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Evolution in Engineering on the Way to Safety

Kalman Ziha*

Professor emeritus of the University of Zagreb, Croatia

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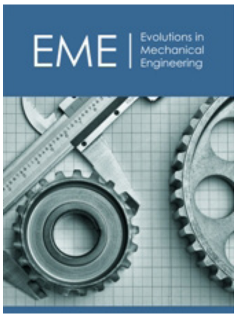

***Corresponding author:** Kalman Ziha, Professor emeritus of the University of Zagreb, Croatia

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Introduction

The need for safety is at the top of human existential needs. It is also a dominant criterion in engineering design, production and operations. Regardless of all the other properties of engineering objects concerning their purposes, functionality and efficiency, the decisive goal of engineering is to provide the required safety in expected missions in environments as they are. Objects in the engineering of many different components are planned, designed and fabricated under unreliable workmanship often from materials of uncertain properties and dimensions and commonly operating in uncertain environments exposed to random loadings and possibly improper management and maintenance. For all these reasons and probably for more others, the safety of engineering objects depends on random circumstances.

Uncertain Character of Safety

States of engineering objects in service may be commonly identified by their status as intact i, operational o, failed f, transient t and collapsed c. In probabilistic system analysis, the states are considered as random events [1-8] defined by their probabilities of occurrences as follows:

Probability of intact mode $p(\mathbf{S}^i)$.

Probability of operation $p(\mathbf{S}^o)$ of N^o operational modes $p(\mathbf{E}^o)$

Probability of failure $p(\mathbf{S}^f)$ of N^f failure modes $p(\mathbf{E}^f)$

Probability of transition $p(\mathbf{S}^t)$ of N^t transient modes $p(\mathbf{E}^t)$

Probability of system collapse $p(\mathbf{S}^c)$.

The probabilistic System Safety analysis (SS) operates with system reliability and system failure:

$$R(\mathbf{S}) = p(\mathbf{S}^i) + p(\mathbf{S}^o) \qquad (1)$$

$$F(\mathbf{S}) = p(\mathbf{S}^c) + p(\mathbf{S}^f) \qquad (2)$$

where $p(\mathbf{S}) = \sum_{j=1}^{N} p_j$ =1 for complete systems of all N events.

Subsequently, the Integral System Safety (ISS) [9] upholds the event-oriented system analysis [10] of engineering objects in services including the redundancy and robustness expressing the uncertainties of operation and failure states [11]. System redundancy implies sufficient residual operational capacity after some component failure. Robustness is perceived as the strength or sturdiness concerning vulnerabilities due to uneven distributions of strengths and weaknesses of different failure modes. The uncertainty of a complete system S of N events generally can be expressed by Shannon's entropy [12-17] accounting for probabilities of all N events as follows:

$$H_N(\mathbf{S}) = -\sum_{j=1}^{N} p_j \log p_j \qquad (3)$$

The unit of entropy (3) is one "bit" when the logarithm is of base two and means the uncertainty of a system of two equally probable events like a flipping of an ideal coin. The entropy HN(S) (3) is equal to zero (no uncertainty) when one of the probabilities is equal to one and all other are equal to zero. The entropy (3) is maximal (full uncertainty) when all events are equally probable and it amounts to log N. The system redundancy expresses the system uncertainty of being operational and can be presented by the conditional entropy of the system So of No operational states with respect to the system S [11] as shown:

$$RED(\mathbf{S}) = H_{N^o}(\mathbf{S}/\mathbf{S}^o) \qquad (4)$$

The system robustness expresses the system uncertainty of ability to respond uniformly to all failures presented by the conditional entropy of the system Sf of Nf failure states relative to the system S [11] as:

$$ROB(\mathbf{S}) = H_{N^f}(\mathbf{S}/\mathbf{S}^f) \qquad (5)$$

The additional knowledge of system partitioning into groups of states of interests provides a more detailed system profile with more subsystems of modes $\mathbf{S}' = \left(\mathbf{S}^i, \mathbf{S}_1^o, \mathbf{S}_2^o, \cdots \mathbf{S}_{n^o}^o, \mathbf{S}_1^f, \mathbf{S}_2^f, \cdots, \mathbf{S}_{n^f}^f\right)$. The general safety relation [9-11] relates the system reliability (1), system uncertainty (2), redundancy (4) and robustness (5) to the entropy of the whole system S and the system operational profile S' as:

$$R(\mathbf{S}) \cdot RED(\mathbf{S}) + F(\mathbf{S}) \cdot ROB(\mathbf{S}) = H_N(\mathbf{S}/\mathbf{S}') = H_N(\mathbf{S}) - H_N(\mathbf{S}') \qquad (6)$$

The concept of integral system safety is an engineering and computational framework for more precise definitions of conditions for evolution of engineering object on the way to safety (Figure 1).

Conditions for Evolution of Engineering Object on the Way to Safety

A. The system uncertainty is increasing by number N of system states indicating system complexity.

B. The operation analysis imposes that the system reliability R(S) is to be as great as possible, which implies:

i. Maximal probability of intact mode $p(S^i)$.

ii. Maximally attainable probabilities of No operational modes $p(S^o)$ in damaged conditions.

C. The failure analysis imposes that the failure probability F(S)=1-R(S) must be low, which implies:

i. Minimal probability of system collapse $p(S^c)$.

ii. Minimally attainable probabilities of N^f failure modes $p(S^f)$.

D. The following requirements are important concerning to system redundancy and robustness:

i. The efficient redundancy RED(S) (1) of the system represents the maximal resiliency that also implies the most uniform distribution of the highest attainable probabilities of most important alternative operational modes in damaged states. It also implies maximally attainable number N^o of operational modes of N possible.

ii. The efficient robustness ROB(S) (2) of the system represents the minimal vulnerability that implies the most uniform distribution of least attainable probabilities of most unfavourable failure modes. It also implies maximal attainable number N^f=N-N^o of failure modes concerning to number N of system states.

The ISS approach enables the definitions of favourable system properties, system configuration evaluation, optimization and decision making in engineering (Figure 1). However, it may impose conflicting conditions on the Reliability, Redundancy and Robustness denoted 3R, requiring multi criterial approach to efficient system performance selection. The design and optimization based on ISS enable system evaluation and selection by adequate distributions of component reliabilities [18-24].

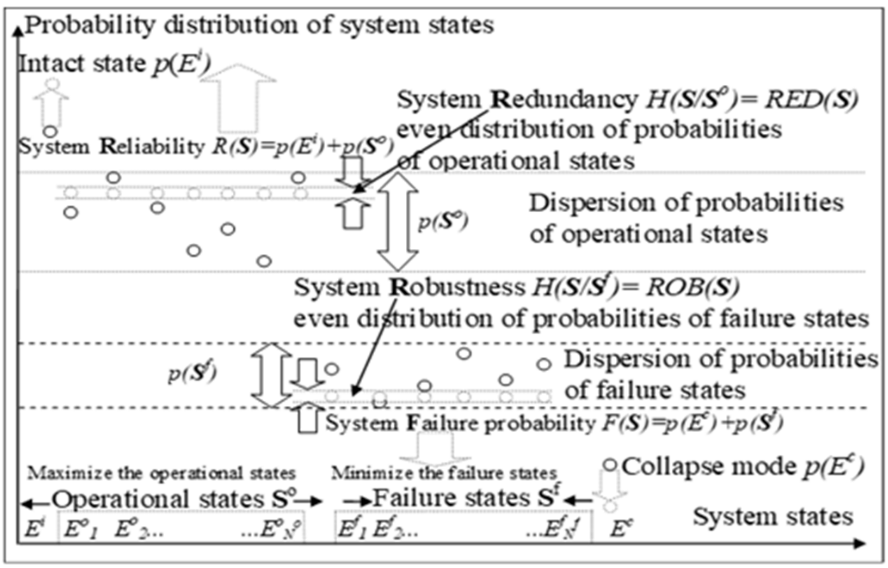

Figure 1: System state probability distributions and definition of favourable system properties.

Conclusion

In uncertain circumstances, there is no absolute safety. Engineering objects evolved arduously on the long and challenging way to safety subjected to continuous balancing with harsh service conditions, high efficiency, affordable costs and levels of socially acceptable safety. Following the long-lasting deterministic concept in engineering, the way to safety was paved by empirical safety assessments and codified factors evolving slowly and painstakingly with a relentless accumulation of practical experiences. The more recent probabilistic system safety concepts lead to the evolution of engineering objects by maximization of system reliability and minimization of failure probability based on statistics and probability theory. The recent concept of integral system opens the avenue to evolution of engineering objects by balancing the uncertainties of operations and failures based on the information theory. It enables multi-criteria decision-making for complex engineering system ordering, optimal member selection, system reliability, redundancy, and robustness optimization as well as compromise solutions. The evolution in this direction may lead to safer, more resilient and less vulnerable objects with increased survival rates. The stay on the way to the safety of engineering objects relies as always on the continuous advances in engineering knowledge, understanding environments, planning and design skills, good workmanship, high-quality materials, responsible management, operations and maintenance.

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