ASSESSMENT OF CLASSICAL AND MODERN DEPENDABILITY METHODS TO ANALYSE ELECTRICAL FAULTS IN THE LHC SUPERCONDUCTING MAGNETS AND CIRCUITS

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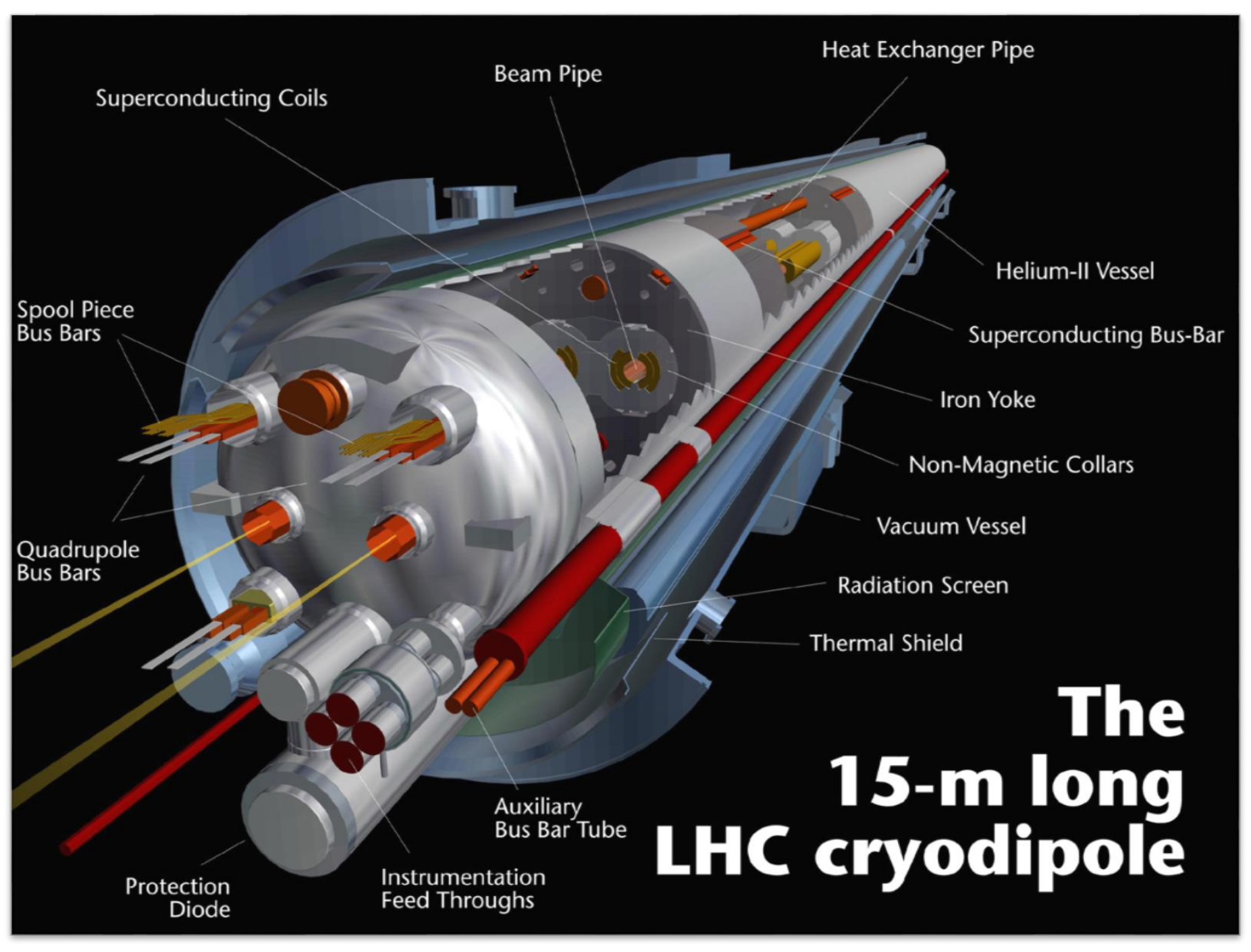
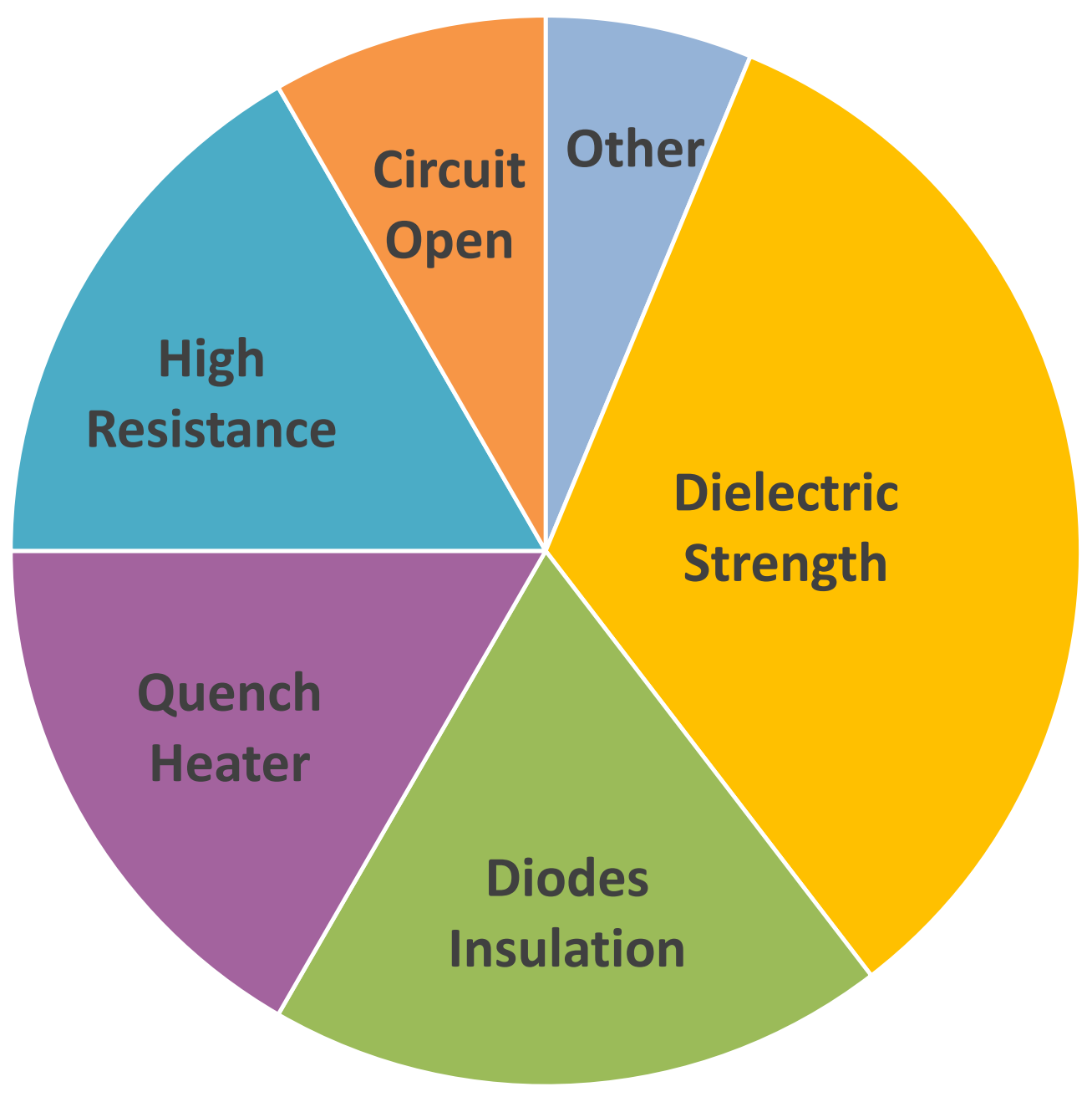
Electrical Faults Overview

The Large Hadron Collider (LHC) at CERN has been operating with beam since September 2008 achieving an integrated luminosity of over 100 fb^{-1} at energies up to 13 TeV. 1572 circuits [60 A – 13 kA] power 9398 superconducting (SC) magnets throughout the LHC ring. A total of 48 electrical faults in the SC magnets and circuits have been overserved since the LHC commissioning in 2006. Bottura, Tock et al. [1] have divided them into six categories:



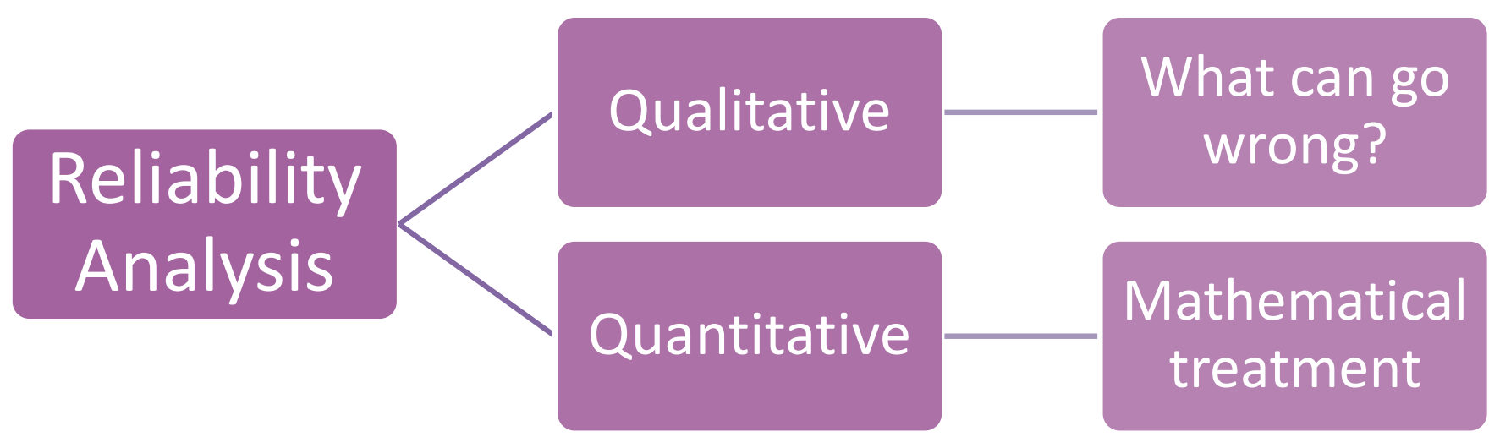


Fault by Categories

- **Dielectric strength** (16): failure to resist the high voltage tests to pass the HV test or detected by the on-line continuous monitoring system.
  - **Diode insulation** (9): subcategory of dielectric strength at the level of the dipole protection cold diode box.
- **High resistance** (8): splice resistance above the specification value that could generate a fatigue phenomenon.
- **Quench heater** (8): failure on quench heater circuit traced to specific manufacturing issues.
- **Open circuit** (4): circuit damaged due to lack of electrical continuity.
- **Other** (3): fault related to instrumentation and powering issues.

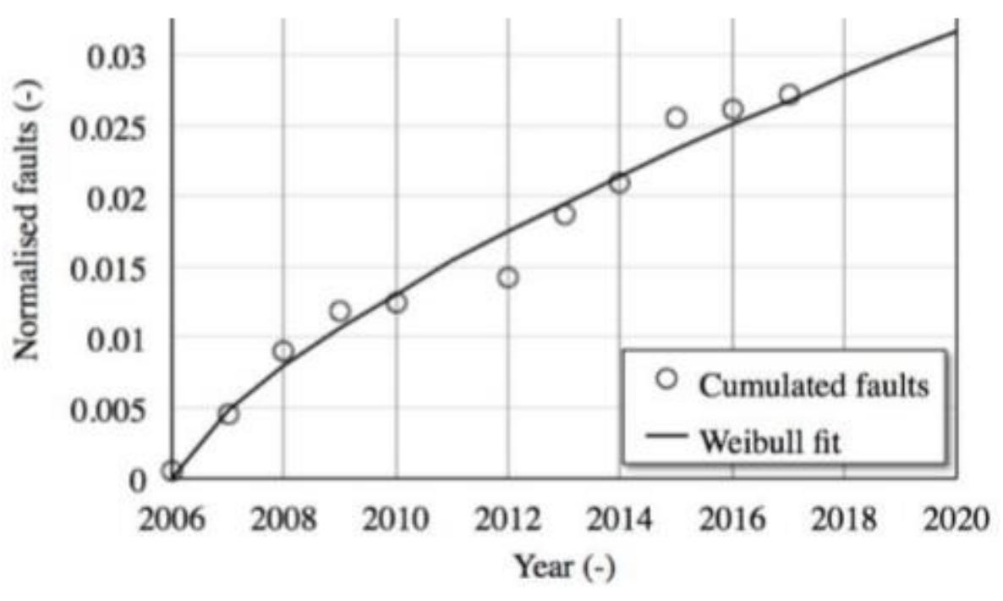
Reliability Analysis Goal

- ✓ Failure rate Prediction
- ✓ Expected lifetime of SC magnets
- ✓ Support long-term LHC operation
- ✓ Benchmark for future similar projects



Despite the low statistics due to few faults during the LHC operation, Bottura, Tock et Al. [1] have provided a first statistical analysis of the electrical faults observed in the SC magnets and circuits. Using an instrumented *cryomagnet** as a basic unit, they have performed a failure rate analysis based on **Weibull statistic** to attempt an extrapolation for the duration of the LHC lifetime.

Each fault is consider as failure in order to estimate Failure Rate (FR) and Mean Time To Failure (MTTF). The plot shows cumulated failures (normalized to the total number of cryomagnet) vs. time.



The data has been modeled with a two-parameter Weibull distribution:

$$F = 1 - e^{-\left(\tau/\lambda\right)^{k}}$$

F : distribution function
τ : time from the first commissioning in years
λ : characteristic time of failure mode
k : shape parameter

Results

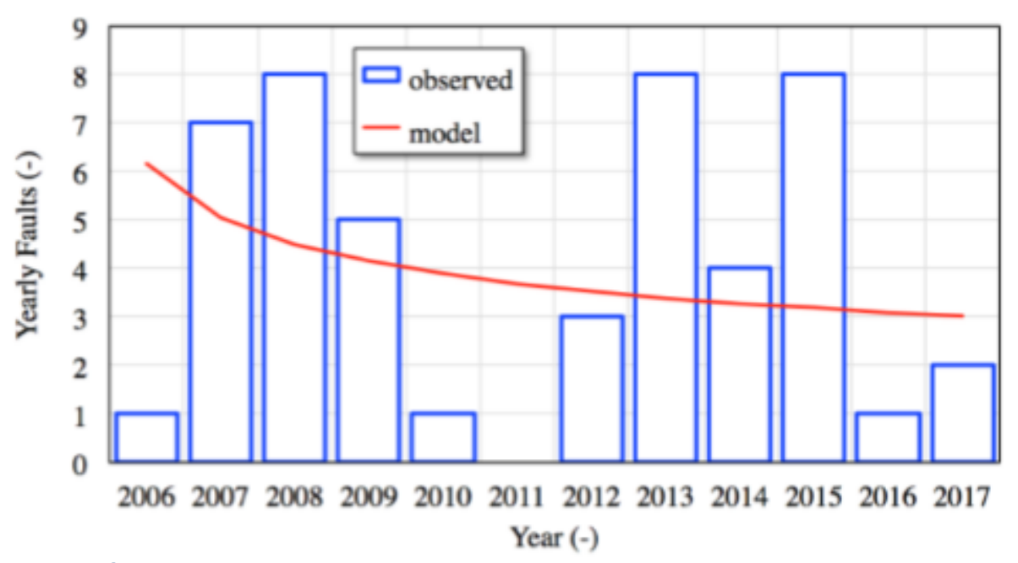
$$\mathbf{FR} = \frac{k}{\lambda}\left(\frac{\tau}{\lambda}\right)^{k-1}$$

$$\mathbf{MTTF} = \lambda \cdot \Gamma\left(\frac{1}{k}+1\right)$$

$$\Gamma(n) = \int_0^{\infty} e^{-x} x^{n-1} dx$$

λ = 1764 ± 976 (years)
k = 0.71 ± 0.05
(95% confident level)

- $k > 1$ → infant mortality regime
- MTTF ≈ 2000 years
- ≈ 4 faults/year → expected ≈ 2 faults/year at the end of LHC (35 years)



The next step is to perform an extended dependability study on the mentioned electrical faults to provide better figures for operation

*instrumented cryomagnet: a cold mass containing an assembly of single SC magnets instrumented , possibly complemented by quench heater and diodes, and connected to busbars.

Classical Methods [2]

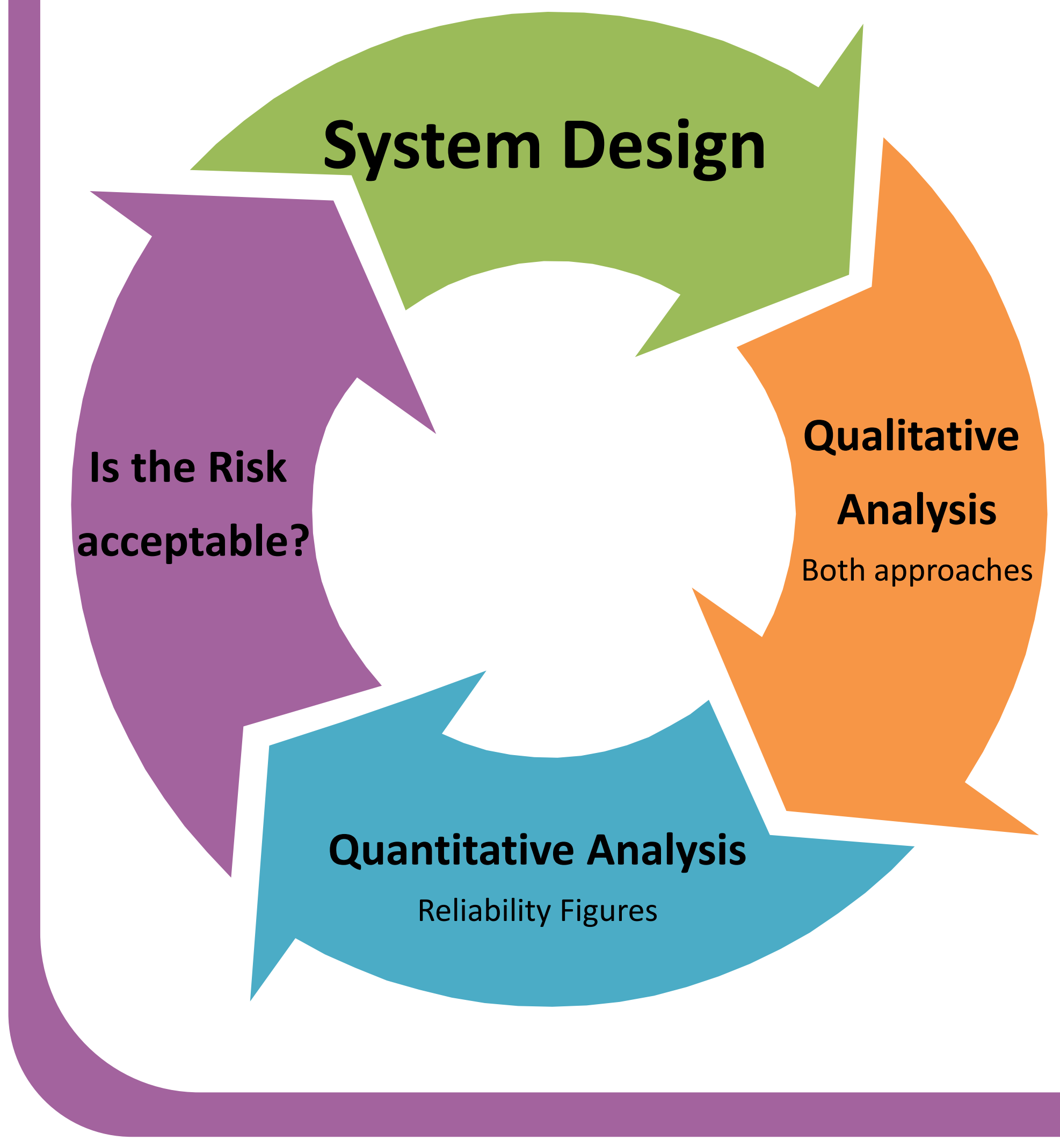
- Failure Mode and Effect Analysis (FMEA): Systematical **Qualitative** method to rate failure modes by danger.

PHASE 1 System Structure	PHASE 2 Function Structure	PHASE 3 Failure Analysis	PHASE 4 Risk Assessment	PHASE 5 Optimisation
System breakdown in system elements	Allocation of functions to system structure	Determination of all potential failure functions	Evaluation of the risk of the current system	Setting measures to achieve an acceptable risk

- Failure Rate Prediction: **Quantitative** analysis to estimate **failures rates** based on Handbooks, Standards or experience.
- Fault Tree Analysis (FTA): **Quantitative** and **Qualitative** method for predicting reliability and system optimization.

PHASE 1 System Analysis	PHASE 2 TOP event Definition	PHASE 3 Failure Analysis	PHASE 4 Fault Tree	PHASE 5 Assessment
System study and its interfaces with the environment	Definition of undesired events to be assessed	Failure rates calculation for each component	TOP event causes study through a Fault Tree	Qualitative and Quantitative analysis feasible

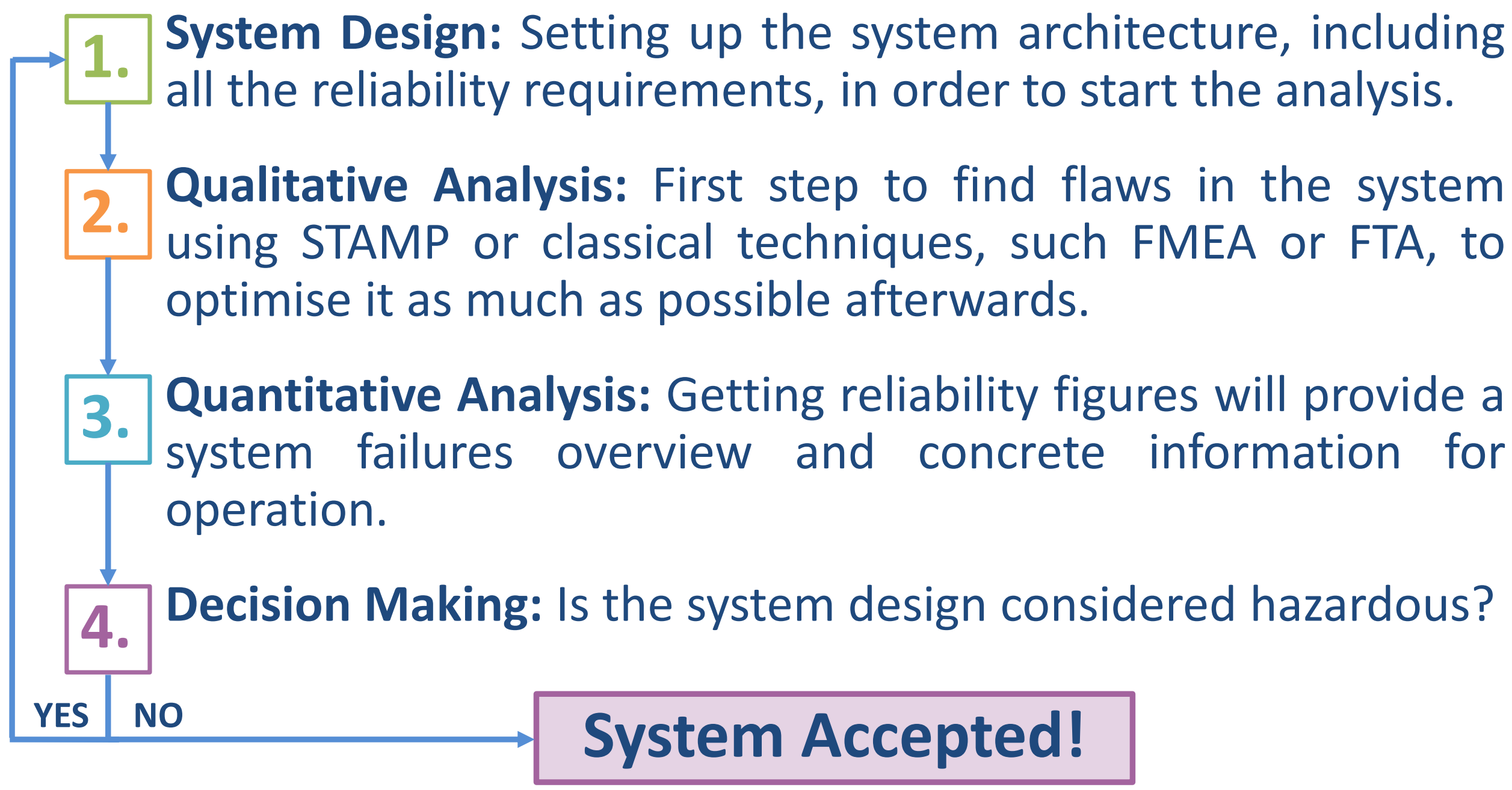
Winning Combination



A deeper analysis on the electrical faults in the SC magnets and circuits will provide more solid figures and establish a common benchmark for future similar complex projects.

STAMP claims that it is not a method that will replace the classical approach, yet it will provide a wider and more exhaustive view of risk analysis. Therefore, a reliability analysis strategy (combining two approaches) of the electrical faults in the LHC superconducting magnets and circuits is proposed:

Risk Assessment Cycle



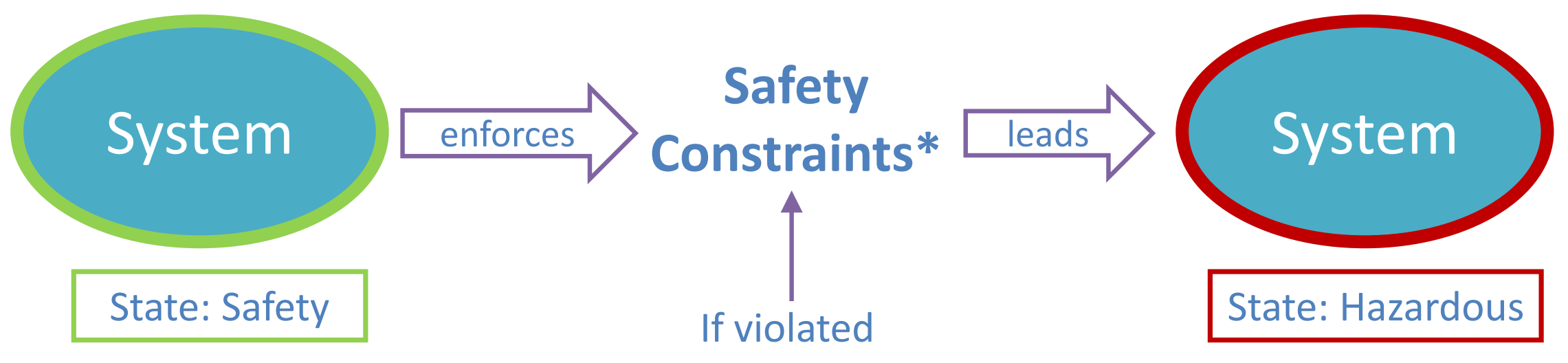
1. **System Design:** Setting up the system architecture, including all the reliability requirements, in order to start the analysis.
2. **Qualitative Analysis:** First step to find flaws in the system using STAMP or classical techniques, such FMEA or FTA, to optimise it as much as possible afterwards.
3. **Quantitative Analysis:** Getting reliability figures will provide a system failures overview and concrete information for operation.
4. **Decision Making:** Is the system design considered hazardous?

System Accepted!

STAMP [3]

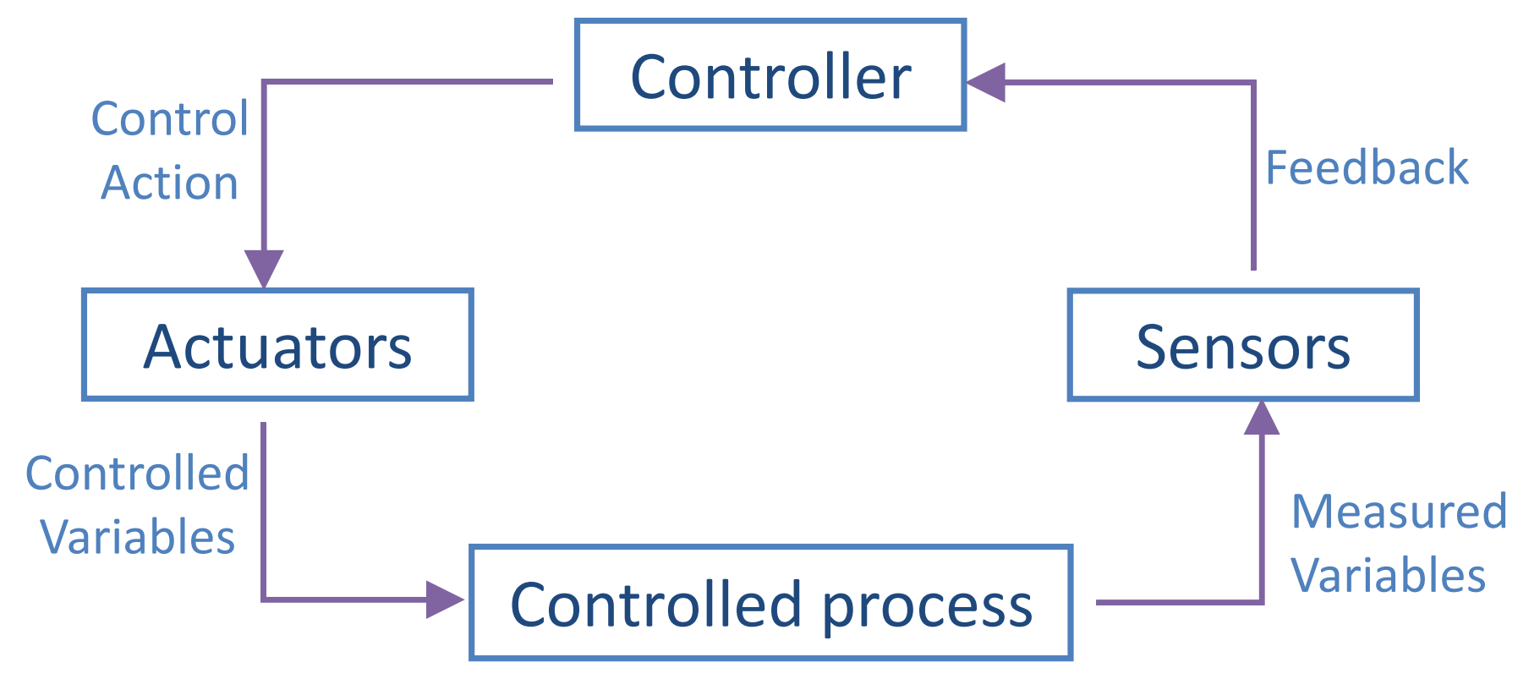
System-Theoretic Accident Model (STAMP) is an accident model based on system theory. It applies to very complex systems and expands the traditional approach of the accident causation.

System-Theoretic Process Analysis (STPA) is an iterative Top-down hazard analysis tool based on STAMP. It was developed in order study system hazards dealing with all the safety constraints (not all of them were taken into account in the classical method).



*Safety constraints taken into account: physical design, operation, management, social interaction and culture.

STPA treats Safety not as a failure problem, but as a hierarchical **CONTROL PROBLEM**.



It allows to identify accident scenarios that could lead to an accident process, not just the electromechanical components.

References

[1] BOTTURA, L., TOCK, J-Ph. Et al.: *A Statistical Analysis of Electrical Faults in the LHC Superconducting Magnets and Circuits*. Paper to be published in MT25 Proceedings, Amsterdam, 2017.
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