Global Safety Management Method in Complex System Engineering

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Abstract. In System Engineering, one of the most critical process is the requirement management, particularly when it deals with the safety requirements. These one are non-functional requirements and are related to emergent properties, which come from the integration of the different system components. They must be identified as soon as possible, because they are guards to validate or not the system, which can require changes in system architecture. Moreover, they are formulated at system level and need to be declined at sub-system level.

The objective of this paper is to propose a global safety management method based on well-known safety methods, in order to organize the different tasks to make the system safe. The method focuses mainly on the definition of the system safety requirements following risk and hazard analysis, and also on their declination according to a top-down approach. It is based on the famous Failure Mode, Effects, and Criticality Analysis (FMECA) and the use of Fault Trees and Event Trees.

Keywords: Safety requirement ; Requirement engineering ; Complex system.

1 Introduction

Modern systems are increasingly complex [1]. Indeed, they integrate more and more different technologies, offer more functions, and have complex interactions between their components. The processes and the design methods must evolve to reflect this growing complexity [2], [3]. In particular, for our purposes, the management of properties such as reliability or security [4] must evolve accordingly, to ensure and enable the necessary level of confidence [5]. For an effective consideration of safety in the design process, it is necessary to consider safety in overall studies by the engineering system processes. The safety properties must be defined globally ; that is to say elicited [6]. Once these safety properties are identified, they must be declined locally to be actually realized by the system. The local properties associated with subsystems must be satisfied to ensure the global properties, reaching issues of traceability [7], [8] and requirements engineering [9].

Requirements Engineering (RE) is one of the System Engineering (SE) processes. RE is a crucial process within the development of complex system. Safety requirements are classified as non-functional requirements and are related to emergent system properties. They cannot be attributed to a single system component. Furthermost, non-functional requirements are fundamental to determine the success of a system. Two activities are defined in RE. The first one concerns requirements development including the processes of elicitation, documentation, analysis and validation of requirements. The second one concerns requirement management which includes the processes of maintainability management, changes management and requirements traceability.

The work presented in this paper concerns a part of our approach for the integration of safety in system engineering processes [10]. It is an improvement and extension of the method presented in [11], that was inspired from [12] with a engineering process and requirements point of view. The approach allows taking into account the safety requirements in system engineering process to facilitate traceability of these requirements throughout the life cycle of the system. It concerns the two activities of RE: the development and the management activities. The paper presents a method that allows to define, derive and decline system safety requirements, with the combination of several FMECA (Failure Mode, Effects, and Criticality Analysis) [13], Fault Trees analysis [14] and Event Trees analysis [15]. This paper contains four parts. The second one presents the system engineering framework of the method. The third one exposes the method for safety requirement definition and declination, with its different steps. Finally, the last section concludes the paper and presents some perspectives.

2 Context

In this part, the context of our work is exposed. The first section presents the System Engineering notion. Then, the standard that we adopt is presented with its useful concept of building block that devises the design in different system layers. To finish, a focus is done on the safety requirement management.

2.1 System Engineering

System Engineering (SE) is an interdisciplinary approach, whose objective is to assist the development of new systems. It contains collaborative and interdisciplinary processes of resolution of problems, supporting knowledge, methods and techniques resulting from the sciences and experiment to define a system, which satisfies an identified need, and is acceptable for the environment, while seeking to balance the total economy of the solution, on all the aspects of the problem in all the phases of the development and the life of the system. SE concepts are adequate specifically for complex problems [16].

SE is the application of scientific and engineering efforts to:

- Transform an operational need into a description of system performance parameters and a system configuration, through an iterative process of definition, synthesis, analysis, design, test and evaluation.
- Integrate reliability, safety, maintainability, expandability, survivability, human engineering and other factors into the total engineering effort to meet cost, schedule, supportability and technical performance objectives.

SE is the global framework of the approach proposed in this paper.

2.2 EIA-632 Standard

A standard currently used in the industrial and military fields is the EIA-632 standard [17]. Our work is also based on it.

Briefly, this standard covers the product life cycle from the needs capture to the transfer to the user. It is constituted by 13 processes grouped into 5 sets (see Figure 1):

1. Technical management processes (three processes): these processes monitor the whole process ranging from the initial idea to building a system until the delivery of the system.
2. Acquisition and supply processes (two processes): these processes ensure the supply and acquisition (and are very close to logistics).
3. System design processes (two processes): these processes deal with the elicitation and the acquisition of requirements and their modelling, the definition of the logical design and its physical solution.
4. Product realization processes (two processes): these processes deal with the implementation is-sues of the system design and its use.
5. Technical evaluation processes (four processes): these processes deal with verification, validation and testing issues.

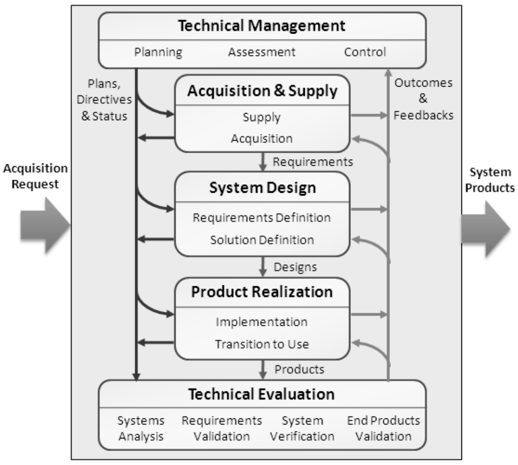


Fig. 1. EIA-632 Standard System Engineering Processes

2.3 Building Block Concept

The EIA-632 standard adopts an original and interesting system decomposition based on the concept of "building block". A building block is the association between one (or several) final product and a set of enabling products, as shown in Figure 2.

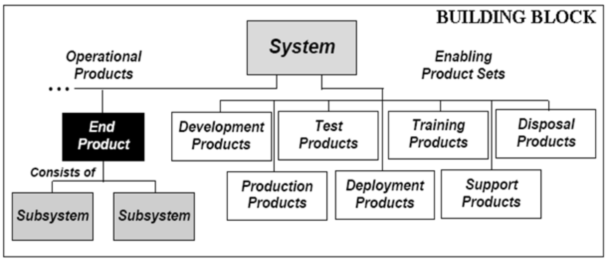


Fig. 2. One Building Block

In fact, the system is seen as a hierarchy of building blocks. The solutions defined in the upper layer (level) blocks, described by a set of specified requirements, are allocated as input requirements for the lower layer blocks (see figure 3). Finally, the building block decomposition is stopped when blocks correspond to on-the-shelf components or when their realization can be subtracted. With this description, we identified the need of deriving the safety requirements through the hierarchical decomposition.

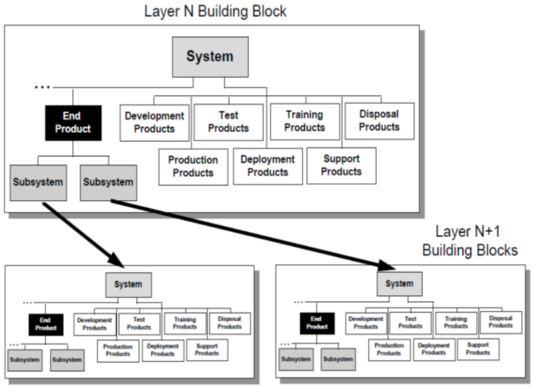


Fig. 3. Multilayer building block

2.4 Safety Requirement Management

To clearly situate the position of the method for deriving safety requirements, the Figure 4 gives an overview of the involved EIA-632 system engineering processes.

Among the different possible sources of safety requirement we can find the requirement provided by some dependability analysis as shown in the Figure 4. In this paper we consider this source of requirements. The proposed approach is used to define, derive and decline safety requirement with different safety analysis.

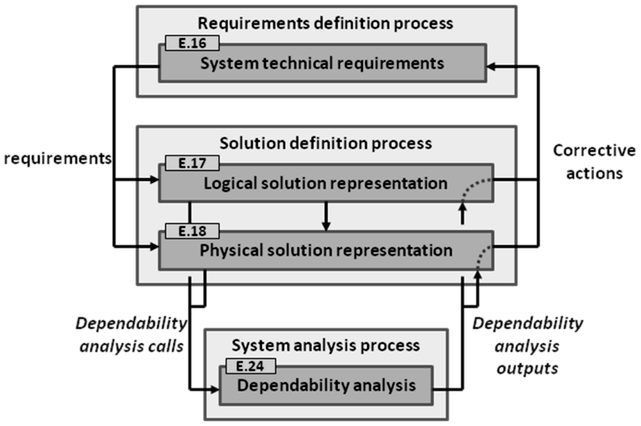

Requirements definition process
E.16
System technical requirements
Solution definition process
E.17
Logical solution representation
E.18
Physical solution representation
requirements
Corrective actions
Dependability analysis calls
Dependability analysis outputs
System analysis process
E.24
Dependability analysis

Fig. 4. Dependability analysis as a source of requirements

3 Global Safety Management Method

In this second part, the global safety management method is presented. First, an overview of the method is given, following by an explanation about the different kinds of safety requirements that are taken into account in the current version of the method. Afterwards, the 9 steps of the method are explained in details.

3.1 Overview

The method assumes that a complex system is composed of some subsystems (the principle of Building Block of the EIA-632 standard). It combines FMECA, fault trees and event trees, and has the objective to define all safety requirements at system level and to decline them locally at subsystems level with a goal of traceability. The Figure 5 summarizes the process associated to the method and illustrates how the different steps are integrated together.

3.2 Classification of the considered Safety Requirements

The method enables to identify and deals with several kinds of *safety requirements*. We have classify these requirements into subcategories, which are :

- *Reliability requirement*, that claims a quantitative objective in term of reliability properties.
- *Architectural requirement*, that defines an architectural design to deal with safety (like redundancies).
- *Active functional security requirement*, that is related to an additional security equipment (protective barrier) that can participate to reduce the probability of an accident.
- *Passive functional security requirement*, that is related to an additional protective or mitigation equipment that can reduce the severity of an accident.

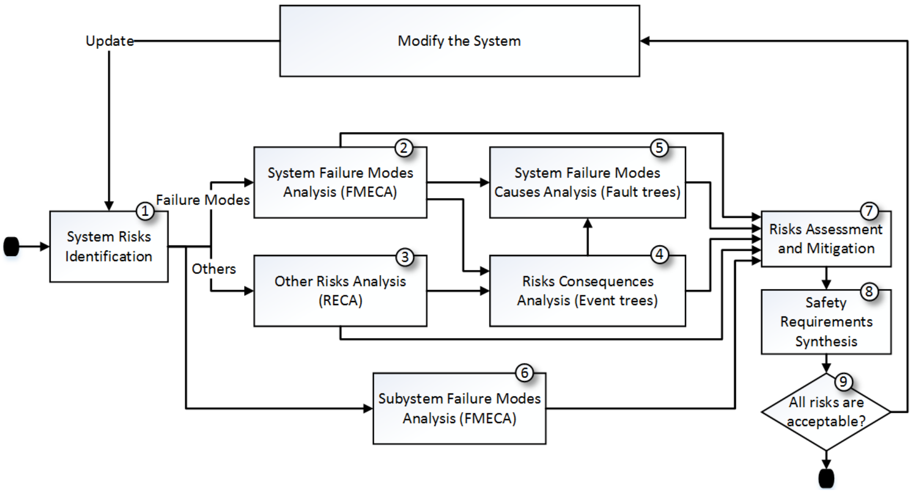

Update
Modify the System
System Failure Modes Analysis (FMECA)
2
System Failure Modes Causes Analysis (Fault trees)
5
Failure Modes
1
System Risks Identification
Others
Other Risks Analysis (RECA)
3
Risks Consequences Analysis (Event trees)
4
Risks Assessment and Mitigation
7
Safety Requirements Synthesis
8
Subystem Failure Modes Analysis (FMECA)
6
All risks are acceptable?
9

Fig. 5. Overview of the global safety management method

3.3 Step 1: Risks Identification

The first step is to identify and classify all the system risks. These can be human actions, external failures, internal failures (those of the system) or environmental conditions. The classification must be done in two groups: the risks representing internal failure modes and the other risks.

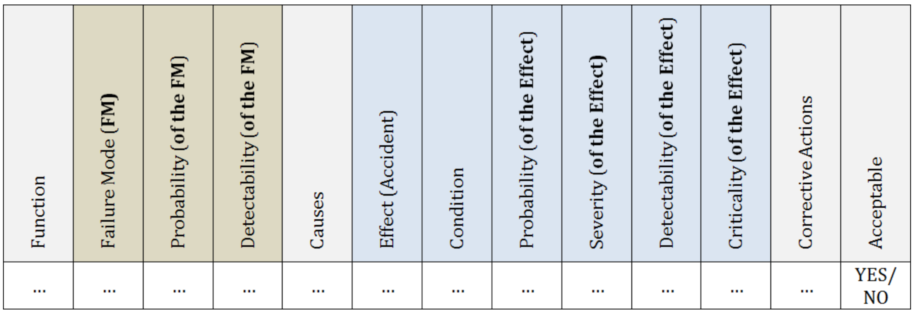
3.4 Step 2: System Failure Modes Analysis

The second step is to begin the analysis of risks that correspond to system failure modes. The recommended method is the FMECA [13], that is a technique used to identify, prioritize, and eliminate potential failures from a system, a design or a process. Concretely, this step is to complete few columns of the FMECA table (others than severity, probability, criticality and corrective action) (see Table 1). For each system function, we identify failure modes, causes of these modes and effects on the system (possibly depending on the phase, state or mode). For the identification of failure modes, lists of generic modes have been defined in some standards like CEI 60812: 1985 [18]. The effects are here the potential accidents.

In fact, we also propose some changes in the classical FMECA to clarify the method, visible in the Table 1. A distinction is made between the probability and the detectability of the failure modes and those of the effects. Indeed, between a failure mode and an effect (accident), there is a set of involved cofactors (protection barrier, environmental condition ...), recorded in the "condition" column of the table. These conditions will be identified during the step of consequences analysis.

The assessment of the probability of the risk and the assessment of the severity, probability and criticality of the effect will be done during the step of risk assessment. The corrective actions will be proposed at the risk mitigation step.

Table 1. FMECA table

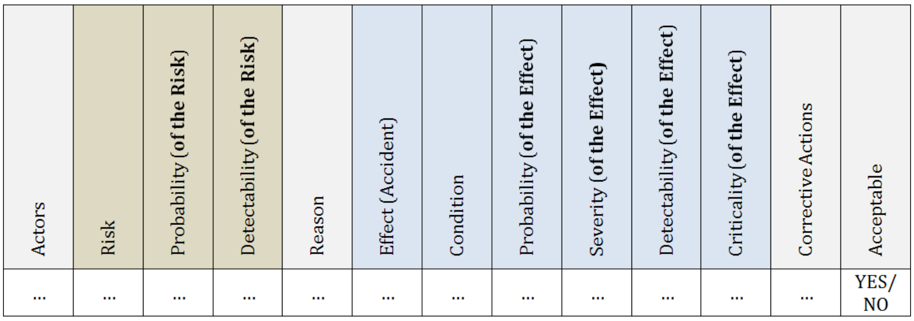


Function	Failure Mode **(FM)**	Probability **(of the FM)**	Detectability **(of the FM)**	Causes	Effect (Accident)	Condition	Probability **(of the Effect)**	Severity **(of the Effect)**	Detectability **(of the Effect)**	Criticality **(of the Effect)**	Corrective Actions	Acceptable
...	...	...	...	...	...	...	...	...	...	...	...	YES/ NO

3.5 Step 3: Other Risks Analysis

This step is similar to the previous step of system failure modes analysis, but focuses on the other risks (external). The recommended method is to use the principle of an FMECA, that we can call here RECA (Risks, Effects, and Criticality Analysis) (see Table 2). This step is to complete few columns of the RECA table (others than severity, probability, criticality and corrective action). The effects are also the potential accidents.

Table 2. RECA table



Actors	Risk	Probability **(of the Risk)**	Detectability **(of the Risk)**	Reason	Effect (Accident)	Condition	Probability **(of the Effect)**	Severity **(of the Effect)**	Detectability **(of the Effect)**	Criticality **(of the Effect)**	Corrective Actions	Acceptable
...	...	...	...	...	...	...	...	...	...	...	...	YES/ NO

The same remarks as for the FMECA remain true concerning the probability, the detectability and the severity of the failure modes and the effects, and the conditions.

3.6 Step 4: Consequences Analysis

In this step, the consequences of all the identified risks (system failure modes and others) must be analysed. This step is to identify how the risks contribute to an accident. It can be done using event trees [15] to visualize the possible chains of events that led from the risk to the accident, through branching points representing protective measures or interventions (cofactors) (see Figure 6). The minimal cuts associated with the various accidents are also identified.

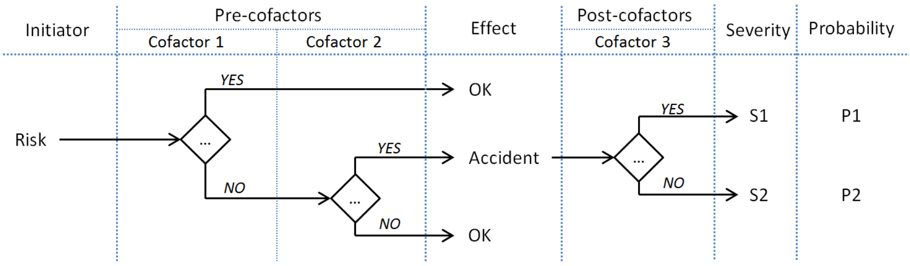


Fig. 6. Event tree

A generic example is given in Figure 6. The effects correspond to accidents, whereas the term consequences refers to events or factors involved in the causes to consequences relationship, starting from the analysed risk.

3.7 Step 5: Causes Analysis

The fifth step is to conduct an internal analysis of the system by identifying the causes of system failure modes. These causes analysis must lead to subsystems failure modes. For this step, the use of fault trees [14] is recommended. Indeed, a fault tree provides a simple modelling way to represent the interactions between components from the point of view of reliability. Static fault trees use traditional Boolean logic functions to represent the combination of component failures (events) that cause system failure.

So, the top event of each tree corresponds to a system cause. The objective is to determine the causes of the top event (using logical operators such as AND and OR) in the sub-systems. The leaves of the fault tree correspond to sub-systems failure modes (see Figure 7).

In fact, the system failure modes analysed correspond either directly to a system risk (defined in the first step), or to a cofactor of an event tree which is a system failure mode.

3.8 Step 6: Sub-systems Failure Modes Analysis

An analysis of the subsystems failure modes should be leaded in parallel, using FMECA. The subsystems failure modes used in step 5 re-appears (the principle of the FMECA analysis). This FMECA will define the corrective actions at the sub-systems level that are representative of subsystem reliability requirements.

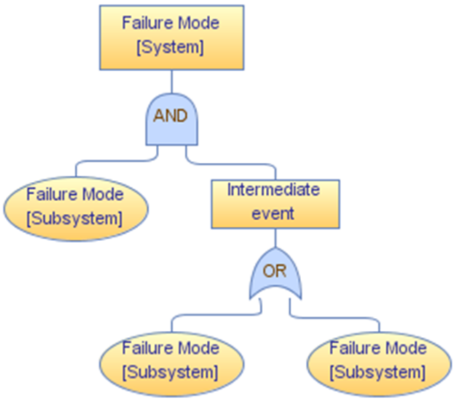


Fig. 7. Fault tree

3.9 Step 7: Risks Assessment and Mitigation

The seventh step is the central one. It deals with risks assessment and risks mitigation with definitions of corrective actions.

Assessment The risk assessment consists in defining the severity and the probability of the identified accidents, in order to evaluate the criticality. This information must be recorded in the various FMECA and the RECA tables. Concerning the probability, this one must be evaluated based on the fault trees and the event trees. Finally, it must be decided whether the risks are acceptable or not.

Mitigation The risk mitigation consists in advocating corrective actions (to be filled in the FMECA and the RECA) for the risks qualified as "non-acceptable" during the risk assessment step, in order to make them become "acceptable". The corrective actions can:

- Reduce the *probability* of the accident, by:
  - Fixing an *objective of reliability* with a *reliability requirement* (at system or subsystem level).
  - Modifying the system architecture for a better reliability (with redundancies for example) with an *architectural requirement*, that derives from the *reliability requirement* of the *objective*.
  - Adding an additional security equipment (protective barrier) with a *active functional security requirement*, that derives from the *reliability requirement* of the *objective*. During the next iteration of the method, reliability requirements will be defined for this security equipment based on the analysis of the failure modes in which it participates.
- Try to satisfy a *criterion*, for example:

- A *single failure criterion*, adding a security equipment (barrier) to increase the number of failures before the occurrence of an accident, with an *active functional security requirement*.
- A *spatial dispersion criterion*, with an *architectural requirement*.
- A *redundancy with separate development criterion*, with an *architectural requirement*.

– Reduce the *severity* of the accident

- Adding a protection or mitigation equipment, with an *passive functional security requirement*.

Note: This is not the only possible corrective actions (preventive maintenance for example). Other types of corrective actions will be incorporated in future work to improve the process.

3.10 Step 8: Safety Requirements Synthesis

Before eventually transferring the change requests to modify the system, this step will summarize the results in terms of requirements, declination of requirements, and traceability links between requirements and accidents, or requirements and requirements. As in the first version of the method [11], the declination part is based on the following 3 types of relations:

– System causes and system corrective actions,
– System causes and sub-systems failure modes,
– Sub-systems failures modes and sub-systems corrective actions.

A generic example of this synthesis is given in Figure 8.

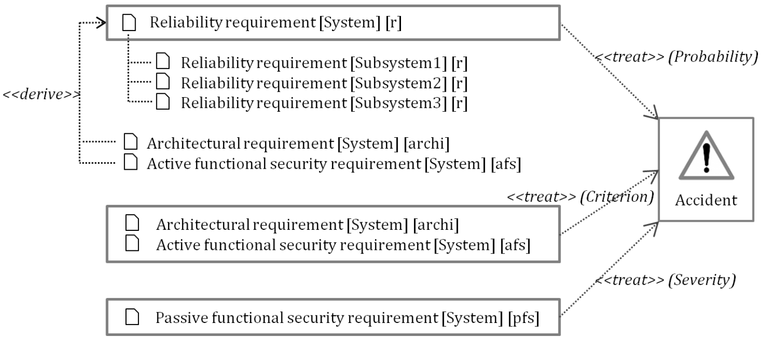

Reliability requirement [System] [r]
Reliability requirement [Subsystem1] [r]
Reliability requirement [Subsystem2] [r]
Reliability requirement [Subsystem3] [r]
<<derive>>
Architectural requirement [System] [archi]
Active functional security requirement [System] [afs]
<<treat>> (Probability)
Accident
<<treat>> (Criterion)
Architectural requirement [System] [archi]
Active functional security requirement [System] [afs]
<<treat>> (Severity)
Passive functional security requirement [System] [pfs]

Fig. 8. Requirements traceability synthesis

3.11 Step 9: Stop Criterion

The process is finish once all the risks are considered as "acceptable". If this is not the case, a change request must order to modify the system and the method must be reapplied from the beginning by updating the different analysis.

4 Conclusion

The method provides a support framework to define system safety requirements with an objective of traceability and requirements declination and derivation. The interest is multiple for the safety field: the method deals with the safety elements (failure modes, safety requirements...) and it is done with a comprehensive system engineering (with traceability and requirements declination) which is a factor contributing to safer systems. This method is compatible with the standard EIA-632 [17], and it extends the principle and strengthens the links between failure modes researches and analysis (FMECA), causes analysis and effects analysis.

In this work, several safety attributes are taken into account, like reliability, passive security and active security. They correspond to the given classification of safety requirements, which are themselves defined from the corrective actions. Other requirements concerning maintainability or availability should also be considered in further study. The probability, the severity and the criticality was treated through the FMECA. However, the work still doesn't consider the detectability aspect. We also should update the tool that implements the first version of the method presented in [11].

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