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A quantitative approach to risk management in Critical Infrastructures

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Abstract

In the last ten years, an efficient Security Management System (SEMS) has acquired an important role for organizations working in transportation sector. In many cases, Critical Infrastructure legislation plans specific and mandatory quality requirements for the implementation of a security management system. The organizations are encouraged by the legislative requirements and the competitiveness to certify the SEMS in accordance with the current international standards (e.g. ISO 27001 and ISO 28000). As well known, certification can be either a mandatory or a voluntary process but it is usually voluntary and qualitative. In the SEMS, as in other management systems, current certification uses a qualitative approach deriving from the ISO 9000. Normally in certification, quantitative assessment characterizes only some technological systems while every other application including human factor or procedures uses qualitative assessment. The development of security management system certification should bring to introducing risk-based and quantitative assessment methods. Benefits arising from the residual risk quantification of the SEMS can set certification a tool enabling to bargain with insurances, a warranty for the investments undertaken when facing stakeholders and shareholders, a proof to justify decisions during a legal action and last but not least a good publicity for company's image and hence company's competitiveness. This paper proposes the implementation of risk-based methodologies in use by process engineering to achieve a quantitative assessment of security management systems. The methodology is exposed and applied to a railway case study. The first steps show how to analyze the system (study of macro operability functions, identification of subsystems, etc.) and how to integrate technological, human and procedural aspects by flow charts. The later steps describe how to manage threats, vulnerability and criticality of Critical Infrastructure subsystems and how to identify "primary causes" and "Top Event consequences" drawing fault trees and event trees, and finally how to calculate the residual risk for security management system. In conclusion, the methodology is applied on a case study of one railway subsystem and the results of the quantitative risk analysis are exposed.

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1. Introduction

The risk management of Critical Infrastructure is taking an increasingly important role. Whether at first, the demand of risk management turned to provide safe services against technological failure (safety), in the last ten years, security and natural disasters have significantly expanded its purpose. The international authorities, at different levels, decided to address the problem through a standardization of procedures for risk analysis and assessment. The latest decisions of the Europe Union (2008) and the Europe Commission (2012) and the introduction of specific international standards of risk management underline this common policy (ISO/IEC 27001, 2013; ISO 28000, 2007; ISO 31000, 2009).

The risk measurement refers to the well-known expression:

$$\text{Risk} = \text{Treat} \times \text{Vulnerability} \times \text{Consequence} \quad (1)$$

where the risk R is the product of the probability of occurrence of the threat T, the vulnerability V (i.e. the probability of fulfillment the threat) and the damage caused C. In case of natural and intentional threats, the probability of occurrence T is a variable difficult to evaluate because strongly dependent by external factors not always predictable. The hazardous weather events have very complex dynamic and it is difficult to obtain a long-term forecasting reliable enough. Similarly, the intentional threat, being a deliberate action, depends on time changing socio-political context and opponent utility therefore, also in this case, are difficult to predict (Bier et al., 2005; McGill et al., 2007). In risk assessment, apart from technological failures, the threat is often an element of great uncertainty requiring hypothesis assumption and/or different scenarios to study.

In risk analysis and in risk assessment, there are international standards indicating qualitative, semi-quantitative and quantitative approaches, but in practice, the most used methods are qualitative or semi-quantitative. This aptitude is greater when the Critical Infrastructure analysis regards a large number of factors such as technological systems, human factor and procedures. In this case, the most used approach is the semi-quantitative using ad-hoc evaluation tables to rate threat, vulnerability and consequence by brainstorming activity. This method does not allow an effective risk management because it is difficult to detect and measure assessment errors.

The European Union demanding to introduce methods for quantitative assessment of the safety level emphasized this problem in the context of rail traffic. Complying with this request, Cesario et al. (2008) presented an analytical method for the quantitative assessment of the safety level in railway transportation. This paper deals the general problem of risk management in Critical Infrastructure. Section 2 presents a methodological approach for risk management: the first part introduces the techniques used to model the Critical Infrastructure and carry out the risk analysis while the second part describes the Alarm & Intervention Management System (AIMS) analysis and the vulnerability assessment. In section 3 the key steps of methodology are applied on a railway case study and finally the results of the quantitative risk assessment are presented.

2. Quantitative Evaluation Methodology for Risk Management

This section presents the main features of the methodological approach aimed at a quantitative risk assessment: the process and functional analysis of Critical Infrastructure and the evaluation of risk management system. Figure 1 shows the quantitative assessment scheme in the risk management process, which is briefly described from step 1 to step 6 in section 2.1.

The aim of the methodology is to quantify the risk in all processes and operations that compose the core business of the system under analysis. Among the given techniques for quantitative risk assessment of ISO 31010 (2009), Process Flow Diagram (PFD) and Enhanced Functional Flow Block Diagram (EFFBD) are used to model the

Critical Infrastructure (see step 1 and step 2 in fig. 1). Then, specific loss parameters are drawn up on the Critical Infrastructure to allow the identification of threats for each critical assets (see step 3 in fig. 1).

Following the threat assessment, the Recursive Operability Analysis (ROA) of the Critical Infrastructure allows the assessment of consequences and the Fault Tree and Event Tree drawing (see step 4 and step 5 in fig. 1). In conclusion, the effectiveness assessment of Alarm & Intervention Management System (AIMS) which also include the human behavior factor, completes the risk quantification (see step 6 in fig. 1).

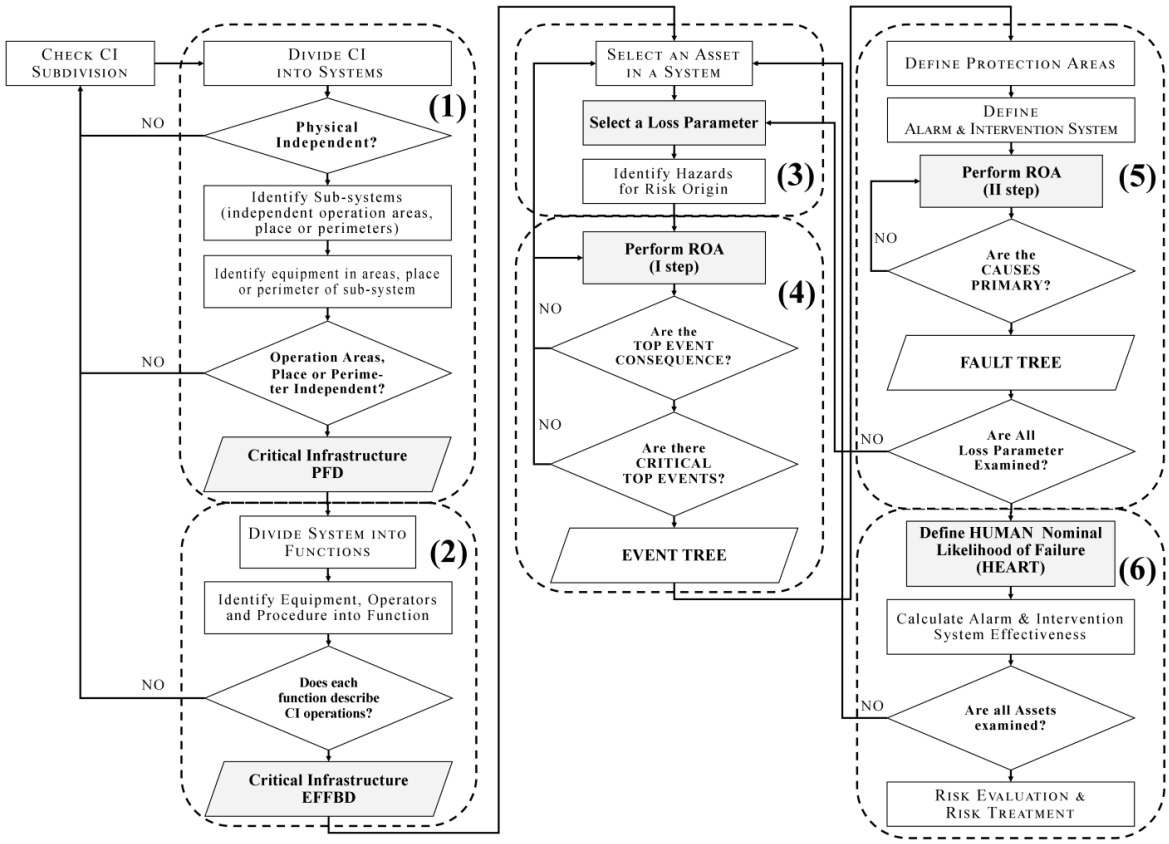


Fig. 1. Flow diagram of risk analysis methodology for a quantitative assessment

When multi-risk analysis is required for situation where technological systems, human factors and procedures coexist, the methodology runs as a decision-making tool, which can be adaptable in any context (e.g. transport, e-commerce, energy, etc.).

In addition, the multi-scenarios approach allows the definition and the assessment of protection system in different configurations in relation to the safety/security level required (e.g. ISPS Code).

2.1. Quantitative Risk Management Procedure

The Critical Infrastructure analysis, developed through consecutive steps, is aimed at creating a physical and functional model and represents an essential task for a correct identification of assets and threats. Starting from step 1 (see fig. 1), the Critical Infrastructure (CI) is divided into physical and independent systems in order to obtain a complete model of the core-business dynamics by means of a Process Block Diagram (Towler and Sinnott, 2013).

Dividing the Critical Infrastructure into subsystems by areas, places and perimeters operating independently, the CI model allows the identification of the elements required by the different processes and the physical interconnections between the various system structures. Drawing the Critical Infrastructure PFD permits a manageable representation of the core assets and their connections. Using the Enhanced Functional Flow Block Diagram – EFFBD (NASA, 2007), step 2 (see fig. 1) concerns a functional analysis of the subsystems aimed at identifying the elements required in order to carry out correctly the core-business processes. The EFFBD studying and analysing the functions of each CI process in detail, including procedures and human behaviour, completes the CI model. Based on the PFD and EFFBD, the next steps (see 3, 4 and 5 in fig. 1) concern the Recursive Operability Analysis (ROA) of the Critical Infrastructure. Among the operability analysis methods, the decision was taken to use the ROA because it allows the fault tree and event tree drawing in a simply way for each type of risk analysed (Piccinini and Ciarambino, 1997; Demichaela and Tamasi, 2011). In this methodology the ROA is performed by three consecutive stages: the first (step 3) identifies the threat that is analysed through ROA in the following two stages to put out Top Event (step 4) and Primary Causes (step 5).

On the experience of BS 7799, specific loss parameters were opportunely defined (step 3) to carry on the ROA and identify the threats by the analysis of "initiating events" or process "deviations":

- *Integrity Loss:* the asset is no longer available.
- *Compliance Loss:* the asset is available but its features do not correspond to those expected from the process or function.
- *Confidential Loss:* the asset confidentiality is broken without causing a loss integrity or a compliance loss.

The European Union (2008) recently recommended that the risk analysis of Critical Infrastructure should consider terrorism, sabotage and vandalism, theft of sensitive information or natural disaster by a multi risk approach. Therefore, the methodology proposes to split the risk causes into three appropriate categories: intentional attack, technical failure and environmental event. The "initiating events" are set out for each risk category analysing each asset by the loss parameters. In step 4, starting from the initiating events the ROA identifies the consequence top event and allows the Event Tree drawing for every asset threatened. The Top Event severity evaluation considers the consequence C from an economic point of view and in terms of loss of human life. It allows for each asset the identification of critical consequences and for which one the need is of risk management.

In step 5, the ROA identifies the "primary causes" of the threats. Based on PFD and EFFBD of Critical Infrastructure, the ROA allows setting and modelling the Alarm & Intervention Management System (AIMS) through the definition of the asset protection areas.

A protection area comprises alarm systems and protective devices in defence of a particular target and its crossing needs to carry out an attack or in general a threat. Consecutive physical and/or logical protective devices (e.g. barriers, access doors, access systems with identification keys, etc.) delimit consecutive protection areas. Referring to intentional threats, the probability of intercepting an opponent before that it reaches its target can change from one protection area to another. Therefore, the outputs of alarm systems (e.g. motion sensors, video cameras monitoring, etc.) are uniquely associated to the own protection area. This step is useful to define the configuration of alarm systems, protection devices and communication systems that make up the Alarm & Intervention Management System (AIMS).

The definition of operator activities, operator responsibilities and system procedures performed after setting the AIMS technological components complete the AIMS modelling. Step 5 establishes by Recursive Operability Analysis the "primary causes" (as process deviations) leading to the failure of one AIMS macro-function:

- *Recognition.* The alarm system and the operator correctly detect the threat.
- *Warning.* The threat presence is pit off to operators responsible to interception.
- *Interruption.* Procedures and operations required to intercept the threat before that was full-finished.

Then, the ROA allows the Fault Tree drawing of the "primary causes" underlining the failures of the Alarms & Intervention Management System and the assessment of the AIMS effectiveness and risk for Critical Infrastructure (step 6).

The eq. (2) assumes the vulnerability of Critical Infrastructure is equal to the AIMS vulnerability (Dessert, 1987; McGill et al., 2007):

$$V = \left(1 - E_{AIMS}\right) \tag{2}$$

where: $E_{AIMS} = P_I \, P_{N|I}$
P_I = probability of interruption
$P_{N|I}$ = probability of neutralize the threat given interruption

Assuming the probability of interruption P_I is equal to the reliability R_{AIMS} of the alarm and intervention system ($P_I = R_{AIMS}$), the assessment requires to consider the human behaviour component and to quantify the Human Error Probability (HEP). The authors decided to assess the human behaviour with the HEART method (Kirwan, 1994; Salmon et al., 2003). The HEART method, used in nuclear power plants and chemical processing industry, estimates the human error probability on eight task categories (from not-totally familiar to highly automated) by parameters of Error Producing Condition (EPC). The EPC parameters allow the assessment of the human reliability depending on different operability conditions. Hence, the AIMS reliability results equal to the reliability of the macro functions: Recognition and Warning.

The probability of interruption given neutralize the threat $P_{N|I}$ is the probability that the response time is less than the time needs to the threat to reach their target and hence it results equal to the reliability of the Interruption macro function. Therefore, the vulnerability V needs the evaluation of P_I and $P_{N|I}$ for each asset.

The quantification of different threat scenarios completes the risk assessment by defining the probability of occurrence T. For environmental threats, drawing up scenarios based on "experiential learning" is appropriate. Similarly, for intentional threats, the study of reference scenarios (in stationary socio-political environment) and additional scenarios based again on "experiential learning" is appropriate. Analysing various threat scenarios allows the evaluation of different risk management configurations that could be adopted (in operation) in relation to the socio-political evolution. In some cases, specific intentional threat scenarios could define the $P_{N|I}$. For instance, doors or windows with a burglary resistance certification (UNI EN 1627, 2011) bring to assume the probability of attack by an expert adversary T_{Exp} equal to the interruption failure ($1- P_{N|I}$) (see case study for details).

3. Case Study

3.1. Railway Analysis

In this section, the methodology described above applies to a railway infrastructure. The PFD of railway infrastructure (see fig. 2) consists of 11 systems (operating independently). Each system is split into subsystems by areas, perimeters and places considered operationally independent and analysed for subsequent levels. In figure 2 "boxes" and "cylinders" represent systems with sub-systems: the "boxes" identify the railway infrastructure systems, while the "cylinders" the management and remote monitoring systems.

A code identifies each subsystem in order to have an easier reading of the diagram (e.g. P- 7.1.1 - Overhead Line Station: "System ID" . "First level subsystem ID" . "Second level subsystem ID"). The bold arrows represent the flow of the elements (3kV DC - power energy, passengers, rolling stock & locomotives) powering the Train system (P- 6.0) and providing the railway transport. Instead, the dotted arrows represent the flow of data and information that allow managing and controlling the transport service: power electric system data; rail traffic data; driver-dispatcher communication; signalling data; ticket data and transaction data. The interaction between the Train system (P- 6.0) and the Railway Line system (P- 7.0) carries out the railway service (see fig. 2 - arrow interconnection between box P- 6.0 and P - 7.0). The PDF elements identify the assets of the railway infrastructure.

The functional study allowed the identification of the existing logical connection between technological systems, operators and procedures, and similarly by the EFFBD the flow dependence between subsystem/subsystem and system/system visible during operations.

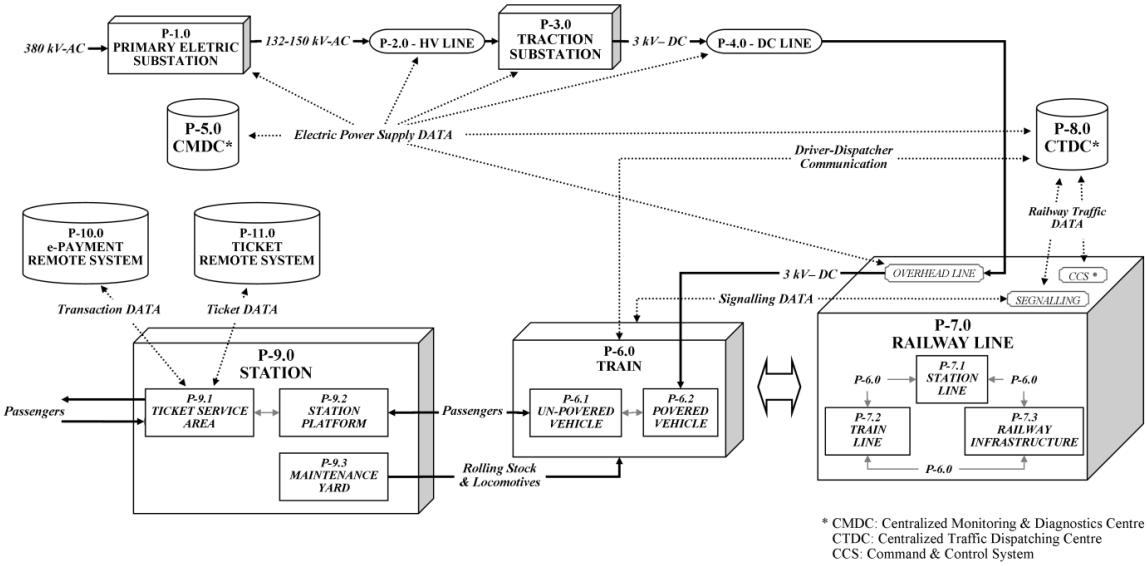


Fig. 2. PFD of Railway Infrastructure

3.2. Risk Assessment

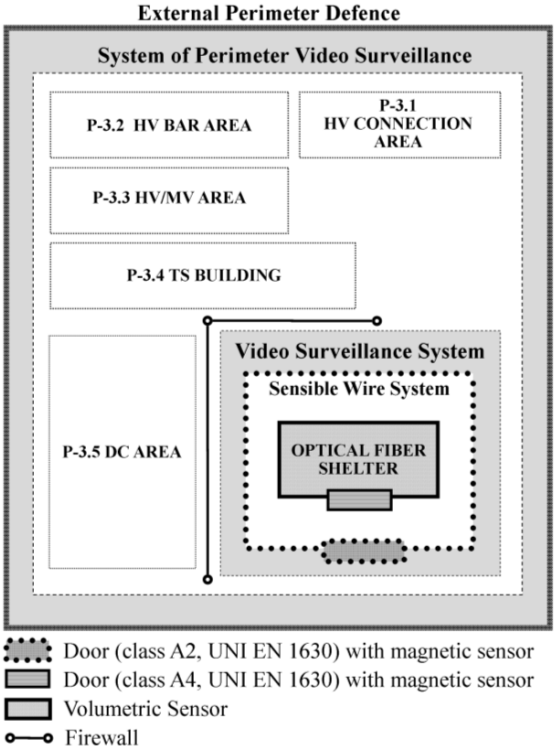
This section presents the results of the risk assessment of the optical fibre shelter (P-3.6) inside the Traction Substation system (P-3.0). In some cases, the optical fibre shelter receives telecommunication equipment and the Central Automation Unit (CAU) necessary to the functions of Command & Automation and Control & Command; hence, it represents a critical asset of the Traction Substation system.

Table 1. Initiating Event for Shelter Optical Fibre

LOSS PARAMETER	RISK CAUSES	INTIATING EVENT
INTEGRITY LOSS	Intentional Attack	Arson
		Bomb
		Operative Equipment Theft
	Technological Failure	Short Circuit
	Environmental Event	Overflowing
COMPLIANCE LOSS	Intentional Attack	Sabotage Air-conditioning System
	Technological Failure	Air-conditioning System MI
	Environmental Event	Overflowing Air-conditioning System
CONFIDENTIAL LOSS	Intentional Attack	In Store or Stand-by Equipment Theft

Table 1 reports the initiating events identified applying the loss parameter (integrity, compliance, confidential) for each category of risk causes.

Figure 3 shows the configuration of alarm systems and protection devices used in the optical fibre shelter and the corresponding values of probability of failure *F* and burglary delay time.



ALARM SYSTEMS	F
TVCC Equipment	5,89E-05
Video-elaboration System	6,47E-07
Magnetic Sensor	4,52E-04
Volumetric Sensor	6,52E-04
Microwave Sensor	1,45E-03
Sensitive Wire Alarm	5,50E-04
Communication System	4,19E-04
Remote Server	1,24E-07
Emergency Communication	6,47E-07

PROTECTION	Burglary Delay
External Perimeter	-
Door — A2	3 min
Door — A4	10 min

Fig. 3. Optical Fibre Shelter (P-3.6) Alarm & Protection System

The four protection areas comprise: the perimeter video surveillance of TS; the fixed video surveillance of optical fibre shelter; the alarmed enclosure around the shelter and the access to the shelter (port class A4) with magnetic and volumetric sensors. The Recursive Operability Analysis of AIMS (see section 2.1) identified top events and primary consequences. Figure 4 reports the results of the ROA only for "initiating events" due to an intentional attack and referring to the loss parameter of "integrity" (see Table 1).

The ROA identified four Top Event consequences: Loss-3.6 P & Service Continuity (see TE-1 in fig. 4), Loss-3.6 P & Train Delay (see TE-2 in fig. 4), Loss P-3.6 and P-3.5 & Service Continuity (see TE-3 in fig. 4), Loss P-3.6 and P-3.5 Train Delay (see TE-4 in fig. 4).

The Fault Tree in figure 4 evaluates the effectiveness E_{AIMS} of AIMS. The assessment assumed the probability of Protection System Failure equal to (1- $P_{I|N}$) and the response time of the guards equal to 5 minutes from the warning time. The burglary delay time of the protection systems (doors, windows and barriers) was evaluated in function of the opponent experience on the burglary classes from 1 to 6 (UNI EN 1630 , 2011). The protection devices system (see fig. 3) has a burglary delay time of 13 minutes for inexperienced opponents (class 2) and 10 minutes for experienced opponents (class 4). The intervention could fail when the opponent is very experienced (class 5 and 6) and consequently $P_{I|N}$ = (1 - $T_{Att.EE}$). Considering the event probability $T_{Att.EE}$ of a very experienced opponent unlikely, the effectiveness E_{AIMS} of AIMS is assumed approximately equal to the reliability R_{AIMS} of AIMS ($E_{AIMS} \approx R_{AIMS}$).

The probability of security operator failure (see grey box in fig. 4) appeared the critical element for the reliability assessment of the Alarm & Intervention Management System, despite the assessment considered an Intelligent Supervision System (ISS) supporting the security operator task.

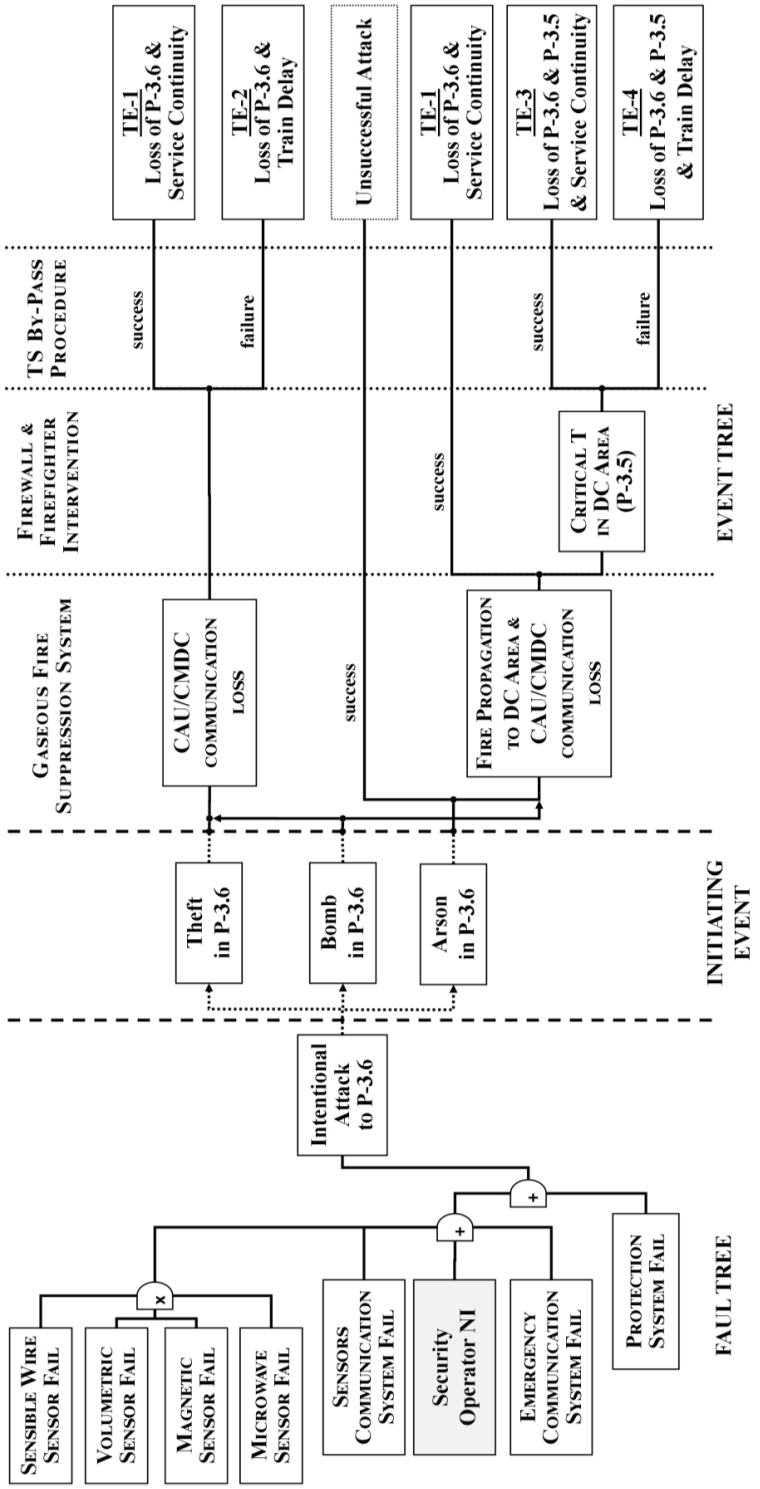


Fig. 4. Bow-tie Diagram for Intentional Attack – Arson in P-3.6

The eq. (3) was used to calculate the reliability R_{SO} of security operator assisted by an ISS using the method of conditional probability:

$$R_{SO} = \{R_{SO},\ ISS\ Run\} \cdot R_{ISS} + \{R_{SO},\ ISS\ Fail\} \cdot (1 - R_{ISS}) \quad (3)$$

The reliability R_{ISS} of the Intelligent Supervision System (ISS) refers to the eq. (4) where the ISS comprises a pre-Alarm System (p-AS) and a CCTV system (CCTV) placed in series.

$$R_{ISS} = R_{p-AS} \cdot R_{CCTV\ System} \quad (4)$$

where: $R_{p-AS} = \left(1 - F_{Mgn} \cdot F_{Vol}\right) \cdot R_{Sen.Wire} \cdot R_{microWire} \cdot R_{RemoteServer} \cdot R_{Comm}$

$$R_{CCTV\ System} = R_{Camaras} \cdot R_{Video-elab} \cdot R_{RemoteServer} \cdot R_{Comm}$$

The HEART method made possible to quantify both with and without the supervision system the reliability of the security operator (on the recognition and warning macro functions). The security operator task was considered being part of the group G and six different Error Proceduring Condition (EPC) parameters were picked and chosen to evaluate the operator reliability loss (Kirwan, 1994). An engineer POA was estimated for each EPC both for the scenario of ISS in operation and ISS failure.

Figure 5 shows the six EPC and engineer POA associated for both operating scenarios.

Type of task	G
Nominal Human Reliability	0,0004

Error Producing Condition	Total HEART effect	Engineers POA with supervision system	Engineers POA without supervision system	Assessed Effect with supervision system	Assessed Effect without supervision system
Shortage Time for Error Detection & Correction	11	0,2	0,4	3,00	5,00
Non-redundant Information	6	0	0,8	1,00	5,00
Risk Misperception	4	0,2	0,5	1,60	2,50
No Clear, Direct & Timely Confirmation of Intended Action	4	0,2	0,6	1,60	2,80
SO Inexperience	3	0,2	0,6	1,40	2,20
Distraction	1,8	0,8	0,2	1,64	1,16

	Reliability	Human Error Probability (HEP)
SO with supervision system	0,99294	7,05E-03
SO without supervision system	0,82136	1,79E-01

Fig. 5. Security Operator Reliability (HEART Method)

The HEART method quantified in 7.05 E-03 the human error probability of the security operator with ISS in operation. While for the ISS failure scenario the human error probability increased to 1.79 E-01. From the eq. (3), the reliability R_{OS} of security operator is 7.64 E-03. The reliability R_{AIMS} of AIMS derives from the Fault Tree of figure 5 and results equal to 8,06 E-03 ($R_{AIMS} \approx E_{AIMS}$).

4. Conclusions

The methodology presented underlines how the reliability (effectiveness) of AIMS is deep-influenced by the human error probability. Despite the positive effects of the Intelligent Supervision System (ISS) on the human task reliability, a high level of AIMS reliability R_{AIMS} (effectiveness E_{AIMS}) could be reached or duplicating the operator number (redundancy) on critical tasks and functions or using full-automated systems.

However, the replacement of human functions with technological systems is not always an achievable goal. In this context, the decision making of risk management (in terms of technology allocation, responsibility and functions) becomes a strategic task for the Critical Infrastructure managers whether they want to reduce the vulnerability of their organization. This paper presents a method of risk analysis and assessment responding to the decision-making needs (Mora et al., 2003). The method allows developing an integrated analysis of the elements an organization comprises (technological systems, procedures and human factor) through a multi risk analysis aimed at assess technological failure, intentional attacks and natural disasters. This allows evaluating, for instance, the effects of the security systems on safety and vice versa.

The methodology application could allow the quantitative risk assessment associated to the assets of the organization and it could be used as input for a multi-criteria analysis. The analysis procedure presented (see Fig. 1) could be run iteratively in order to identify the investment threshold of economic convenience with the higher risk reduction. In particular, the methodology could assess, in terms of AIMS reliability (effectiveness), the introduction of new or additional alarm and protection systems as well as the AIMS re-organization opportunity (e.g. tasks, procedures, etc.).

A further advantage of the method presented is the adaptability to any business environment requiring a risk management process and therefore to the Critical Infrastructure (Europe Union, 2008). The tool can be used both to cope independently and efficaciously the risk by the Critical Infrastructure managers and to assess the measures of risk management adopted in a standardization or certification perspective by supervisory Authorities.

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