- Navigation files and report management
- User friendly graphical interface
- Ground connection via data-link

Joint Strike Fighter (JSF) prognostic health management system

- Advanced processing and reasoning
- Hierarchical aircraft areas management
- Comparison between sensors data and model-based reasoning
- Prognostic Built-In-Test functionality
- Ground connection via data-link

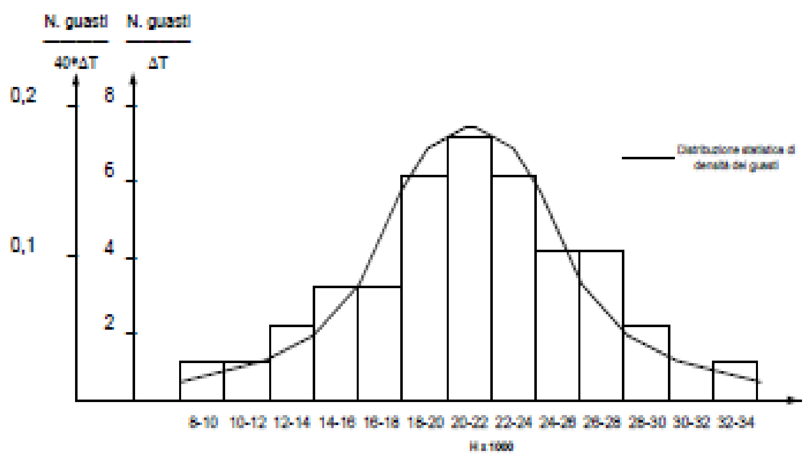
Generally more than 200 aircraft subsistems covered !

State-of-the-art of diagnosis and prognosis techniques are now analyzed

Since various DIAGNOSIS and PROGNOSIS methods are based on **reliability** algorithms, a brief revision on the main reliability concepts could be useful

The first thing to remember about Reliability is that the trend to failure of an item can be observed on a enough numberous population of such items. We can see below how the observation results have to be recorded

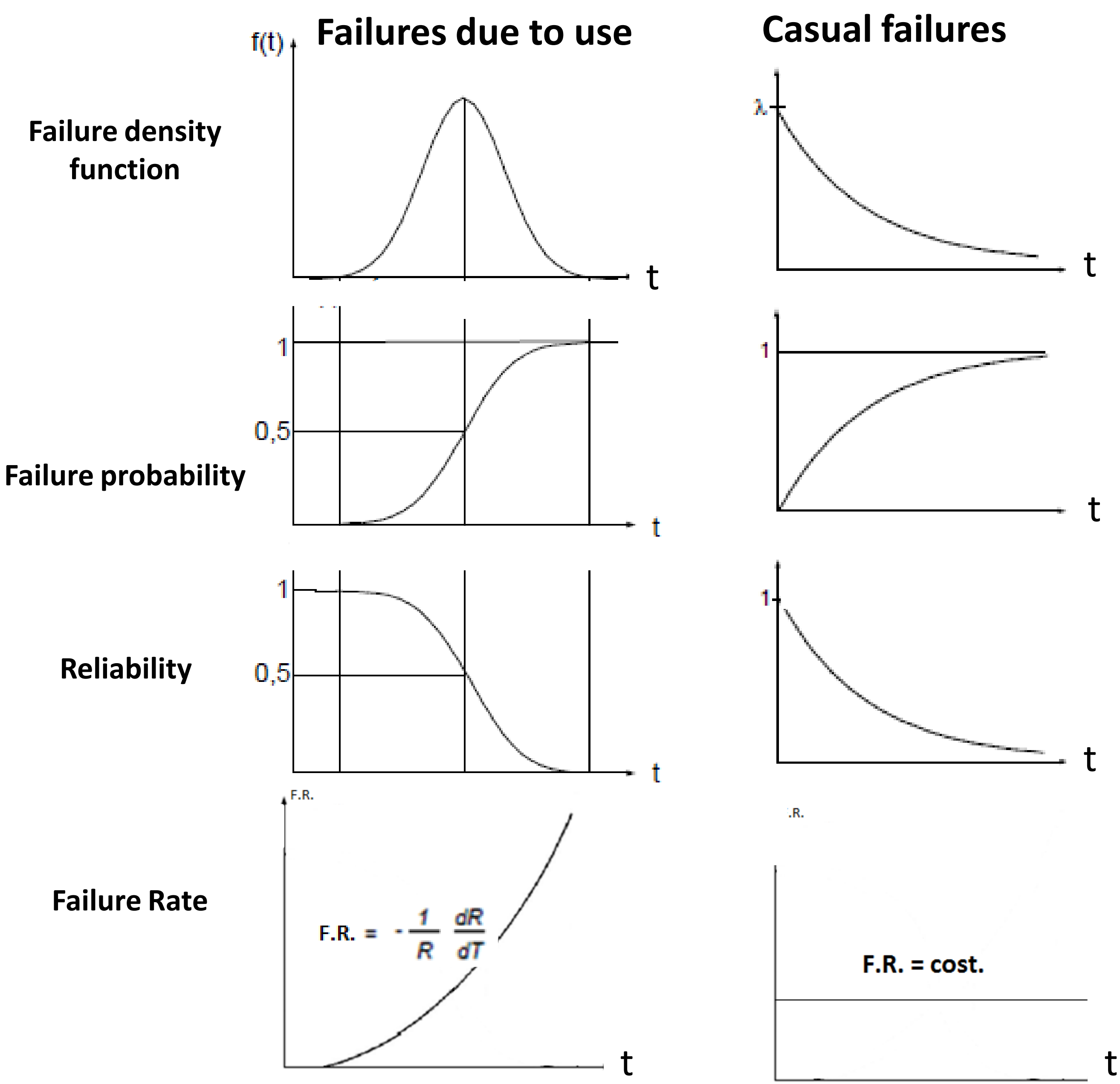
Tra [h] x 1000	e [h] x 1000	rotture
8	10	1
10	12	1
12	14	2
14	16	3
16	18	3
18	20	6
20	22	7
22	24	6
24	26	4
26	28	4
28	30	2
30	32	0
32	34	1
		40



Example of failure due to use obtained by a laboratory test:

The density function is an almost perfect Gauss distribution. This is a typical laboratory result where casual failures have a smaller probability to occur (at the contrary of the "field").

Typically we use to classify failures into **due-to-use** (aging) and **casual.**
Let's recap their distribution, and in particular the PROCEDURE shown below :



PROCEDURE:

Failure density function f(t)

↓

Integration: $\int f(t)\, dt$

↓

Failure probability F(t)

↓

subtraction 1-F(t)

↓

Reliability R(t)

↓

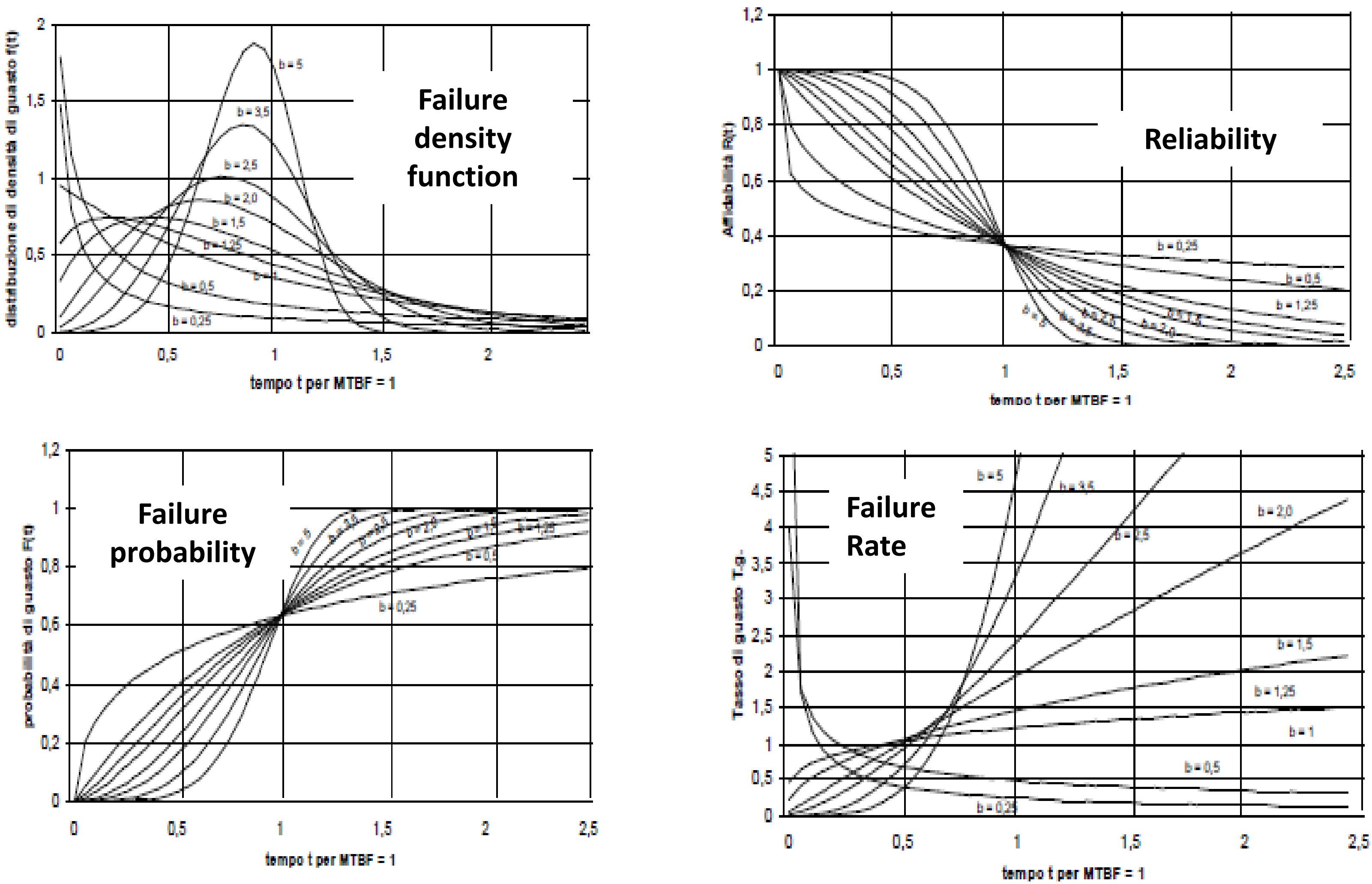
$$\frac{\text{N° of Failures at } t/\Delta t}{\text{N° still running at } t}$$

↓

Failure Rate

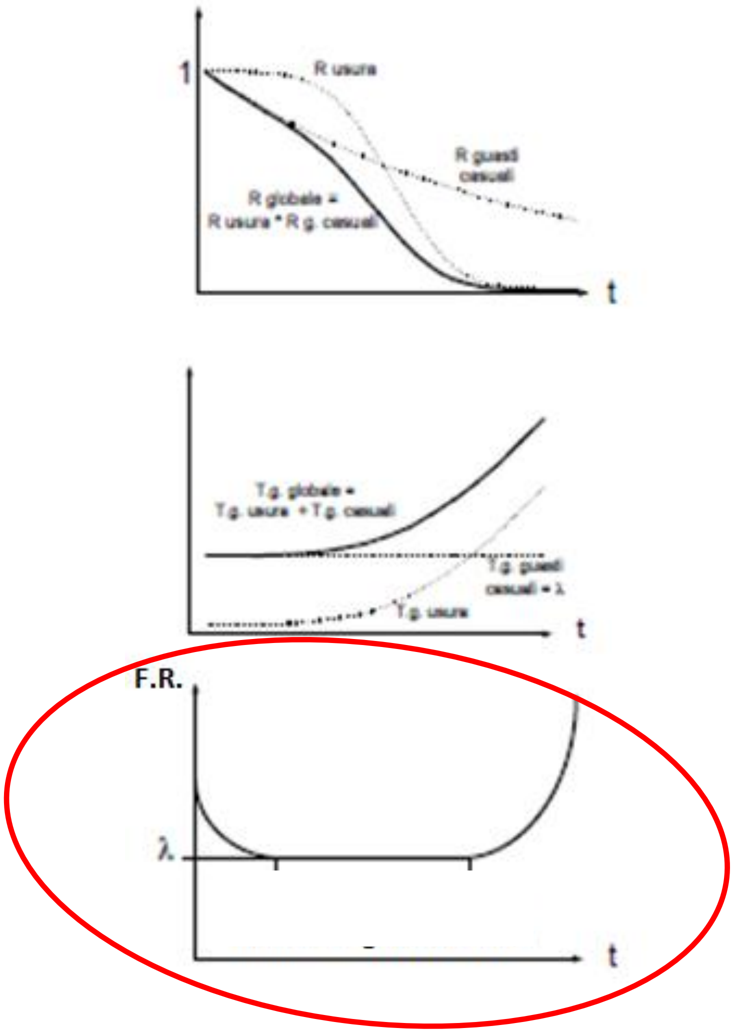
A more complete approach consists in coupling these two type of failure in **one statistical model,** together with other kinds failures, for example the ones that occur in the very first part of operational life: **this is the**

"Weibull model"

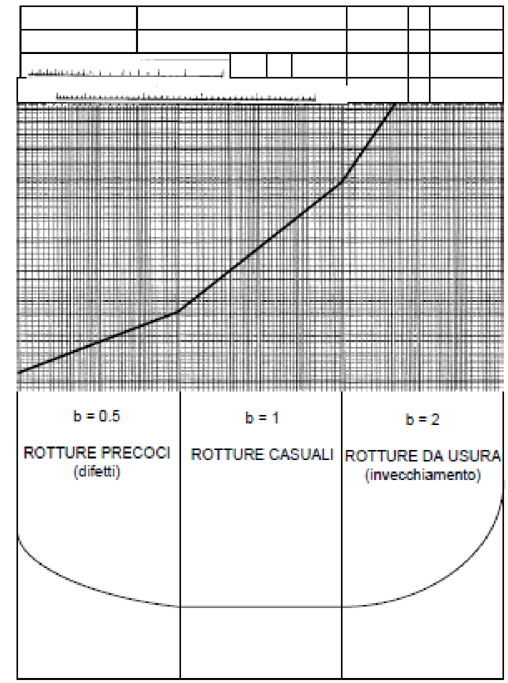


You can notice how curves modify their trend thanks to **Weibull parameter** which is a sort of indicator of the mix of the kinds of failures; it is chosen in order to fit the data

The Failure Rate that results from this type of distribution has the typical “bath shape” and summarizes **young failures, casual failures** and **failures due to use and aging**.



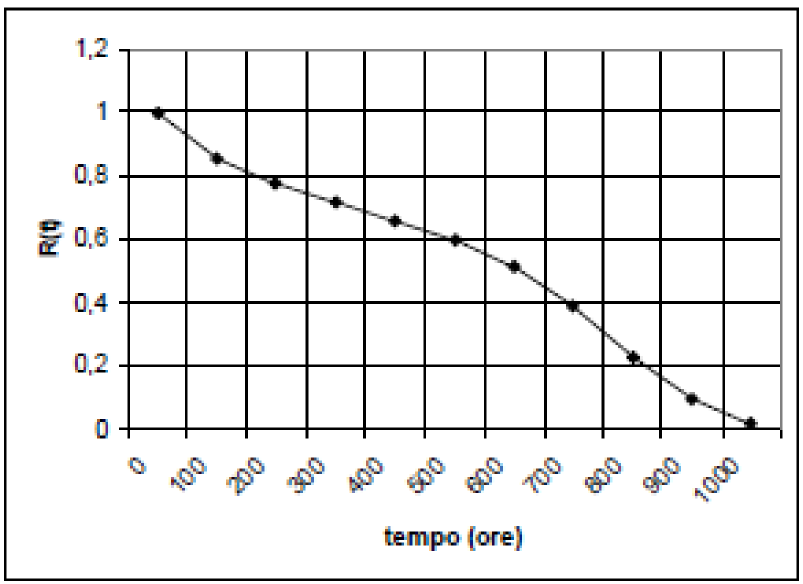
The Weibull distribution uses this coefficient division following “bath shape” curve



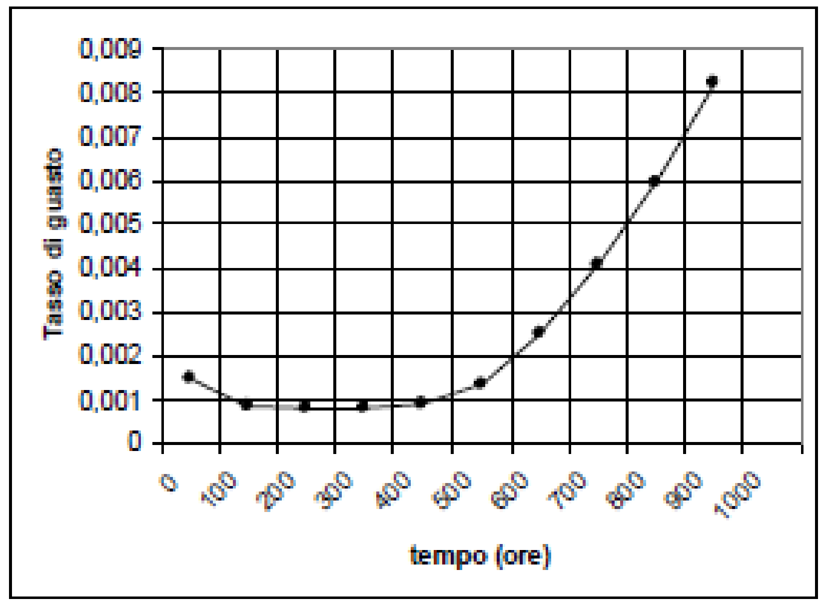
Example of Weibull distribution during a laboratory test:

Tempo di osservazione (ore)	N. componenti ancora funzionanti	N. Guasti/Δt
0	10000	1465
100	8535	745
200	7790	636
300	7154	589
400	6565	586
500	5979	816
600	5163	1295
700	3868	1571
800	2297	1371
900	926	764
1000	162	

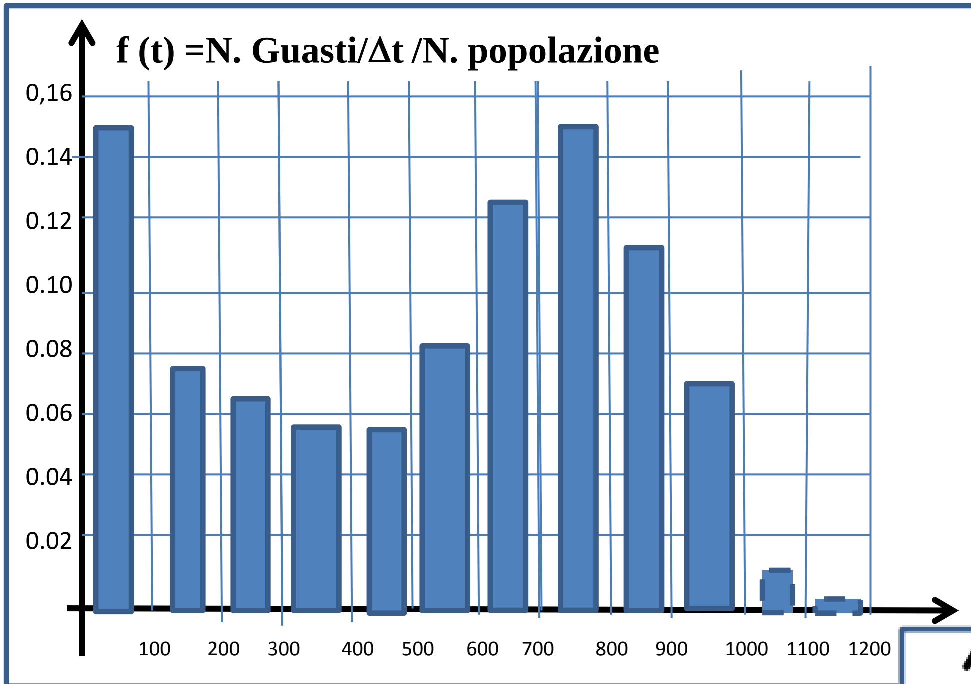
This is the «Failures density function» **f(t)**



Risultati di prova sperimentale affidabilità



: Risultati di prova sperimentale tasso di guasto



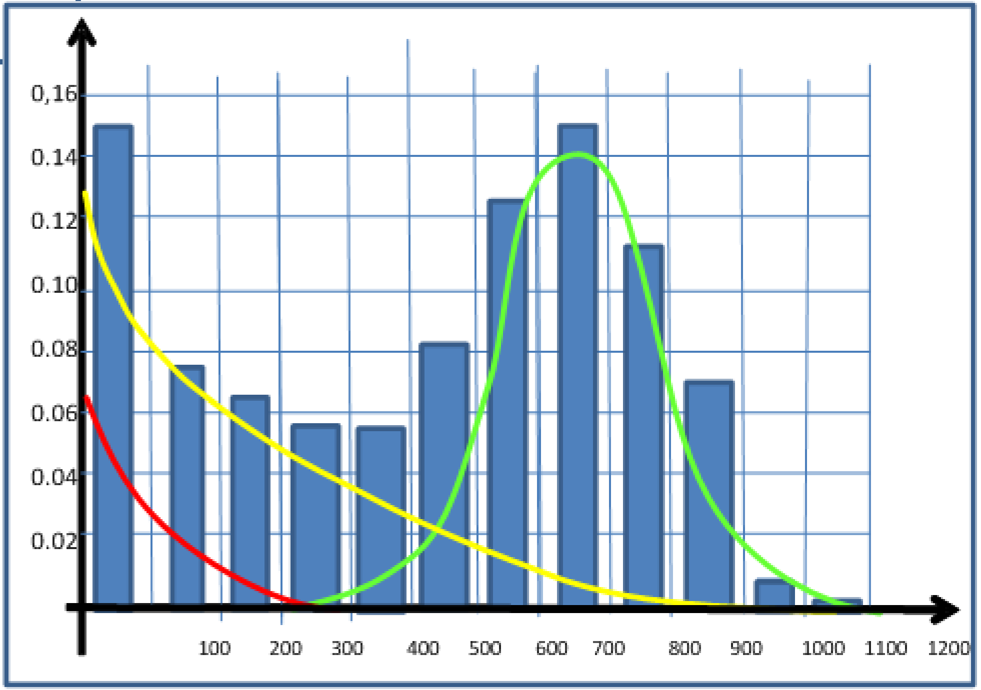
The histogram shows the failure density function

If we try to display the trend we can clearly see:

-Young failure density distribution (red)

-Casual failure density distribution (yellow)

- Aging failure density distribution (green)



DIAGNOSIS

- As stated earlier, diagnostics is the specific process of detecting and deciding the cause of any anomalous or unexpected event.

- The prerequisite to implement diagnostic decision is relied on the sufficient and available data from the monitoring system

- The results of **Functional Hazard Analysis** (FHA), Failure Modes **Effects and Criticality Analysis** (FMECA) and **Fault Tree Analysis** (FTA) are required to understand functions, failure modes and occurrences of each component (discussed later).

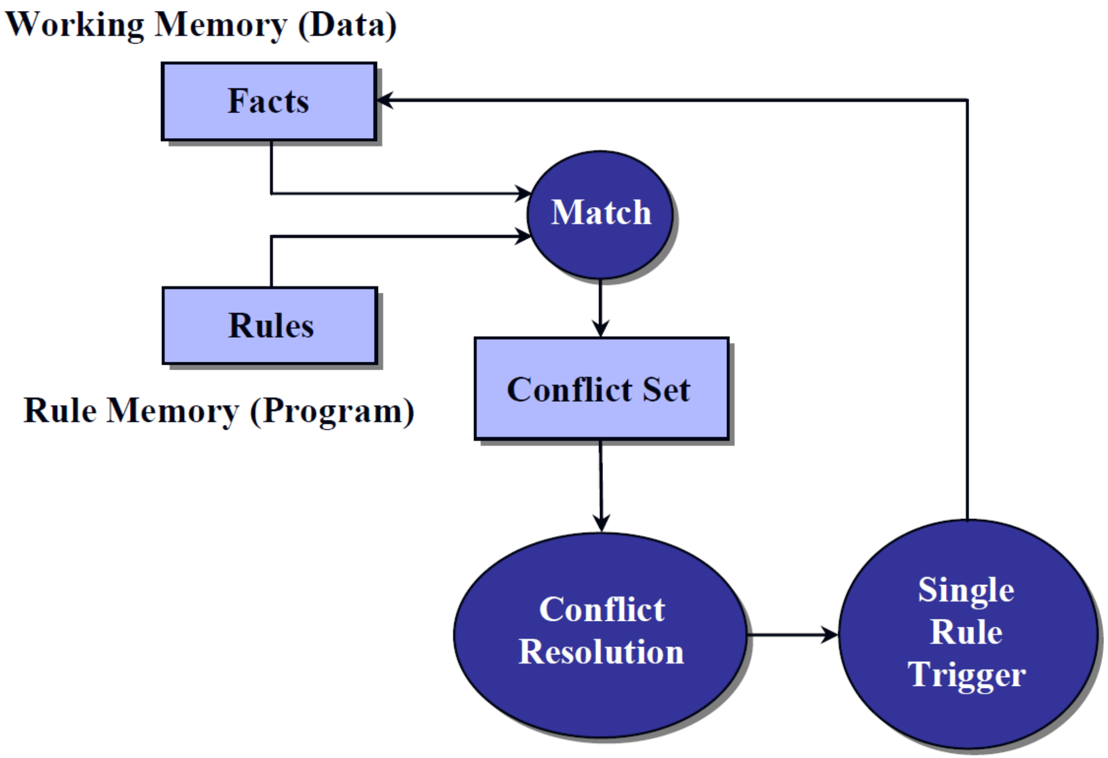
FHA	FMECA	FTA
It is a systematic, comprehensive examination of functions to identify and classify failure conditions of those functions according to their severity.	It is **a bottom-up** approach that traces the effects of component failures through the system.	FTA is **a top-down** approach in which undesirable events are studied to determine all possible causes of that event.

NOW WE WILL EXAMEN 3 DIFFERENT METHODOLOGIES TO PERFORME A DIAGNOSIS:

1-Rule-based expert diagnostic system

- Rule-based expert reasoning system is a <u>typical artificial intelligent technique </u>that relies on the basic reasoning rule statement "if-then-else".

- The **"if"** means "when the condition is true, **"then"** means "take action A" and the **"else"** means "when the condition is not true take action B.



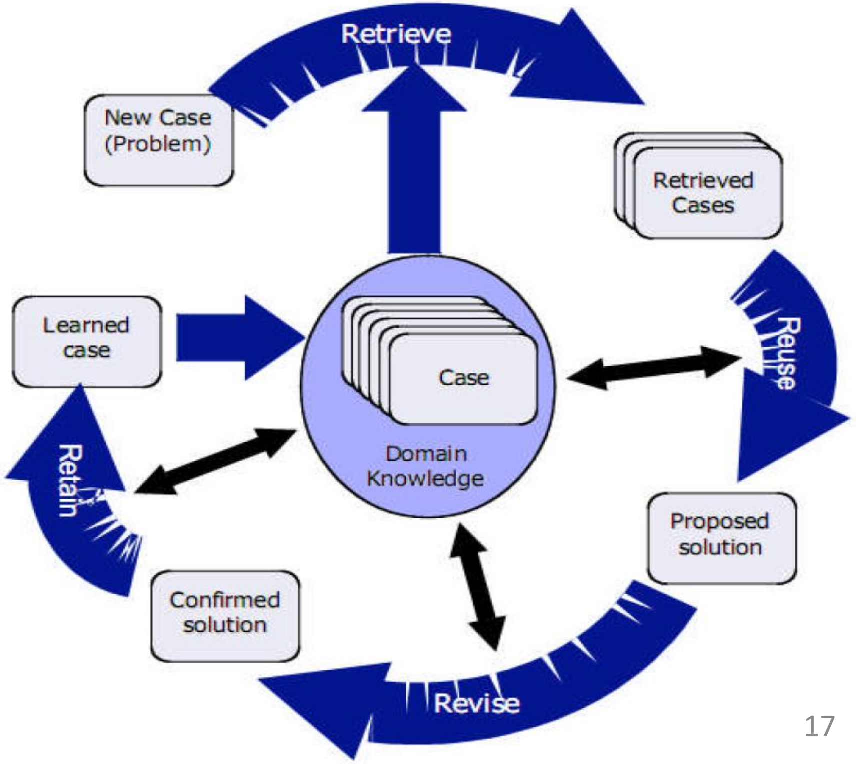
When applicable?
Rule-based expert system has wide application for diagnostic tasks **<u>where expertise</u>** **<u>and experience are available</u> but deep understanding of the physical properties of the system is either unavailable or too costly to obtain.**

2 - Case-based reasoning diagnostic system

- Case-based reasoning system is a specific reasoning engine of knowledge solutions which means to use past problem to solve current problems.

- The first step is to retrieve the best past cases from Domain Knowledge Library for a new problem. Then, after acquiring the difference between these two cases, a proposed solution is conducted by modifying the old solution.

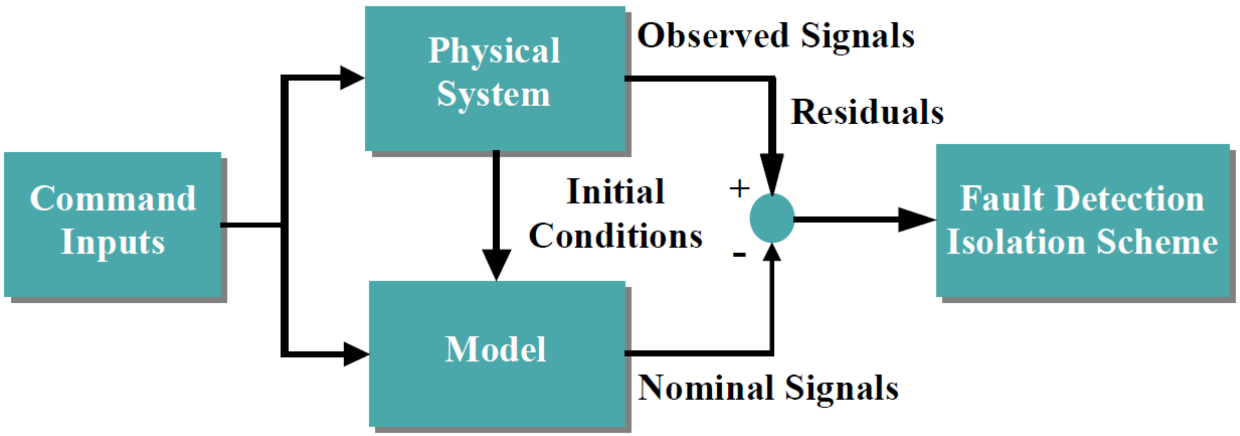
When applicable?
This technique is well suited for **poorly understood problem areas for which structured data is available to characterize operating scenarios**.



3 - Model-based reasoning diagnostic system

➢ Model-based reasoning system is a broad category that describes the use of a wide variety of engineering models as the foundation for the knowledge and the techniques applied for diagnosis.

➢ The model-based approach compares how the system is actually performing to the manner in which the model expects the system to perform given its actual operating conditions.



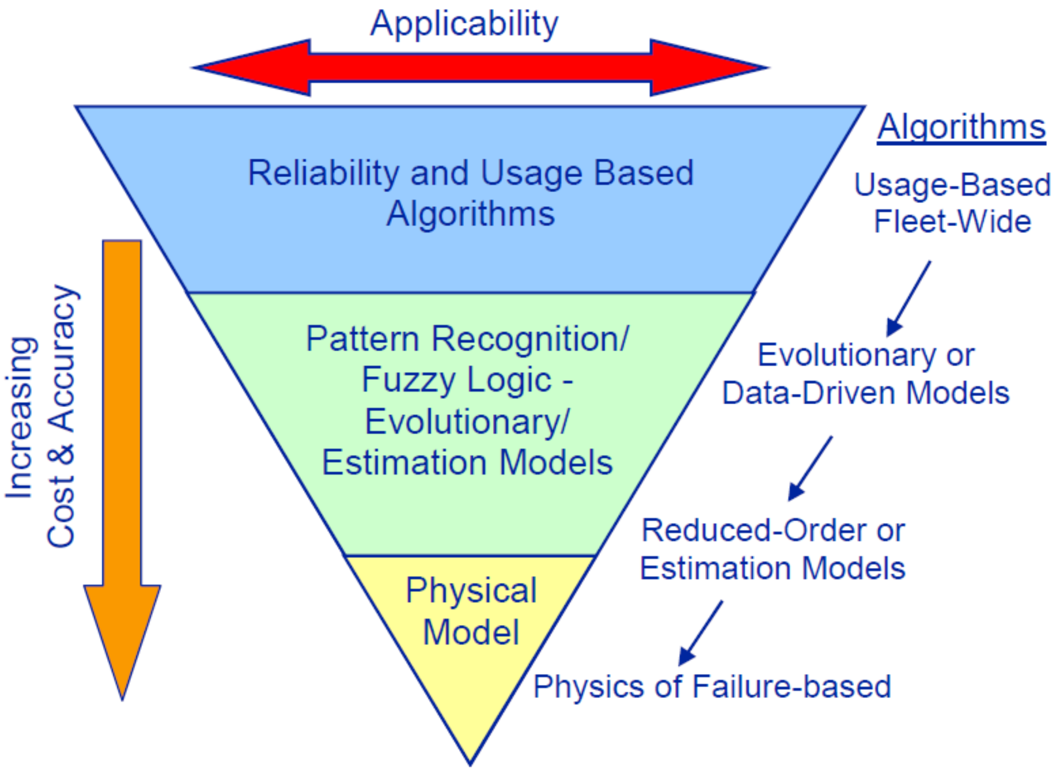
When applicable?

The model-based reasoning technique requires that the **fidelity of physical model shall be accurate** and sufficient to enable a full range of operational characteristics to accurately implement the comparison through the model under various conditions.

PROGNOSIS

➢ The main goal of the prognostic technology is to provide a validated prediction of the **Remaining Useful Life** (**RUL**) for either a component or a system.

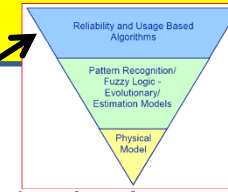
➢ Achieving the best possible prediction on a **Line Replaceable Unit** (**LRU**)/subsystem's health is often implemented using various algorithmic techniques and data fusion concepts that can optimally combine **sensor data, empirical/physics-based models and historical information**.



➢ **Five mainly used prognostic approaches are given in the following sections**.

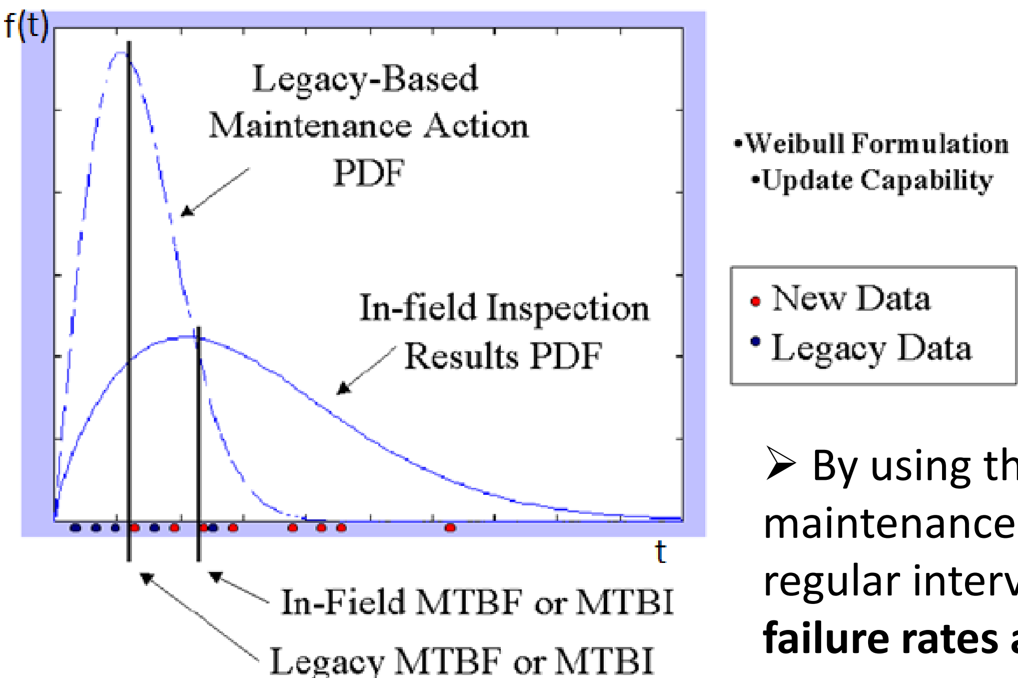
They are based on different evaluation strategy, as shown in the figure, characterized by **increasing level of accurancy**

1-Statistical reliability and usage-based prognosis



➢ Statistical reliability and usage-based approach is a historical data-based method which needs the component/LRU failure history statistical data and operational usage profile, sometimes along with the relevant failure rate data, **Mean Time Between Failure (MTBF)** and **Mean Time Between Interrupts (MTBI)**.

➢ Typically, failure and/or inspection data is compiled from legacy systems and a Weibull **Probability Density Function** (**PDF**) or other statistical failure distribution can be fitted to the data.



When applicable?

➢ This is the least complex method, but the benefit to having a regularly updated maintenance database as happens in autonomic logistics applications is significant for this application.

➢ By using this approach, the interval-based maintenance actions are able to be improved to the regular intervals maintenance practices. Please note that **failure rates are affected from aircraft operating conditions and load profiles**; this means that **in-field inspections can be more/less severe than expected**

Example: helicopter flight mission profile

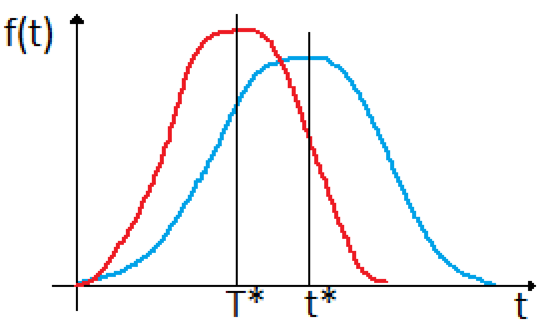
In-field inspection can provide useful reliability and component status informations in order to predict a real limit of Remaining Usable Life (RUL) but it is necessary to **consider mission and load profile of the aircraft**. **In this way it is possible to apply a real usage-based prognosis**

Aerial work

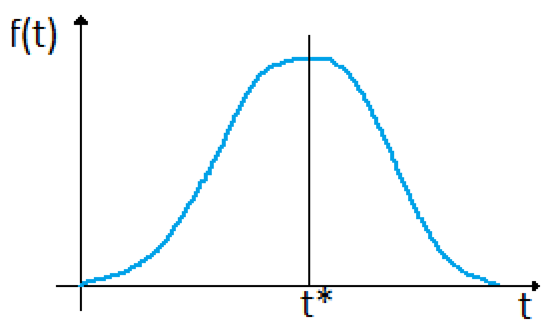
- Usually time is expressed in Flight Hours (FH) or by defining a typical working cycle (take-off, cruise, landing ecc..)

Pilot training

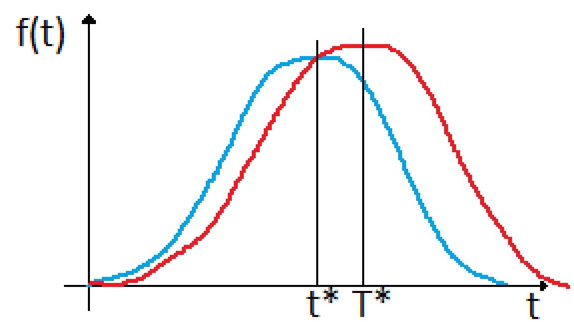
High loads



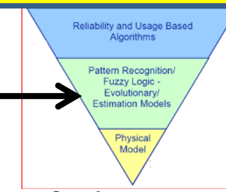
Predicted



Low performance



2-Trend-based evolutionary prognosis



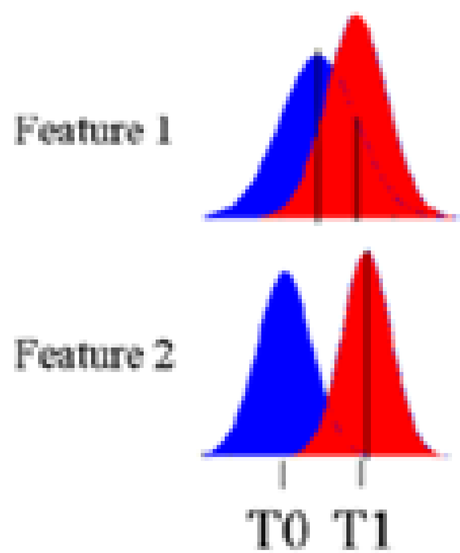
➢ Trend-based evolutionary approach relies on the comparison between the failure damage probability model based on the historical data and the current **multiparameters** probability state space to implement the detection of current health condition and the analysis of trend deviations. (Previous method, on the contrary, considered a single parameter).

When applicable?

Generally, trend-based prognostics works well for system level degradation because **conditional loss is typically the result of interaction of multiple components** functioning improperly as a whole.

Features=Parameters representative of increasing of operational life

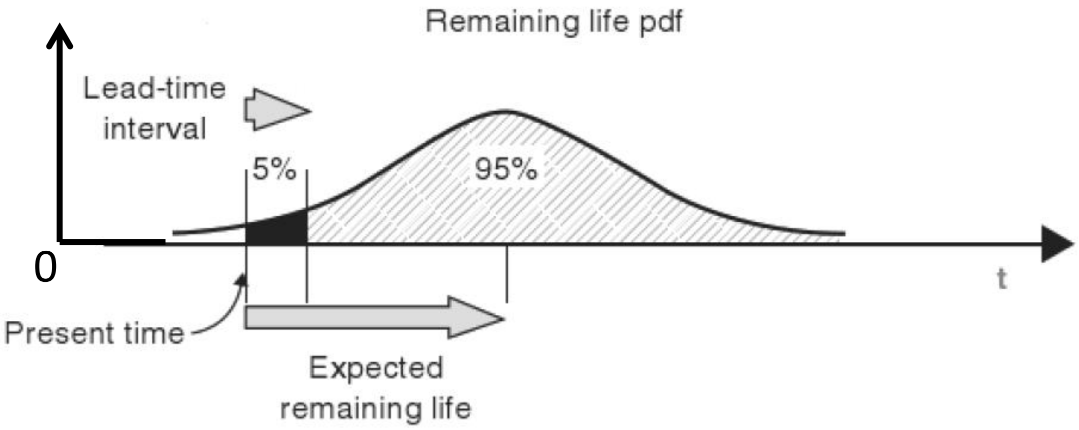
Statistical Features Shift over Time



Time «X»

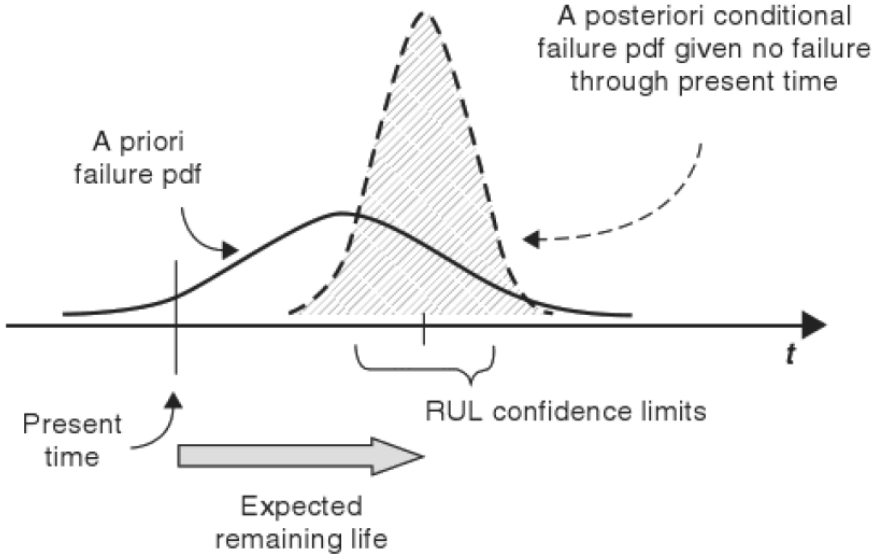
Time «X + ΔT»

Why is there a sort of improvement in failure density function?



- Distribution on the left shows the failure density function predicted at "Time 0". It leads to the prediction of remaining life as well.

- At present time (5%) the failure density function for the component is modified due to the fact that the failure doesn't happened. **Density function is conditioned** and shifts forward with a smaller variance. As time goes by, **density function will became thinner and higher.**



Example: car battery

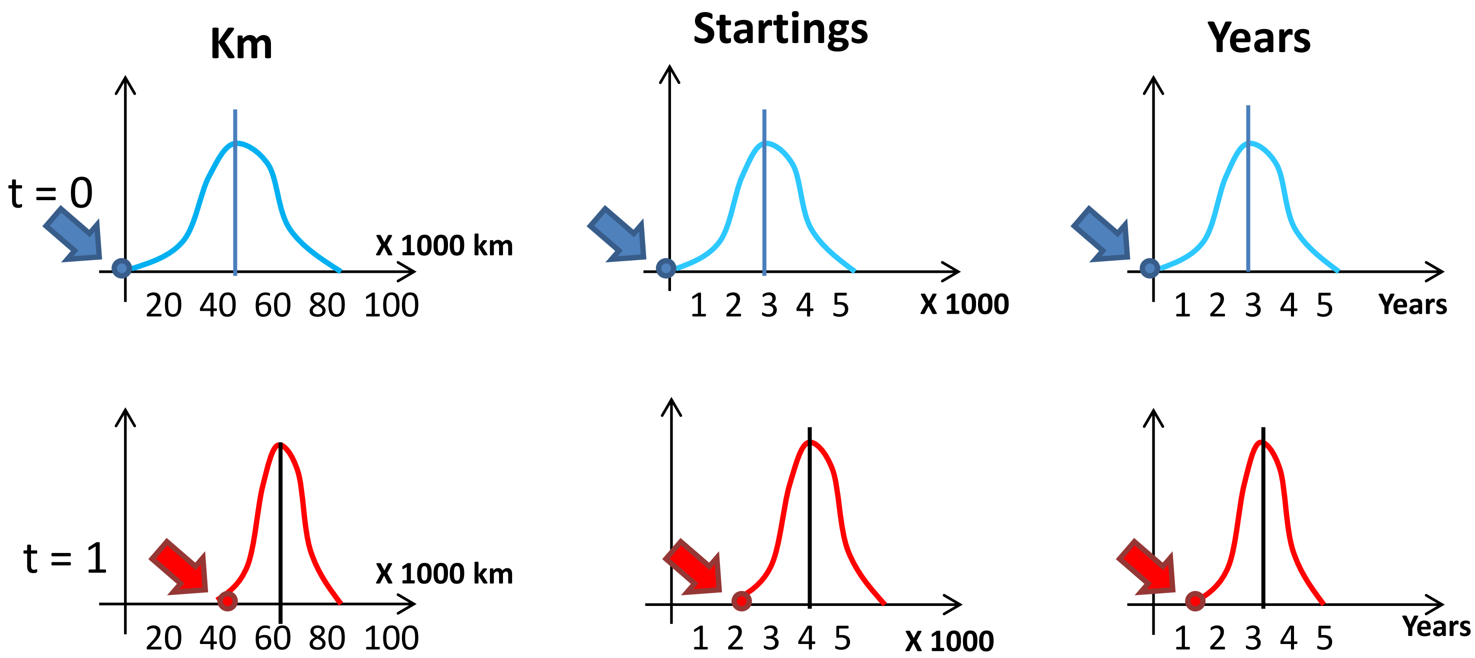
Typically, the life of a car battery depends on three parameters:

1) Number of **Km** travelled on the vehicle

2) Number of **engine's startings**

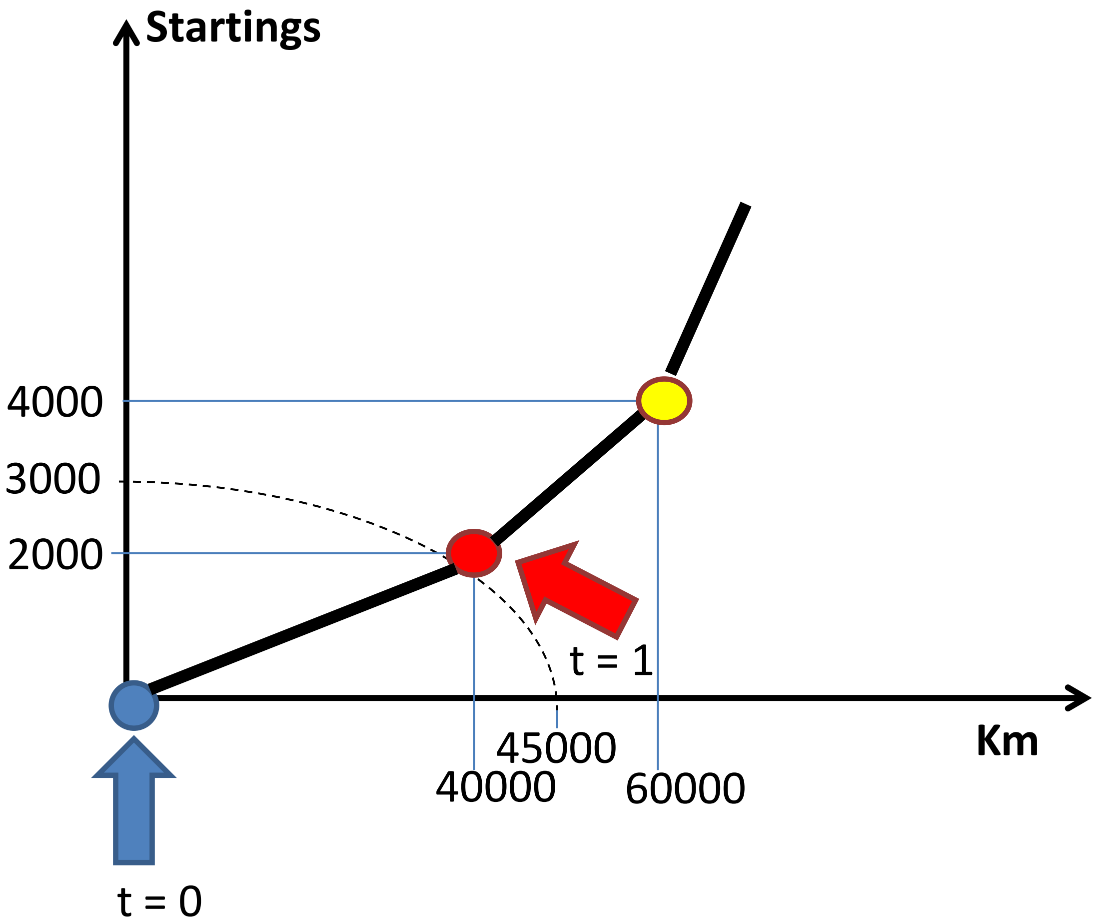
3) Time spent in the actual powerplant (**calendar time**)

Let's consider failure density function of the battery at "Time 0" (new battery) and after a moderate usage ("Time 1"):



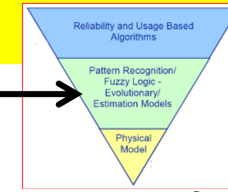
Example: car battery

Considering, for simplicity, only **Km** and **ignitions** we have the following parameters space:



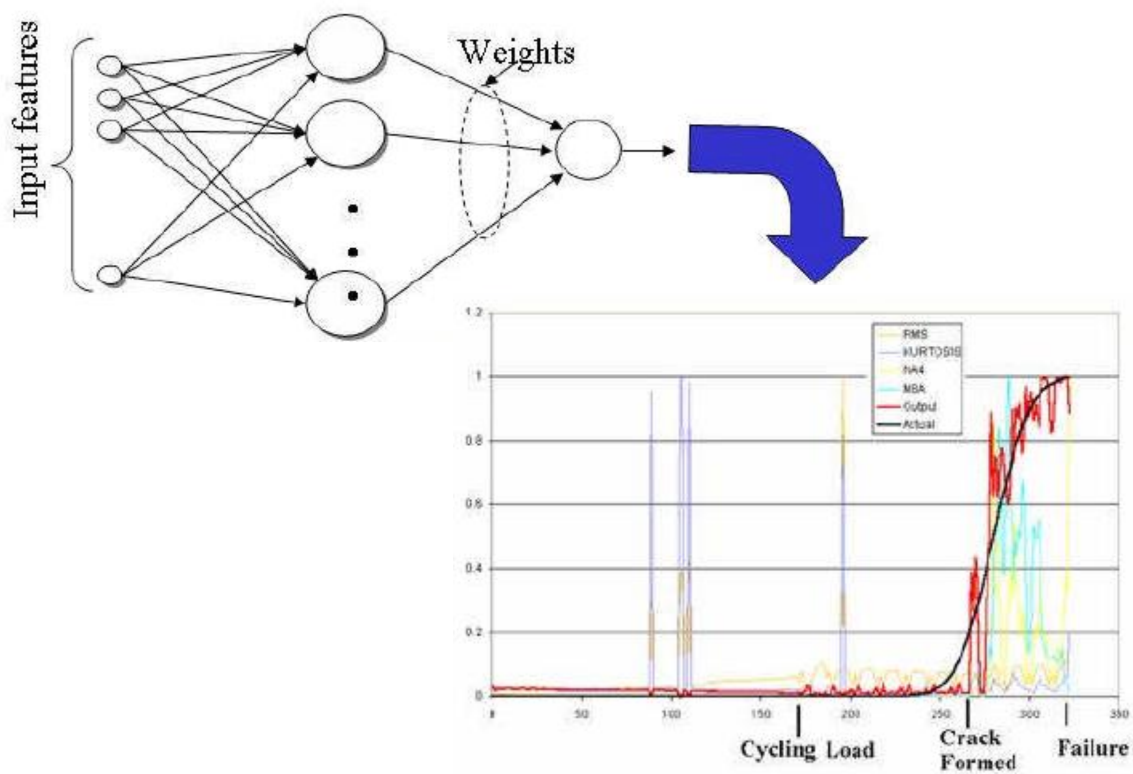
- **Blue, red** dots represent the two situations previous shown and they are connected with the straight **black line** which is the parameters evolution line.
- Advancing on such a line, **the failure probability increase more and more, with values statistically defined**

3-Data-driven model-based prognosis



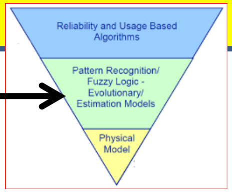
- Generally, **Artificial Neural Network** (**ANN**) is the one of the primary representatives of this diagnostic approach.

- ANN is able to establish a linkage between the monitored failure condition and the damage prediction for a component or system by its nonlinear transformation characteristics and intelligent learning system. **It is a reasoning-capable system with an artificial intelligence.**



When applicable?
ANN is well suited for practical problems **where it is easier to have data than knowledge** governing the underlying system being studied

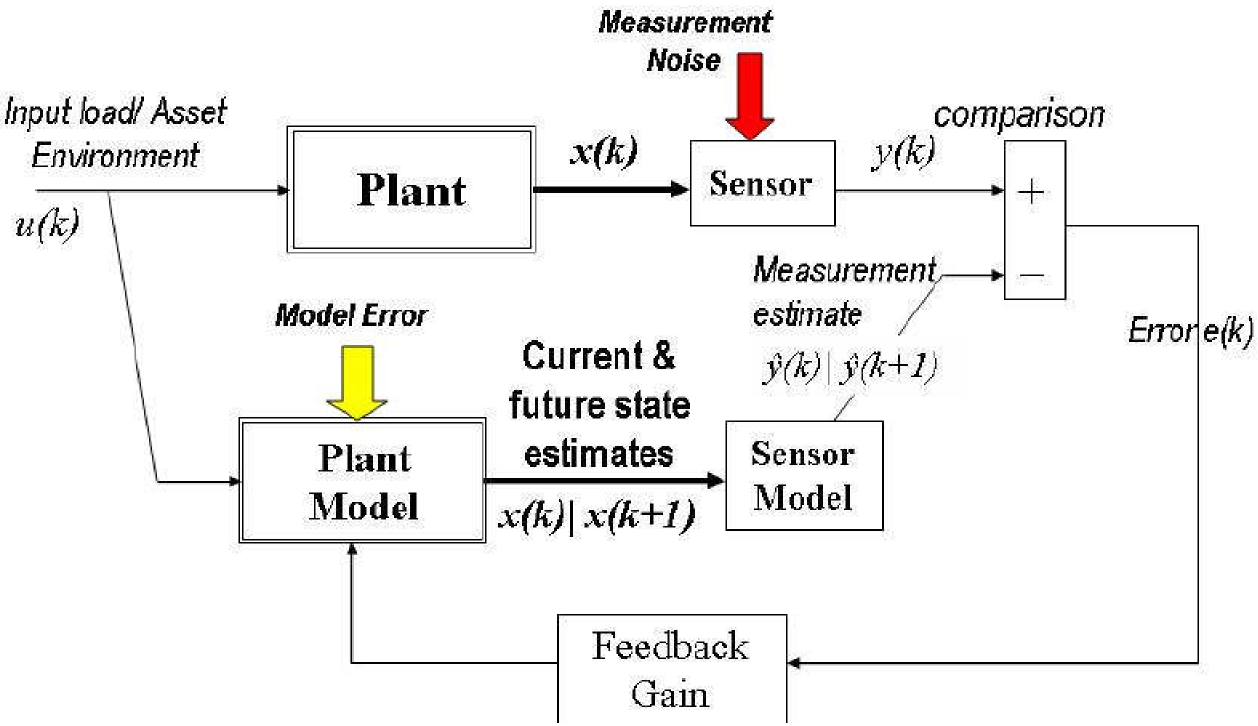
4-State-estimator-based prognosis



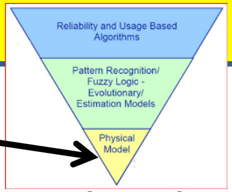
- State estimator based approach is **a dynamical response model** for predicting the unknown states by comparing the recent system outputs with the most recent condition prediction. There is a **direct evaluation and comparison of parameters**.

When applicable?

State-estimator-based approach is useful in these cases where quantities of interest may not be directly measurable.



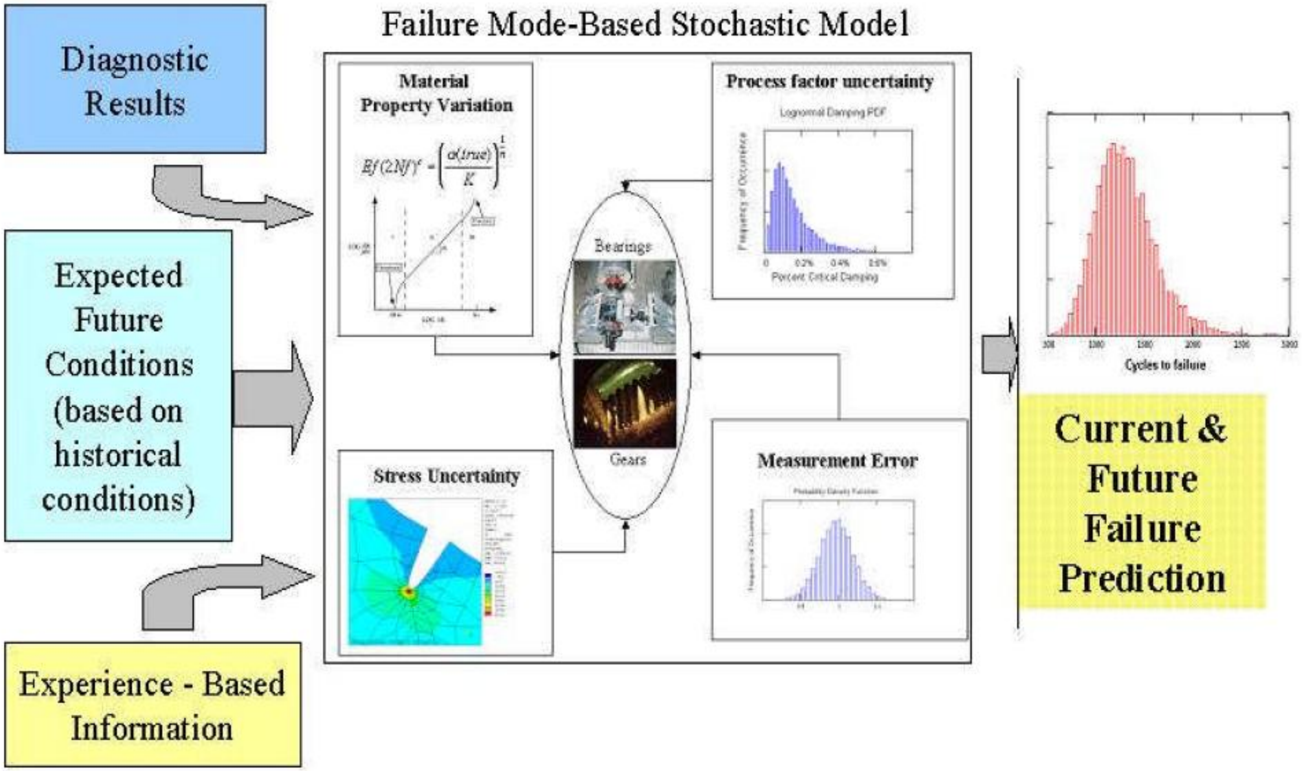
5-Physics-based prognosis



➢ Physics-based modeling approach **is a combination or fusion of the feature-based and model-based approaches** provides full prognostic ability over the entire life of the component, thus providing valuable information for planning which components to inspect during specific overhauls periods.

When applicable?

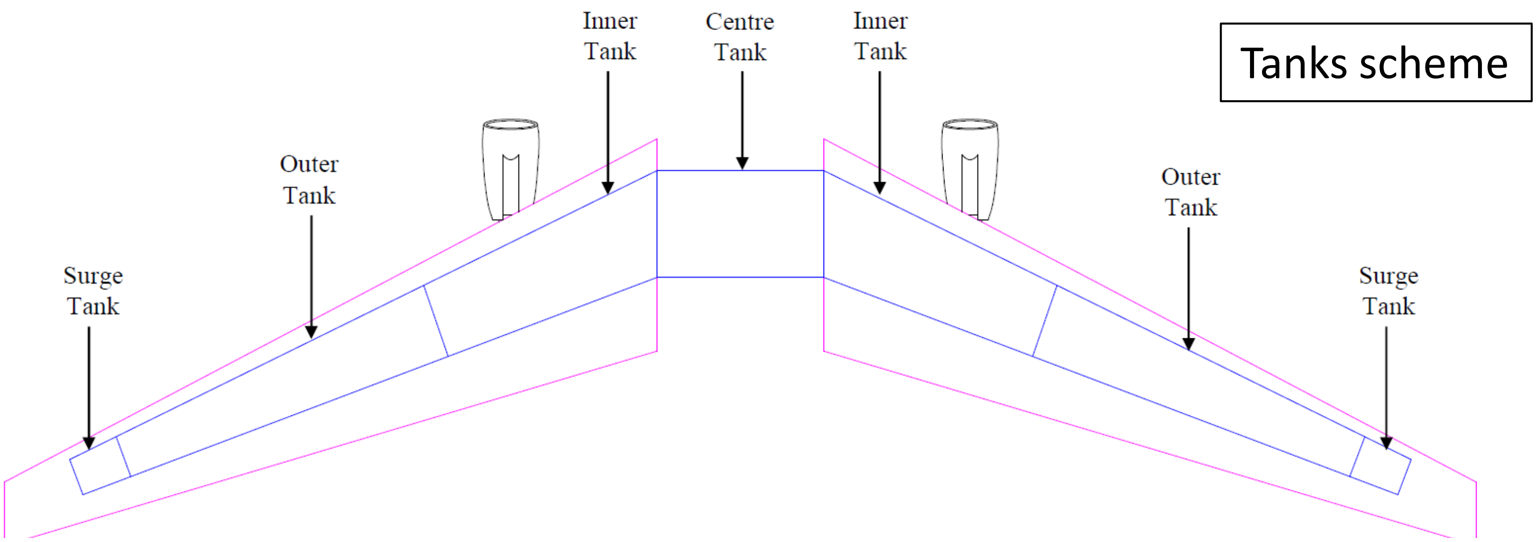
Physics-based prognosis is a very flexible method and can be use widely but requires a lot of information about the component or system.

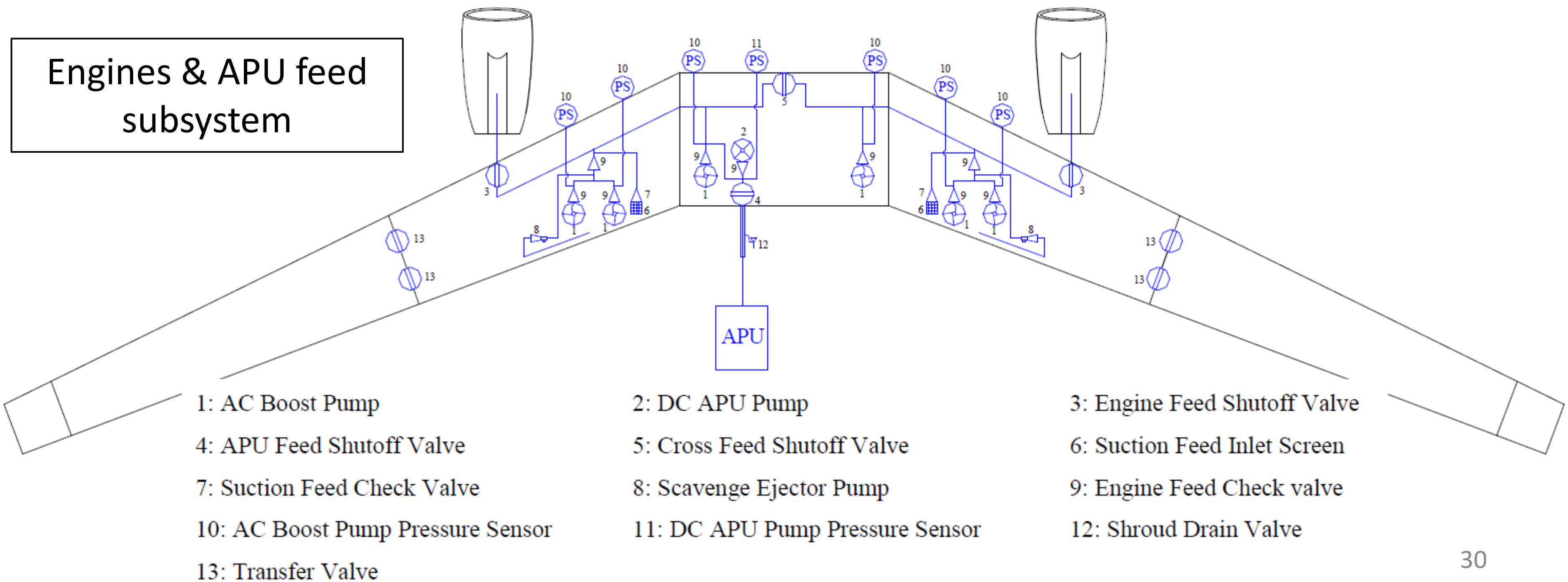


Example of PHM application:

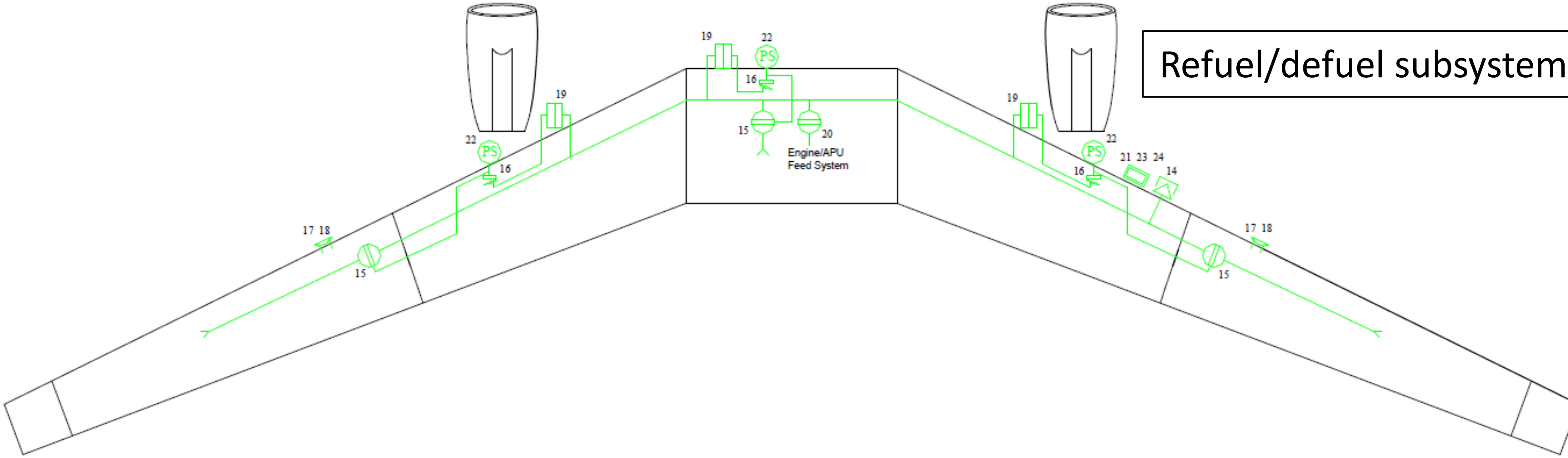
Aircraft fuel system

Let’s consider a typical fuel system architecture for a twin engines commercial jet.



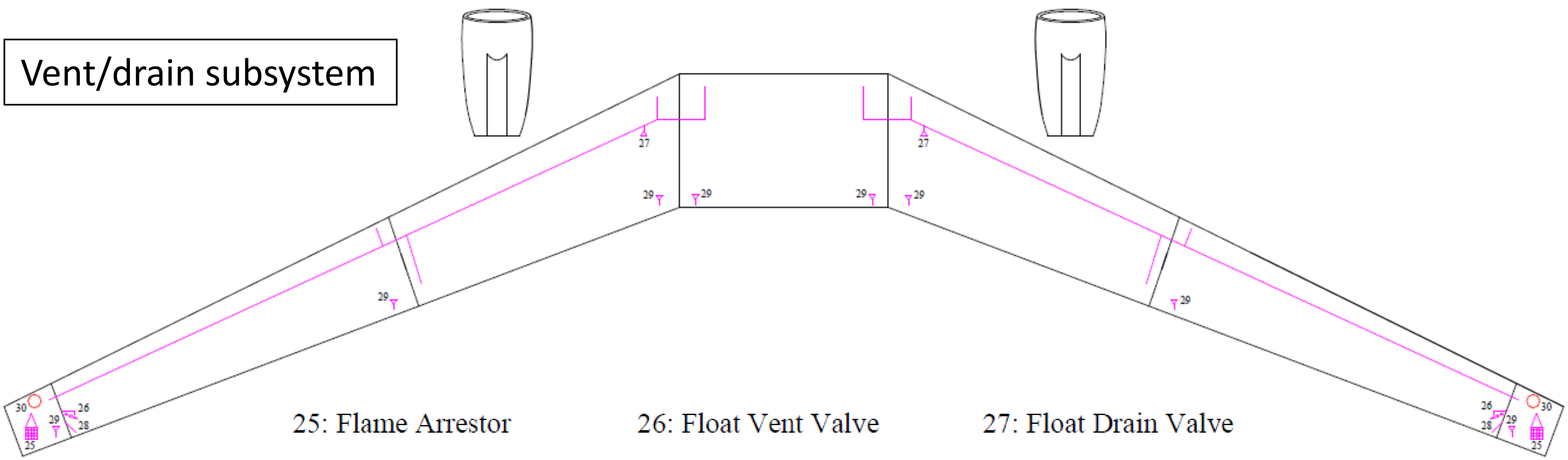


Refuel/defuel subsystem



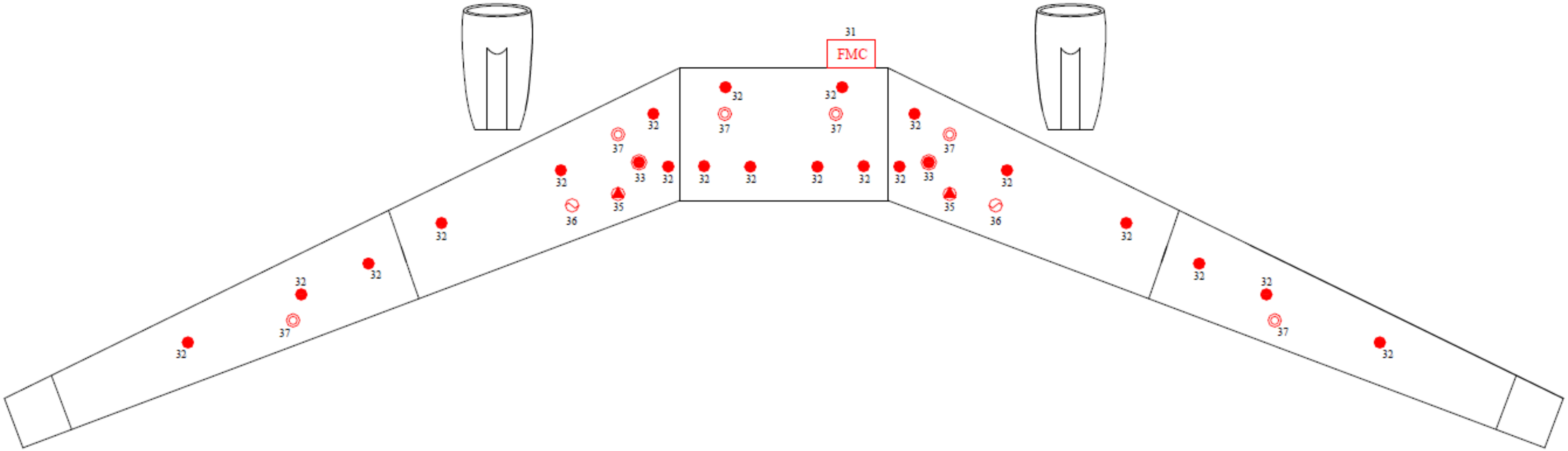
14: Refuel/Defuel Adapter
15: Refuel Shutoff Valve
16: High Level Float Valve
17: Gravity Fill Adapter
18: Gravity Fill Cap
19: Refuel Control Solenoid
20: Defuel Shutoff Valve
21: Ground Receptacle
22: Refuel Pressure Switch
23: Refuel/Defuel Indicator
24: Refuel/Defuel Panel

Vent/drain subsystem



25: Flame Arrestor
26: Float Vent Valve
27: Float Drain Valve
28: Check Valve
29: Water Drain Valve
30. Tank Pressure Sensor

Fuel measurement subsystem



31: Fuel Management Computer

32: Fuel Quantity Probe

33: Fuel Quantity Comp Probe

34: Fuel Gauging Harness

35: Fuel Low Level Sensor

36: Fuel Temperature Sensor

37: Magnetic Level Indicator

Let's have a simple **Bill Of Material** (**BOM**) of components considered in the fuel system shown above:

Item	Components	Item	Components
1	AC Boost Pump	20	Defuel Shutoff Valve
2	DC APU Pump	21	Ground Receptacle
3	Engine Feed Shutoff Valve	22	Refuel Pressure Switch
4	APU Feed Shutoff Valve	23	Refuel/Defuel Indicator
5	Cross feed Shutoff Valve	24	Refuel/Defuel Panel
6	Suction Feed Inlet Screen	25	Flame Arrestor
7	Suction Feed Check Valve	26	Float Vent Valve
8	Scavenge Ejector Pump	27	Float Drain Valve
9	Engine Feed Check valve	28	Check Valve
10	AC Boost Pump Pressure Sensor	29	Water Drain Valve
11	DC APU Pump Pressure Sensor	30	Tank Pressure Sensor
12	Shroud Drain Valve	31	Fuel Management Computer
13	Transfer Valve	32	Fuel Quantity Probe
14	Refuel/Defuel Adapter	33	Fuel Quantity Comp Probe
15	Refuel Shutoff Valve	34	Fuel Gauging Harness
16	High Level Float Valve	35	Fuel Low Level Sensor
17	Gravity Fill Adapter	36	Fuel Temperature Sensor
18	Gravity Fill Cap	37	Magnetic Level Indicator
19	Refuel Control Solenoid		

In order to choose the right diagnosis/prognosis technique for each component it is necessary to **design the reliability of the system** and identify the features of its parts

FHA
FMECA
FTA

➢ **FHA** is the first analysis that the designer performs onto a new system in order to get the **different failure conditions and related severity**. FHA also **provides a starting point for more in-depth FMECA and allow to generate safety requirements**.

➢ A section of FHA with most severe failure conditions follows as example:

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on Aircraft/Crew/Occupants	Hazard Class
Fuel distribution to supply fuel to each engine from the appropriate tank	a) Loss of pressurized fuel flow to both engines	Takeoff, Landing	Loss of engine thrust. Possible two engine flame-out	Catastrophic
	b) Loss of pressurized fuel flow to both engines	Flight	Loss of engine thrust. Possible two engine flame-out	Hazardous
	c) Loss of pressurized fuel flow to one engine	Takeoff, Flight, Landing	Loss of engine thrust. Possible single engine flame-out. Asymmetric thrust would require control trim.	Major
Correct a fuel imbalance	Loss of ability to perform cross feed when necessity to do so arises	Flight	Inability to correct lateral imbalance or asymmetry may need to be controlled by engine thrust settings.	Major
Engine fuel feed shutoff	Inability to shut-off fuel feed to a nacelle in case of fire	All	Loss of ability to isolate engine compartment from source of fuel.	Catastrophic
APU fuel feed shutoff	Inability to shut-off fuel to the APU in case of fire	All	Loss of ability to isolate APU from source of fuel.	Catastrophic

Where:

Category I (Catastrophic)	A failure may cause death or system destroy
Category II (Hazardous)	A failure may cause severe injury, property damage or mission loss
Category III (Major)	A failure may cause minor injury, property damage or mission delay or degradation
Category IV (Minor)	A failure may not cause minor injury or some degree economic loss, but it may result in unscheduled maintenance or repair

For what can be seen partially in previous slide, most critical failure conditions are listed in the following table:

Failure Condition	Severity
Loss of pressurized fuel flow to both engines	Catastrophic
Inability to shut-off fuel feed to a nacelle in case of fire	Catastrophic
Inability to shut-off fuel feed to APU in case of fire	Catastrophic

MOST CRYTICAL SYSTEMS:

- **Engines and APU feed**

➢ **FMECA** is a bottom-up procedure which documents all probable failure in a system, determines the effect of each failure, identifies single failure points and ranks each failure according to a severity classification of failure mode and probability of occurrence.

➢ In detail, **FMEA** is used to analyze the result of failures on system and to classify every potential failure by severity; **CA** (**Criticality Analysis**) is intended to point out combined influence on multiple failures occurrence.

Let's consider, for example, AC boost pump and cross-feed valve (next slide) **FMECA**

Component: AC boost pump

Component function: provides redundant fuel feed

Failure mode	Effect on the system	Effect on aircraft	Hazard class	Flight phase
Loss of fuel flow	Loss of associated AC boost pump fuel flow.	Reduced engine feed capability	Major	Ground & flight
Internal fuel leakage (minimum)	Reduced associated AC boost pump fuel flow.	None	Minor	Ground & flight
Reduced fuel flow	Reduced associated AC boost pump fuel flow	None	Minor	Ground & flight
Internal check valve failed open	When associated AC boost pump is not in use, fuel is back feed through pump	Reduced engine feed capability	Minor	Ground & flight

An other example of FMECA

Component: cross feed shutoff valve

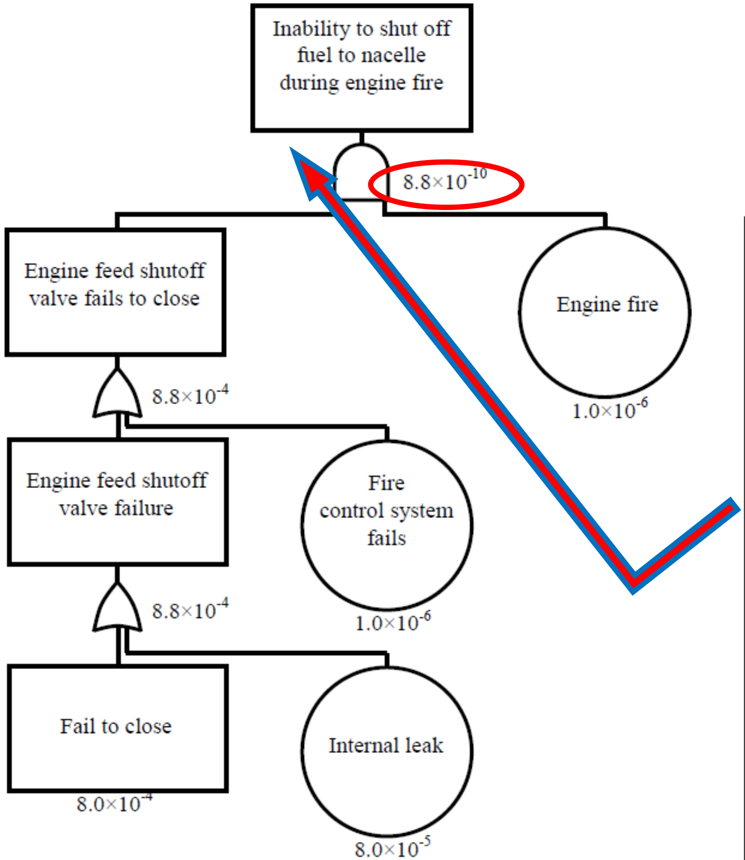
Component function: provides cross fuel feed

Failure mode	**Effect on the system**	**Effect on aircraft**	**Hazard class**	**Flight phase**
Fails to open	Loss of fuel cross feed function	Unable to correct lateral imbalance in flight; Subsequent engine failure will cause growing uncorrectable lateral imbalance	Major	Flight
Fails to close	Unable to isolate left and right fuel tanks	Unable to isolate left and right fuel tanks	Minor	Flight
External leak	Fuel feed line leaks into other fuel tanks	External fuel spillage	Minor	Ground & flight
Actuator status lost	Erroneous indication of cross feed shutoff valve failure	Caution message generated	Minor	Ground & flight
Internal leak	Unable to stop cross feed fuel flow when commanded	Unable to completely stop cross feed fuel flow when commanded, loss of isolation between the fuel feed lines of the two engines	Minor	Ground & flight

➢ **FTA** is focused on one particular undesired top event (failure condition) and provides a method for determining causes of this top event. **FTA** is conducted for each catastrophic and hazardous failure condition.

➢ Generally, the probability of basic event can be expressed as: **P = 1-e^(-λt)**, where P is probability of basic event of fault tree, λ is failure rate, and t is mission time.

➢ The fault tree uses symbols to provide a visual representation of the causes and combinations of causes that lead to the top event, **following Boolean algebra**.



From FHA

From Regulations

Failure condition	Severity	Required probability	Calculated probability
Loss of pressurized fuel flow to both engines	Catastrophic	1.0E-9	4.9E-13
Inability to shut off fuel to a nacelle in case of engine fire	Catastrophic	1.0E-9	8.8E-10
Inability to shut off fuel to APU in case of fire	Catastrophic	1.0E-9	8.8E-10
Fuel tank venting blockage	Hazardous	1.0E-7	1.0E-12
Loss Of Fuel Quantity Data from Left and Right Side Tanks and Loss Of Low Level Fuel Warning	Hazardous	1.0E-7	1.9E-10

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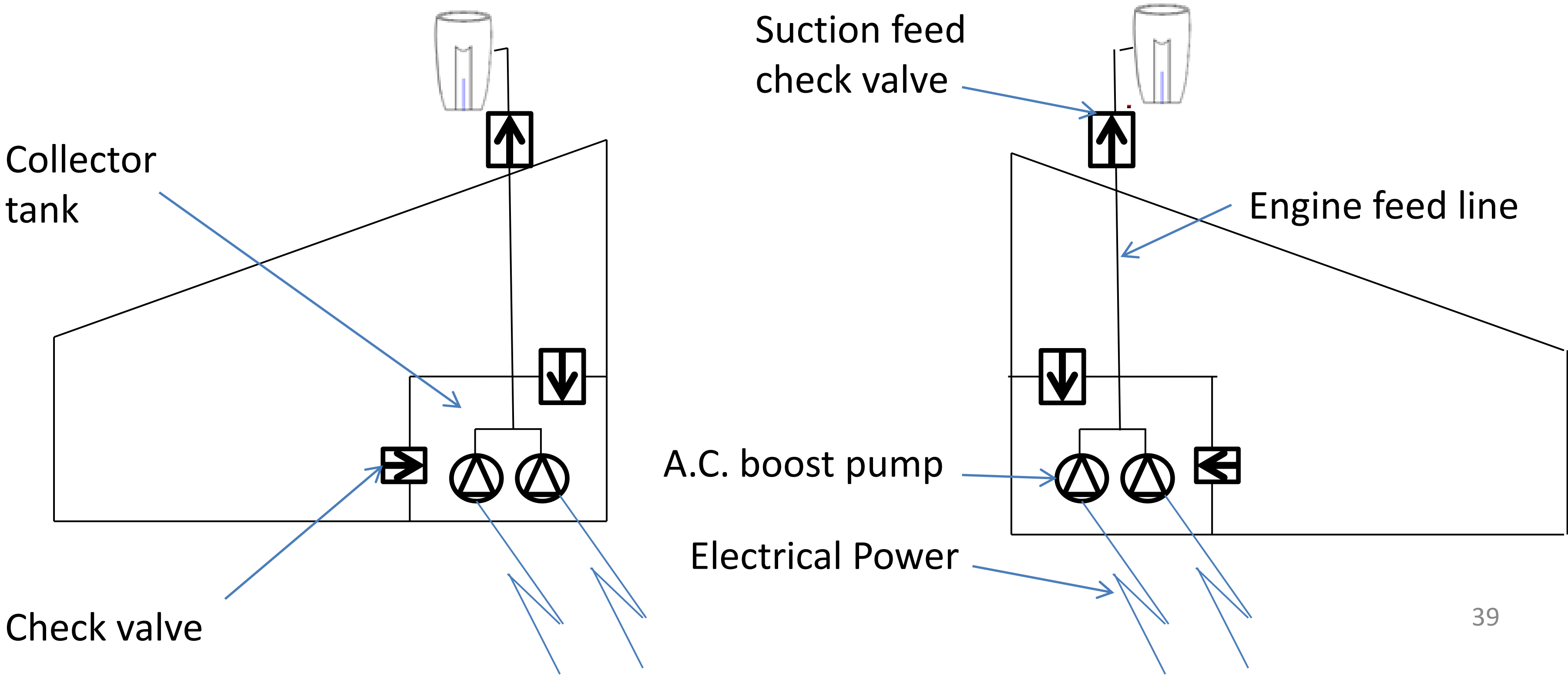
An other example of FTA

Loss of pressurized fuel flow to both engines

$4{,}9 \times 10^{-13}$



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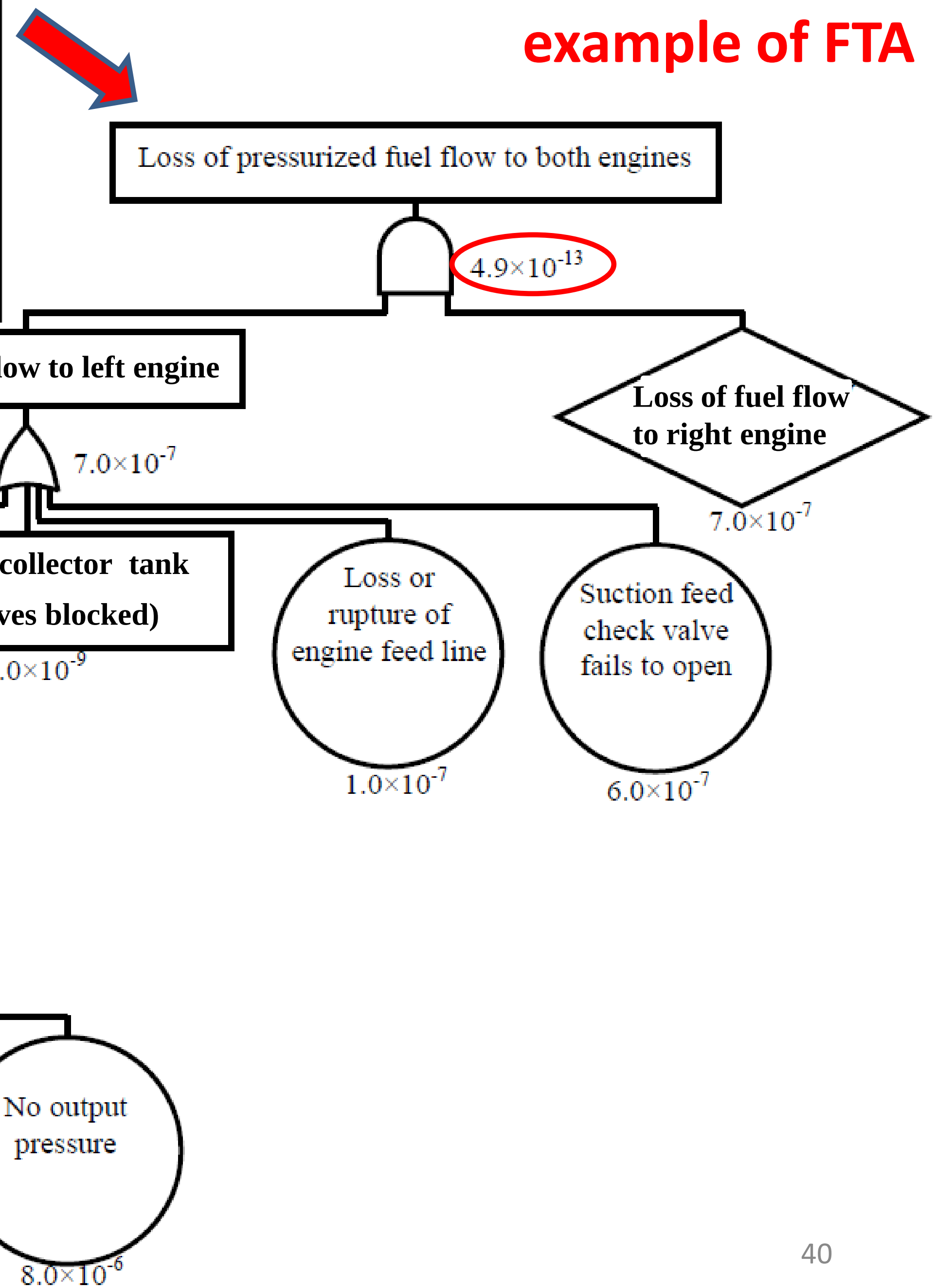
An other example of FTA

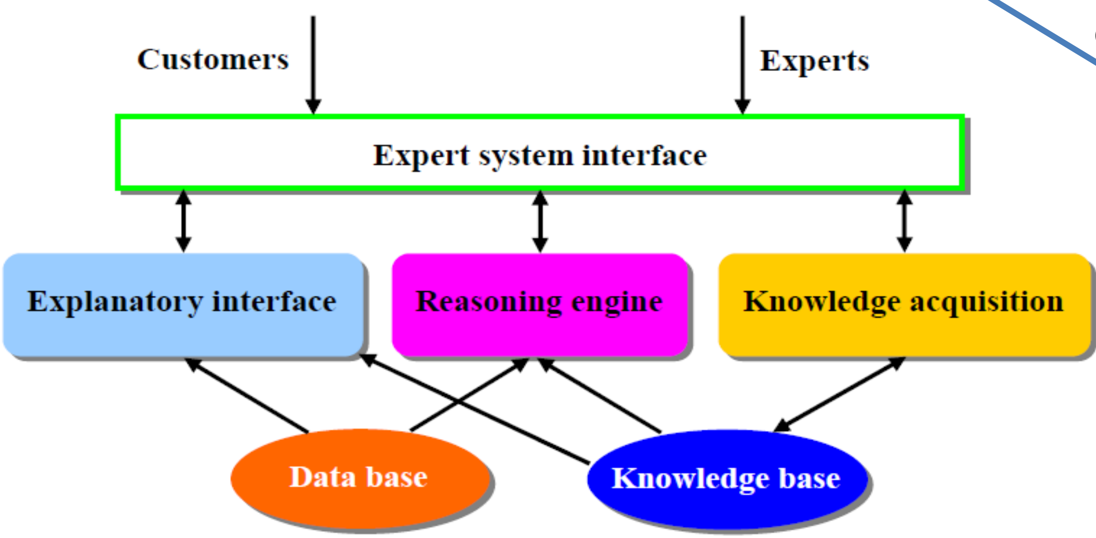


Choice of **diagnosis**/prognosis techniques

➢ Now that the system is well known it is possible to choose diagnosis and prognosis techniques **that fit better the components to be monitored.**

➢ Considering what we have seen above, **Rule-based expert system** is a fast and reliable diagnostic method which is widely used for failure detection and diagnostic decision making. It is very suitable for aircraft fuel system to realize the automated failure diagnosis "if-then-else"-type.

➢ Furthermore, rule-based expert system based on a combination of **FMECA** and **FTA** provides a successful method to enable the automated and high-reliable diagnostic capability.



e.g.

IF {FUEL PUMP CURRENT is "OK" and FUEL PRESSURE is "LOWER THAN 75% RATED PRESSURE" and FUEL QUANTITY is "OK"}
THEN {FUEL PUMP is "BLOCKED BY FOREIGN OBJECTS"}

Rule-based diagnosis: fuel pump example

Rule-based approach requires an on-board reasoning engine that **must contain all expected failure cases.** Let's consider a fuel pump problem:

IF
{FUEL PUMP CURRENT is "OK" and FUEL PRESSURE is "LOWER THAN 50% RATED PRESSURE" and FUEL QUANTITY is "OK"}
THEN
{FUEL PUMP is "BLOCKED PARTIALLY"}

IF
{FUEL PUMP CURRENT is "OK" and FUEL PRESSURE is "NEAR ZERO" and FUEL QUANTITY is "OK"}
THEN
{FUEL PUMP is "BLOCKED TOTALLY"}

IF
{FUEL PUMP CURRENT is "OK" and FUEL PRESSURE is "NEAR ZERO" and FUEL QUANTITY is "NEAR ZERO"}
THEN
{FUEL PUMP is "DRY-RUNNING"}

The weakness of this method is in the coverage of all failure conditions provided during the design of reasoning engine. For example if we consider case 2 in previous code:

IF
{FUEL PUMP CURRENT is “OK” and FUEL PRESSURE is “NEAR ZERO” and
FUEL QUANTITY is “OK”}
THEN
{FUEL PUMP is “BLOCKED TOTALLY”}

The hypothesis can lead to another conclusion:

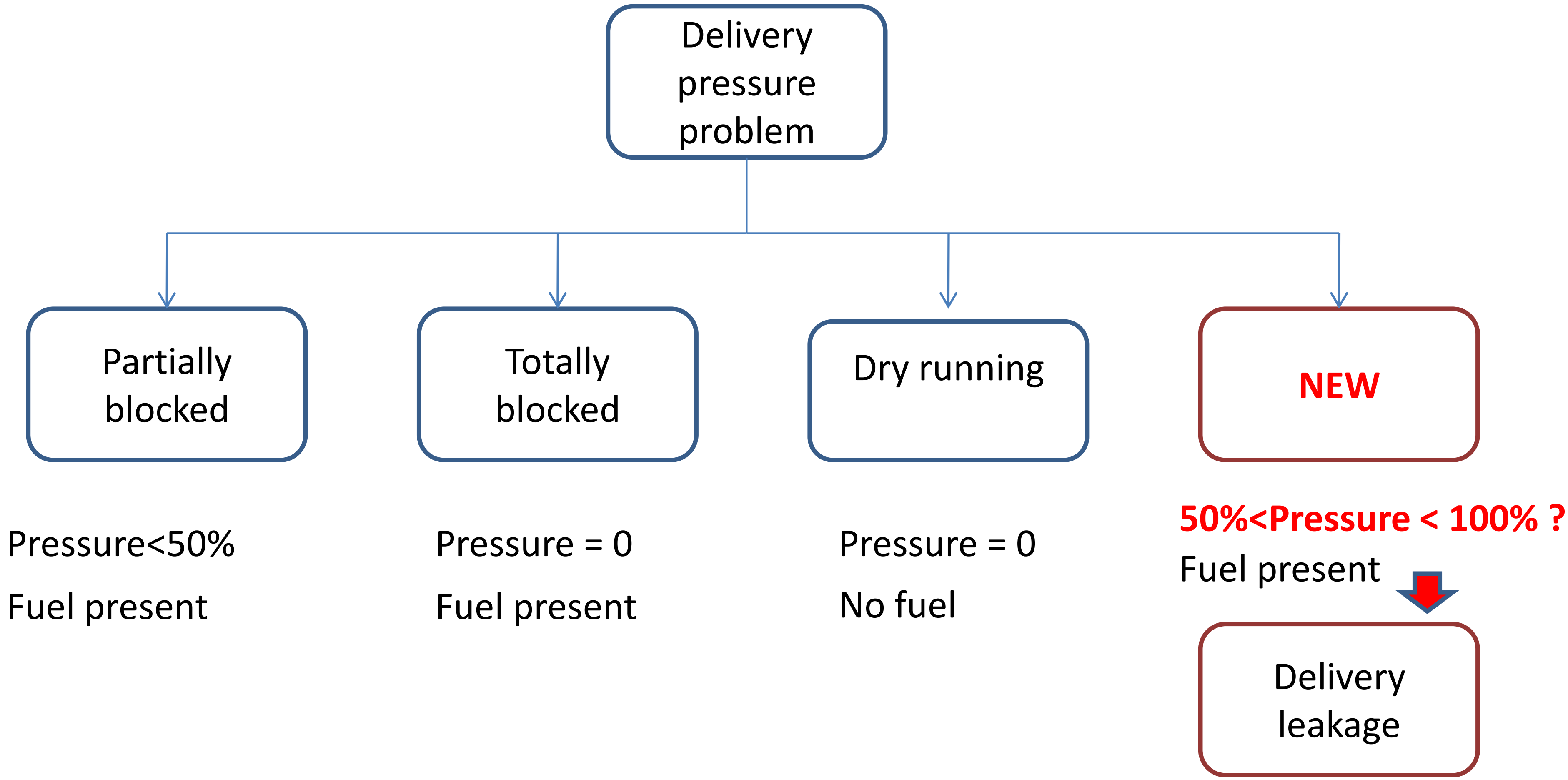
IF
{FUEL PUMP CURRENT is “OK” and FUEL PRESSURE is “NEAR ZERO” and
FUEL QUANTITY is “OK”}
THEN
{FUEL SUPPLY has a “ TOTAL LEAKAGE”}

It is necessary to implement all possible cases and the widest amount of information in reasoning code

The problem has to be very well known

Case-based diagnosis: fuel pump example

Case-based approach has the capability to compare what is going on with past cases, in real time. So we will have:

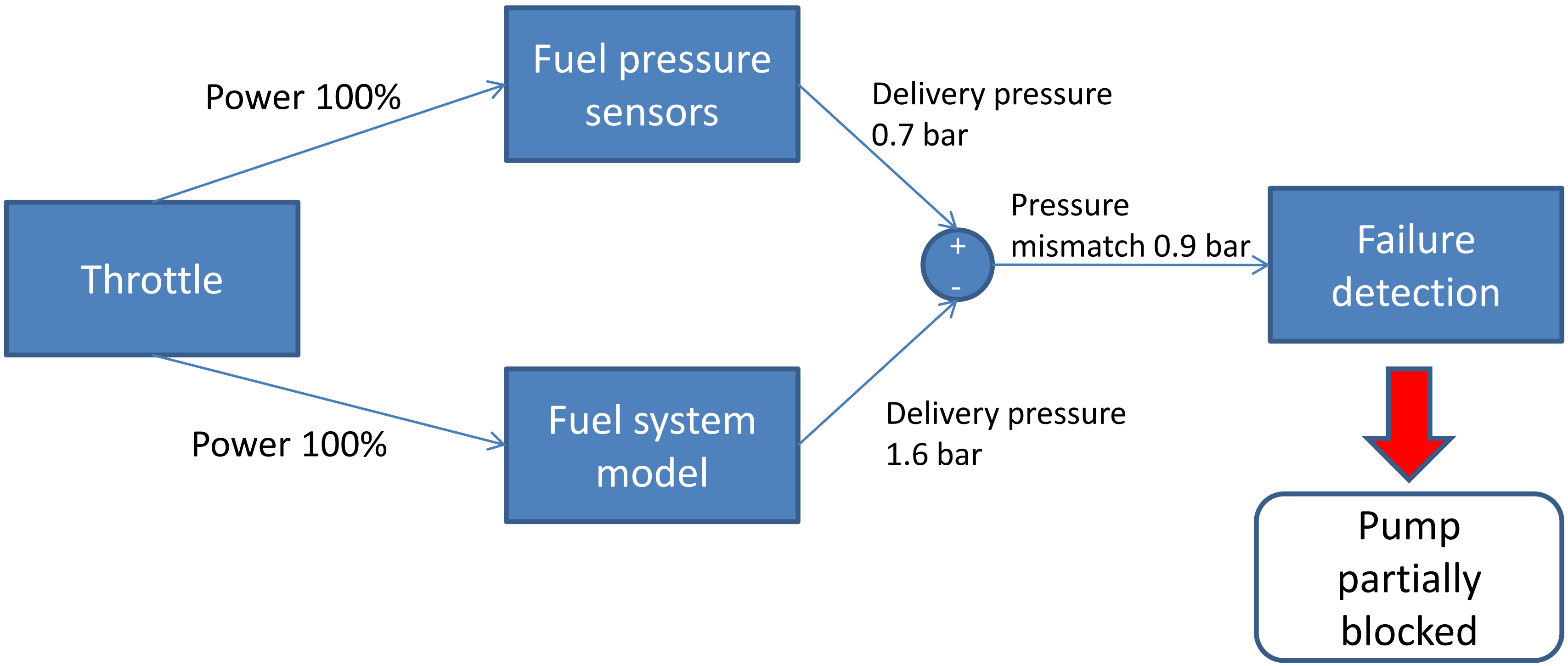


Even if there were no previous cases, the monitoring system, this time, **learns** the new problem and updates its database for the future.

Model-based diagnosis: fuel pump example

For previous diagnosis approach a certain experience of the engine reasoning programmer was required because the computation of failure type was based on input received during design phase.

With model-based approach monitoring system compare real time behavior with a model to get its operational status.



Choice of diagnosis/**prognosis** techniques

- In some cases, when a **few components have very low failure rates** or are at low level of failure severity, along with **few or no sensed data associated** with them, the **statistical reliability and usage-based approach** is an appropriate method to achieve the prognostic capability. (Typical uses are for ***check valves***, ***ejector pumps***, ***vent and drain valves***, ***flame arrestors***).

- A **trend-based evolutionary approach** has instead the ability to track and analyze the trend of a component or system degradation and the rates of this trend. **This approach is mainly relied on a large amount of the monitored parameters** to evaluate the current state of a component or system. (For example ***engines/APU feed subsystem***, ***fuel measurement subsystem***).

- In some instances, even though a sufficient statistical or failure database is available for a component or system, **it is still difficult to complement the prediction of failure progression. In such situations, data-driven model-based approach** that is a nonlinear network method **may be a desirable choice.** (*Used for sensors, probes and panels*).

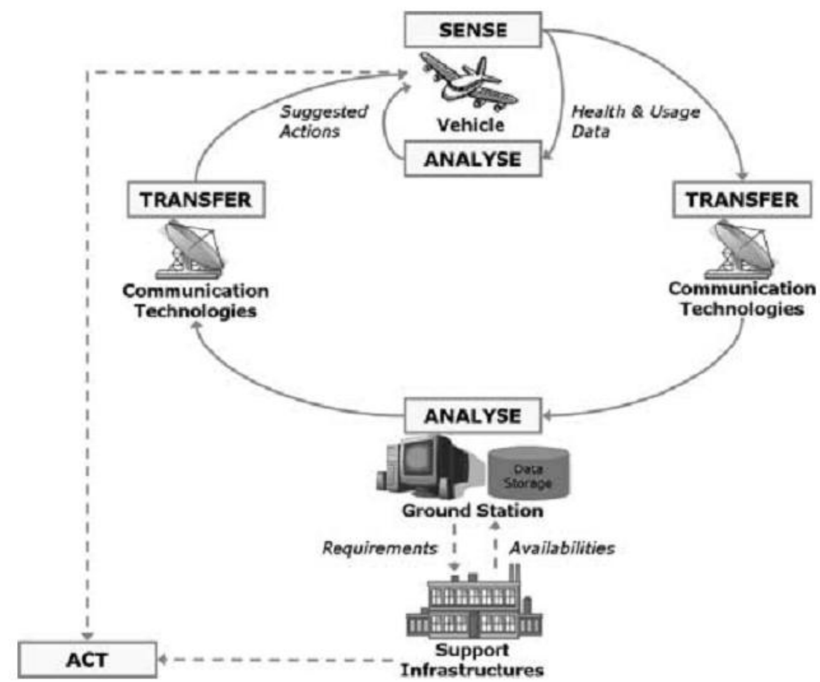
- **State-estimator approach** is useful when it is important to evaluate the behavior of a **component which has poor output**. (*Used for shut-off and cross-feed valves*).

- **Physics-based modeling approach** is a sum of the methods seen above, but it is too complex for this system and it is **not considered for a preliminary PHM design.** (*Not used because too complex for a preliminary design*).

For the reasons exposed above, prognosis techniques chosen for fuel system components are summarized below:

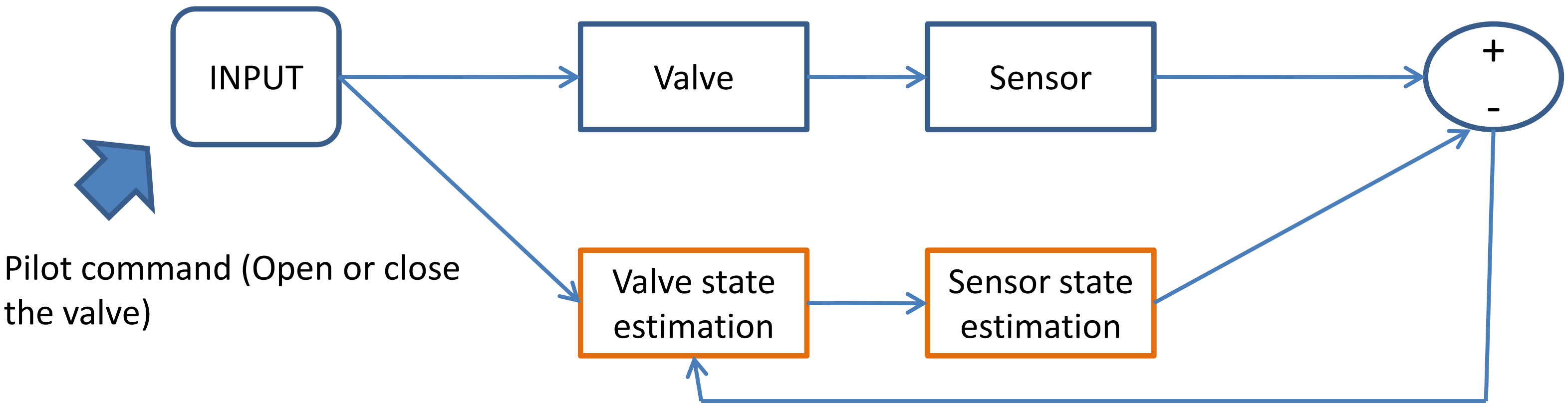
Component/Subsystem	Type	Prognostic approach
Suction Feed Inlet Screen, Suction Feed Check Valve, Scavenge Ejector Pump, Engine Feed Check valve, Shroud Drain Valve, Refuel/Defuel Adapter, High Level Float Valve, Gravity Fill Adapter, Gravity Fill Cap, Ground Receptacle, Float Vent Valve, Float Drain Valve, Check Valve, Water Drain Valve, Magnetic Level Indicator, Flame arrestor	Mechanical	statistical reliability and usage-based approach
Engine Feed Shutoff Valve, APU Feed Shutoff Valve, Cross feed Shutoff Valve, Refuel Control Solenoid, Defuel Shutoff Valve, Refuel Shutoff Valve	Electro-mechanical	state estimator based approach
AC Pump Pressure Sensor, DC Pump Pressure Sensor, Transfer Valve, Refuel Pressure Switch, Refuel/Defuel Indicator, Tank Pressure Sensor, Fuel Quantity Probe, Fuel Quantity Comp Probe, Fuel Gauging Harness, Fuel Low Level Sensor, Fuel Temperature Sensor, Refuel/Defuel Panel, FMC	Electronic	ANN

Component/Subsystem	Type	Prognostic approach
AC Boost Pump DC APU Pump	Electro-mechanical	ANN
Engine/APU feed subsystem, Refuel/defuel subsystem, Fuel measurement and management subsystem	Electro-mechanical, Electronic	trend-based evolutionary approach



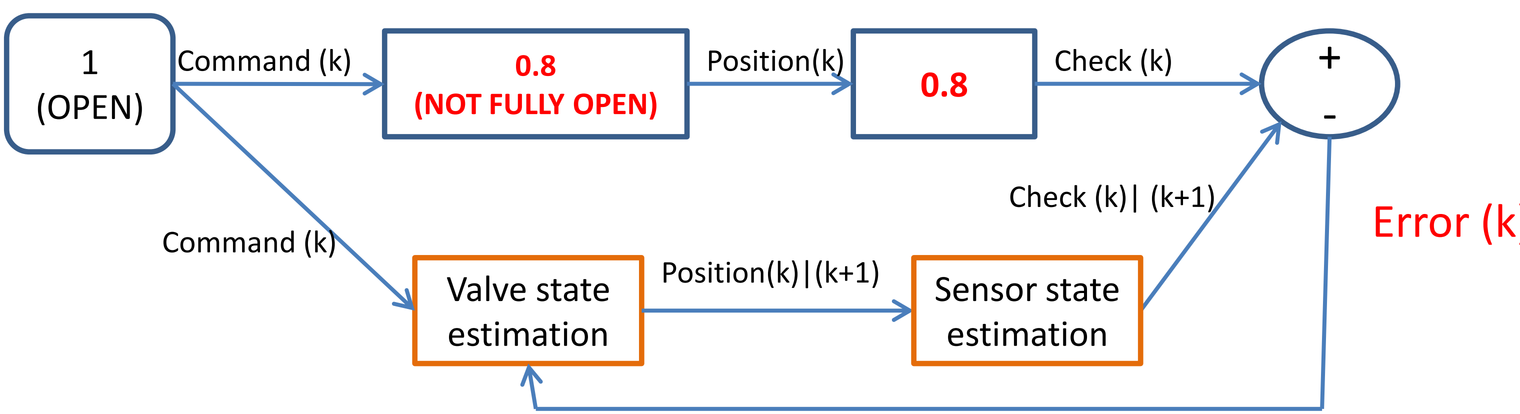
State-based approach: cross-feed valve example

Prognosis capability is based on the comparison between the real valve and its state estimation model.



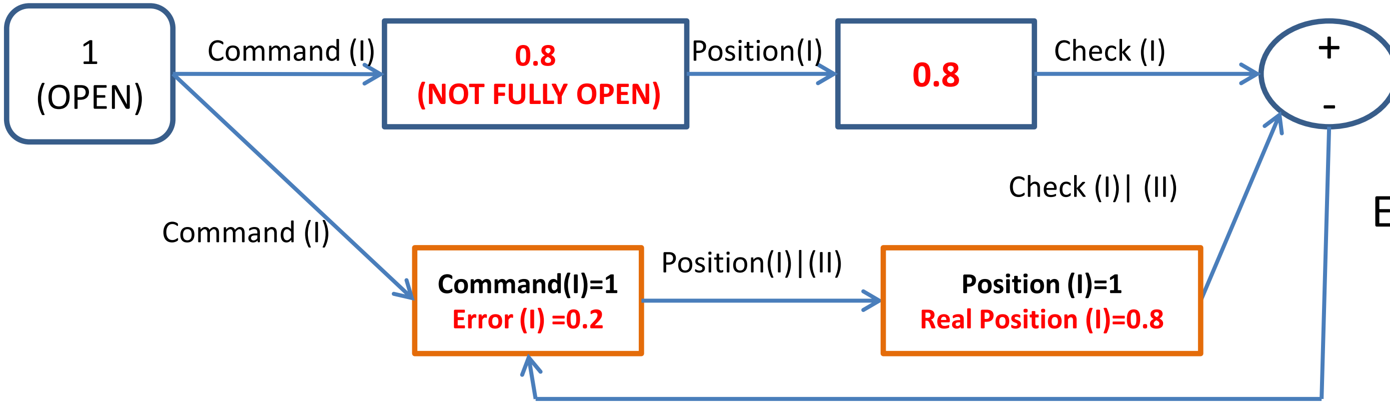
This example is useful to understand this approach and it's easy because the input is Boolean (0 if the valve is closed, 1 if the valve is open). Let's use the **pilot command as main variable**. In theory, if pilot ask for position 1 (open) valve will move to 1 (completely open) and sensor will receive 1 ("the valve is open").

If the system has a failure, there is a discrepancy between real value and model value. This error is used in following iterations to predict future state estimations and component degradation.



So, we have:

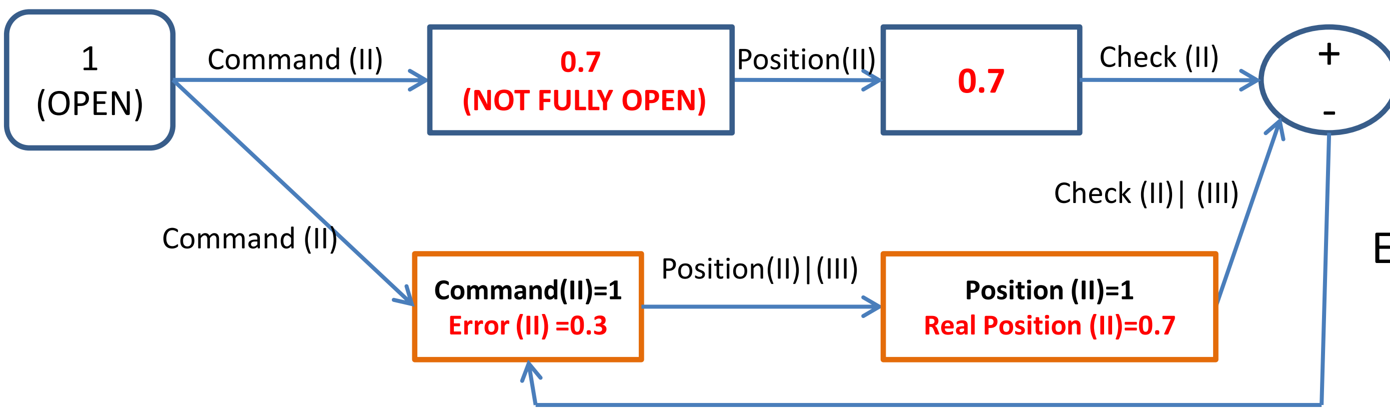
- **K=I**



Error = 0.2 (I)

Then, considering another open-close cycle we can have:

- **K=II**



Error = 0.3 (II)

Considering this state evolution it is possible to predict when the valve will not be able to follow the pilot command anymore and **will have to be replaced**.

A reasoning of the state estimation model of the cross-feed valve can be the following one:

1. Let's consider an activation of cross-feed valve with a open-close cycle every **500 flight hours** (*unrealistic* but just as an example)
2. Considering a degradation in the capability of following the pilot command of 0.1 each cycle (**valve opens 10% less per cycle**) and assuming that **sensor is correct**
3. Considering that the valve **starts with 80% of the maximum opening capability**
4. Admitting a **minimum safety opening of 50%** of the maximum capability

Cross-feed valve shall be checked (or replaced if needed) within the next
2000 flight hours

CONCLUSIONS

Summarizing, the choice of the diagnostic/prognostic techniques depends strictly on:

- maintenance strategy to be applied;
- available data (input/outputs, maintenance records, condition monitoring) for each specific system / subsystem / component;
- type of system / subsystem / component (electrical, mechanical etc.)
- operational background (civil, military etc.);
- performance and minimum operational capabilities requested for system / subsystem / component;
- technological readiness of diagnostic/prognostic techniques;
- development costs;