

Systems engineering approach to functional safety and cyber security of industrial critical installations

Keywords

systems engineering, functional safety, cyber security, control systems, cyber physical systems

Abstract

This chapter addresses the systems engineering approach to integrated functional safety and cybersecurity analysis and management regarding selected references, standards and requirements concerning critical installations and their industrial automation and control system (IACS). The objective is to mitigate the vulnerability of industrial installations that include the information technology (IT) and the operational technology (OT) to reduce relevant risks. This approach includes verifying the safety integrity level (SIL) of defined safety functions, and then to check the level obtained taking into account the security assurance level (SAL) of particular domain, such as a safety related control system (SRCS), in which given safety function is to be implemented. The SAL is determined based on a vector of fundamental requirements (FRs). The method proposed uses defined risk graphs for the individual and/or the societal risk, and relevant risk criteria, for determining the SIL required of given safety function, and probabilistic models to verify the SIL achievable for the SRCS architecture to be designed and then implemented in an industrial installation.

1. Introduction

The complexity of industrial systems and networks, sometimes without clear hierarchy in information flow for controlling various processes, operating in changing internal and external environment, emerging of new hazards and threats, can make significant challenges to reach in practice a high level of the system reliability and safety [5]. No less important are in such systems the security-related issues, especially those influencing potentially the risk of high consequence losses [25].

An important issue in industrial practice is the business continuity management (BCM) [14] that requires careful consideration of various aspects within an integrated RAMS&S (reliability, availability, maintainability, safety, and security) framework. In such analyses the risk evaluation and management in life cycle is of special interest for both the industry and insurance companies [25]. Such issues are of significant interest also in the domain of the performability engineering that has been stimulated by Misra for years [29].

In this chapter an approach is proposed for the integrated functional safety and cybersecurity

analysis and management in critical installations of hazardous plants in the context of the design and operation of the industrial automation and control systems (IACSs) [11], [26]. The idea of Industry 4.0 assumes the openness of markets and flexible cooperation of companies worldwide [13], [27]. It could not be effective without coordinating relevant international standardization.

The main objective of this chapter is to outline a conceptual framework for integrated analyses of the functional safety solutions according to generic functional safety standard IEC 61508 (7 parts) [8], and the IACS cyber security, outlined in IEC 62443 (14 parts) [11]. For reducing vulnerability of the IT and OT systems and mitigating risks of hazardous events, especially of high consequences, a set of seven fundamental requirements (FRs), defined in the IEC 62443-1 standard, is taken into account to determine the SAL of the domain to be considered.

The method proposed uses the individual and/or societal risk graphs for determining the safety integrity level required (SIL_r) [8], [21] of consecutive safety functions to be defined in the analyses.

The SIL_r is then verified to indicate SIL achieved in the safety related control system (SRCS) of architecture proposed, in which given safety function will be implemented.

For that purpose, the probabilistic model of SRCS is to be developed regarding potential common cause failure (CCF), when the redundancy of hardware is necessary. Then, the verified SIL is to be validated regarding the security assurance level (SAL) [11], determined for relevant domain, for instance the domain of SRCS in which given safety function is to be implemented, including internal and communications.

In the analyses and assessments to be carried out, both quantitative and qualitative information available is used, including expert opinions. The analyses and assessments are based on defined classes of distinguished categories of concepts. For related evaluations, some performance indicators are useful, also so-called key performance indicators (KPIs), defined in some standards and publications, for instance [15], [25].

2. Systems engineering perspective on the functional safety and cyber security

Systems engineering (SE) consists of two general disciplines: the technical knowledge domain in which the systems engineer operates, and systems engineering management [30]. It is defined concisely as an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions to satisfy the customer needs.

The SE process includes [30]:

- requirements analysis (analysing missions and environments, identifying functional requirements, defining / refining performance and design, and constraint requirements),
- functional analysis / allocation (decomposing to lower-level functions, allocating performance and other limiting requirements to all functional levels, defining / refining functional interfaces, both internal and external, defining / refining / integrating functional architecture),
- synthesis (transforming architectures from functional to physical, defining alternative system concepts, configuring items and system elements, selecting preferred product and process solutions, defining / refining physical interfaces, both internal and external).

In the functional safety analysis and life cycle management [9], [19] a set of safety functions is to be defined in safety critical installations considering the results of hazards identification, while the safety integrity requirements result from analysis of potential hazardous events. Higher safety integrity levels impose more strict requirements on the architecture design of the safety-related systems [24].

In order to deal – in a systematic manner – with all activities necessary to achieve the required safety integrity for the safety functions to be carried out by the E/E/PE system, the standard IEC 61508 adopts an overall framework for the safety management in lifecycle. A simplified scheme is shown in *Figure 1* that should include also the cyber security related aspects, especially in steps 1, 3, 4, 5 of the analysis, and then 7, 10, 13, and 15 during the E/E/PE system realization and its operation.

All activities related to the functional safety and security management that include determining of the safety function SIL and its verification are not directly shown in *Figure 1*. They should be carefully specified for hardware of the E/E/PE system or SIS (safety instrumented system) [9], software and human factors to avoid as much as possible both the random failures and systematic failures [7], [8]. The requirements concerning functional safety and cyber security management shall run in parallel with the overall safety lifecycle phases.

According to IEC 61508 the safety validation should be performed in terms of the overall safety function requirements and the overall safety integrity requirements, considering the safety requirements allocation for the E/E/PE safety-related system during its designing.

Usually, considerable uncertainty is involved in the risk assessment to determine SIL of consecutive safety functions. The SIL verifying is based on the results obtained from a probabilistic model developed for the SRCS. In the risk assessment for decision making, also the results of a cost-benefit analysis (CBA) are valuable to indicate, which a risk control option (RCO) gains the advantage over a initial option considered, fulfilling relevant requirements and criteria [21]. It was shown in some case studies that a more costly option as regards the capital investment for increasing SIL of given SRCS, for instance from SIL2 to SIL3, can be more justified due to lower the life cycle costs (LCC) [21].

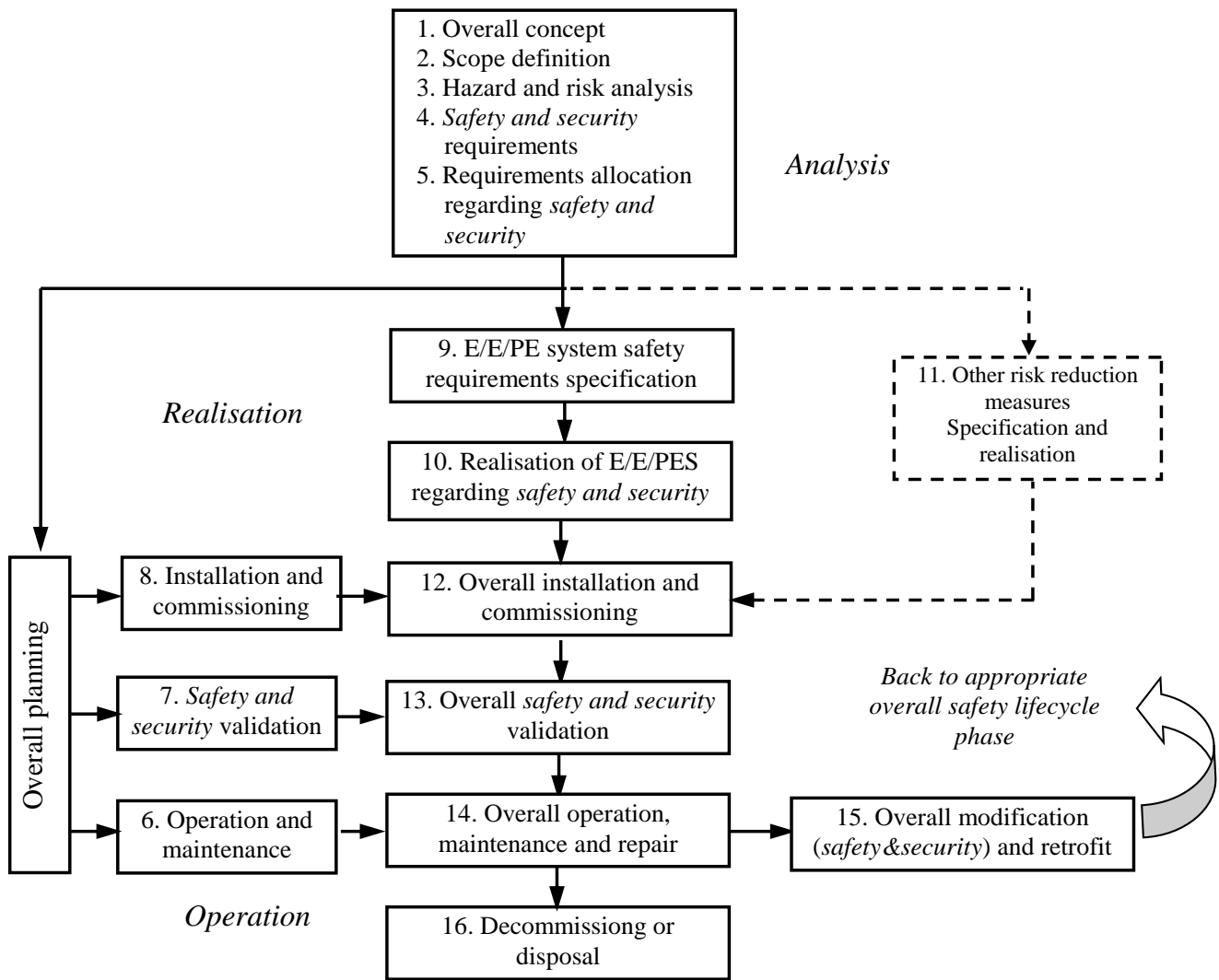


Figure 1. Overall functional safety-related lifecycle, based on [8]

As it was mentioned, due to complexity of the problem, to overcome difficulties in safety-related decision making under uncertainties, it was proposed to apply a methodology based on the risk informed decision making (RIDM) framework [22], [23]. Such methodology seems to be compatible with the functional safety management (FSM) framework described in IEC 61508 [8]. It enables the decision making in a transparent and systematic way during the design stage and then during operation of the SRCS, in overall life cycle, as suggested in the systems engineering approach [30].

3. Reference model of information technology and operational technology including control systems and communications

For effective execution of production processes in an industrial installation the following systems are to be designed, operated, and managed in life cycle:

A. Operational technology and maintenance system (OTMS) to achieve required quality of products and high reliability / availability of production subsystems and entire production system, characterized often using the overall equipment effectiveness (OEE) measure. The OEE represents a synthetic effectiveness measure of specific OTMS and should be periodically evaluated in industrial practice to support decision making in the BCM processes [14].

B. Industrial automation and control system (IACS) that should assure required functionality and reliability to limit manufacturing system outages to effectively achieve production goals, and to reduce adequately the safety and security related risks. The IACS design includes high quality and reliability hardware (HW) and software (SW) to be carefully verified and validated as regards functionality and security aspects, and user-friendly interfaces: the human system interface (HSI) and the human machine interface (HMI) [19], [22].

A reference model of the operational technology (OT) and the information technology (IT) shown in Figure 2, is based on the ISA99 series of standards derived from a general model of ANSI/ISA-95.00.01 (Enterprise-Control System Integration). It represents graphically a production system as the connection of following logical levels.

- **Level 0** – production process; it includes the physical processes and basic equipment: process equipment, sensors and actuators, equipment under control (EUC) [8] that are elements of the safety-related control systems (SRCSSs) designed for implementing the safety functions (SFs); these devices are subjected to periodical tests and preventive maintenance (PM).
- **Level 1** – sensing and controlling; this level includes: input/output (I/O) devices, communication conduits, programmable logic controllers (PLCs), the control and protection systems, and a human machine interface (HMI); the devices of this level contribute to the realization of continuous control (CC), discrete / sequence control (DC), and/or batch control (BC).
- **Level 2** – monitoring, control and supervising; this level allows to implement functions for monitoring and controlling the physical process using the distributed control system (DCS) and the supervisory control and data acquisition (SCADA) software; this level includes: human-system interface (HSI), alarm system (AS), and a decision support system (DSS) for the OT human operators; it includes also some subsystems that support diagnosing of the processes and equipment to alert operators in case of impending unsafe conditions to undertake corrective action.
- **Level 3** – manufacturing operations management and monitoring; this level includes engineering solutions for effective OT operation and maintenance using, for instance, a manufacturing execution system (MES).
- **Level 4** – enterprise business planning and logistics; this level is characterized by measures and computer applications for supporting the business planning and related activities including logistics, using for instance an enterprise resource planning (ERP) system to manage and effectively coordinate business and enterprise resources.

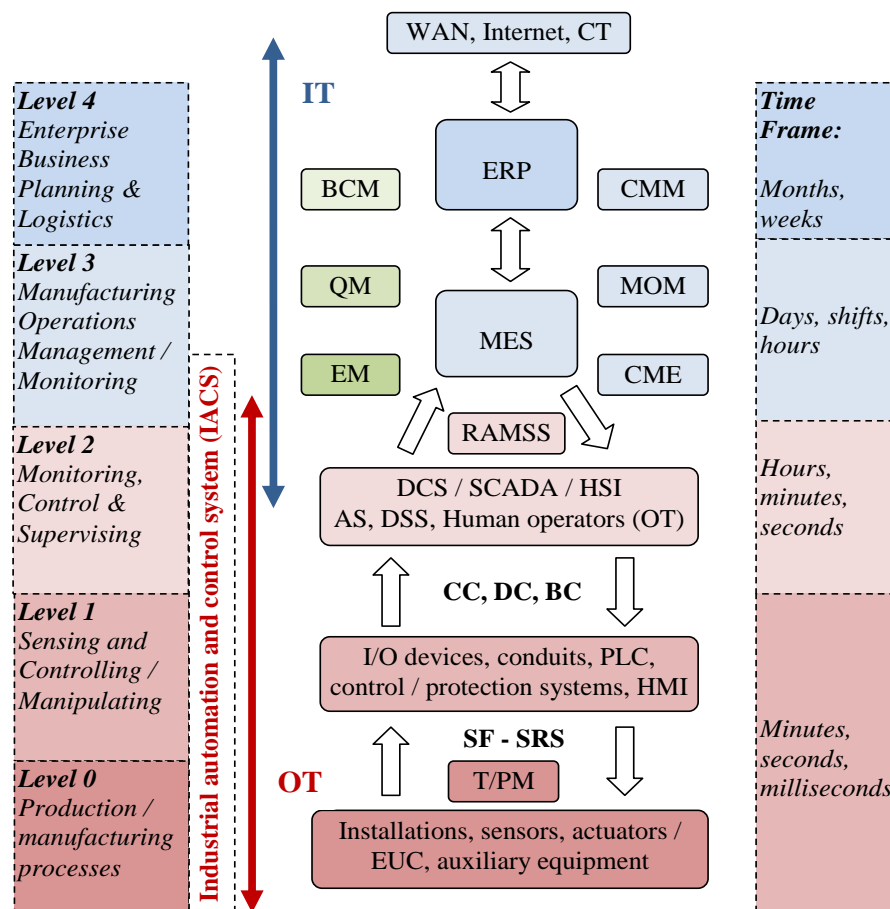


Figure 2. Reference model for the operational management and control in a production system

On the right side of *Figure 2* the time frame categories for typical information processing, to be carried out at the distinguished levels of this reference model, are presented. The time windows range from milliseconds on the levels 0 and 1 (for instance the controlling and protecting signals) to weeks and months at the level 4 (periodical big data analysis for supporting long-term decision making within the ERP and logistics). In case of dynamic processes on levels 0, 1 and 2 it causes difficulties in designing of the reliable control systems and communication conduits for the safety and security-related protections due to a very short reaction time required.

An example of simplified architecture of the OT, IT, and CT interrelated systems and networks is illustrated in *Figure 3*. The OT is nowadays in the process of adopting similar network technologies as

defined in the IT domain at an increasing rate, so these two worlds begin to merge. It is expected that the use of CT with advanced applications (APP), in favor of IT and OT, will make additional business models and automation structures possible and profitable, for instance using an open platform communications unified architecture (OPC UA) and automation mark-up language (AutomationML), being lately in dynamic development for advanced technological Industry 4.0 solutions [4], [27], [32].

Combining of these domains is often referred to as the internet of things (IoT) or the industrial internet of things (IIoT) [13], [27]. However, this merging can have potential to cause some cybersecurity related problems that require special treatment in the design and in operation of the IT and OT systems and networks [6].

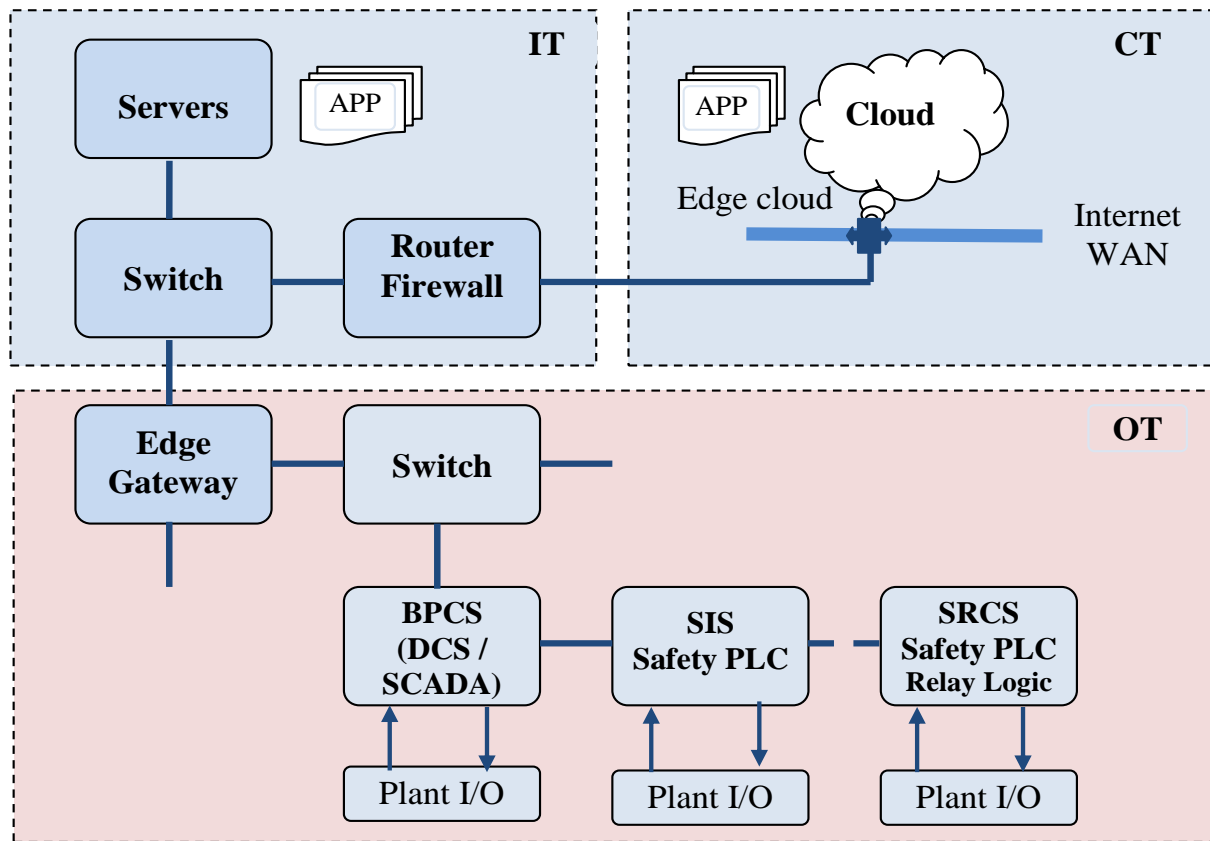


Figure 3. Interrelated domains OT, IT, and CT, based on [4]

Below an approach is outlined for integrated functional safety and cybersecurity evaluation to mitigate risks for potential hazards and threats. In the functional safety approach the safety functions [8], [10] are defined to be implemented within the SRCS of appropriate architecture, for instance, the basic process control system (BPCS) [8] or the safety instrumented system (SIS) in process industry [9].

In case of manufacturing machinery using the safety PLCs or the relay logic solutions [10] (see the OT part in *Figure 3*). Adoption of integrated networks within the OT and IT systems may be of interest regarding costs, but the requirements for applications in the field of OT and IT are quite different, which might lead to serious challenges in bridging these functionally different technological domains [3], [6], [28], [31].

4. Verifying the safety integrity releveles of functions implemented for reducing risks

4.1. SIL determination and verification

The functional safety is defined as a part of general safety of an industrial plant critical installation or production lines, which depends on a proper response of the SRCS during potential abnormal situation or accident to avoid or limit undesirable consequences. The functional safety methodology has been formulated in the generic standard IEC 61508 [8] and is appreciated in industry in the design and operation of the programmable E/E/PE systems in life cycle.

Different names of the SRCS are used in various industrial sectors, for example, a safety instrumented system (SIS) in case of the process industry sector [9], or a safety-related electrical control system (SRECS) for machinery [10]. Such systems are to be designed to perform specified safety functions to ensure that evaluated risk is reduced to a level specified for the particular industrial installation, and then maintained at the specified tolerable level in life cycle [20]–[21].

Two different requirements should be specified to ensure appropriate level of functional safety [8]:

- the requirements imposed on the performance of safety function designed for the hazard identified,
- the safety integrity requirements, i.e. the probability that the safety function will be performed in a satisfactory way when potential hazardous situation occurs.

Table 1. Categories of SIL and probabilistic criteria to be assigned to the SRCS that operates in LDM or HCM

SIL	PFD_{avg}	$PFH [h^{-1}]$
4	$[10^{-5}, 10^{-4})$	$[10^{-9}, 10^{-8})$
3	$[10^{-4}, 10^{-3})$	$[10^{-8}, 10^{-7})$
2	$[10^{-3}, 10^{-2})$	$[10^{-7}, 10^{-6})$
1	$[10^{-2}, 10^{-1})$	$[10^{-6}, 10^{-5})$

The safety integrity is defined as the probability that a safety-related system, such as the E/E/PE system or SIS, will satisfactorily perform defined safety function under all stated conditions within given time. For the safety-related system, in which defined safety function is to be implemented, two probabilistic criteria are defined as presented in Table 1 for four categories of the SIL [8]–[9], namely:

- the probability of failure on demand average (PFD_{avg}) of the SRCS in which a safety function considered is to be implemented, operating in a low demand mode (LDM), or
- the probability of a dangerous failure per hour (PFH) of the SRCS operating in a high or continuous mode (HCM).

The SIL requirements assigned for the SRCS to be designed for implementing specified safety function stem from the results of the risk analysis and assessment to reduce sufficiently the risk of losses taking into account specified risk criteria, namely for the individual risk and/or the group or societal risk [8]. If the societal risk is of interest, the analyses can be generally oriented on three distinguished categories of losses, namely [8]–[9]: health (H), environment (E) or material (M) damage, then the SIL required (SIL_r) for particular safety function, is determined as follows

$$SIL_r = \max(SIL_r^H, SIL_r^E, SIL_r^M). \quad (1)$$

As it was mentioned above, generally the SIL verification can be carried out for two operation modes, namely: LDM or HCM. The former is characteristic for the process industry [9], and the latter is typical for the machinery [10] or the railway transportation systems, and also for monitoring and the real time control of any installation using the DCS / SCADA technology.

Typical hardware architecture of the E/E/PE system, shown in Figure 4, usually consists of three subsystems [21]: (A) sensors and input devices (transducers, converters etc.), (B) logic device (safety PLC or safety relay modules), and (C) actuators, i.e. the EUC or other output devices.

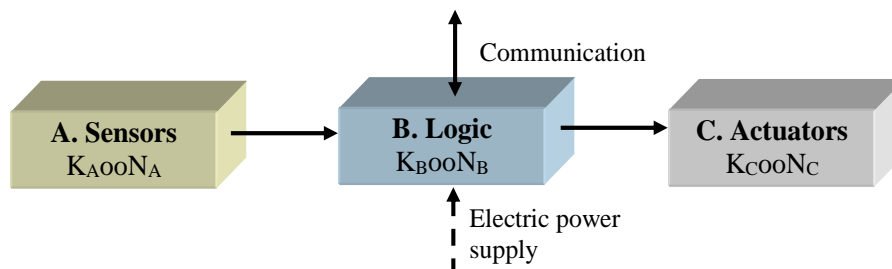


Figure 4. Typical architecture of the E/E/PE system or SIS in which a safety function is implemented

Such safety-related system constitutes a specific architecture of the hardware and software modules, and communication conduits. The logic device comprises typically a safety PLC with its input and output modules. The subsystems shown in *Figure 4* can be generally of K out of N (KooN) configuration, for instance 1oo1, 1oo2 or 2oo3. Their hardware fault tolerance (HFT) is understood as ability of the subsystem to perform a required function in the presence of faults or errors. The HFT (0, 1, 2) is an important parameter to be considered in the final SIL verification of given subsystem, together with the value of a safe failure fracture (S_{FF}) [8].

Any redundant system, also the SRCS, is prone to a common cause failure (CCF) that contributes significantly to decreasing its dependability due to potential failure mechanisms regarding relevant site-specific influence factors. The CCF is a potential failure resulting in one or more elements, causing coincident failures of two or more channels in redundant subsystem, leading to a failure of entire system. The multiple failures may occur simultaneously or over a period, shorter than testing time interval.

Various probabilistic models are proposed to deal with CCF in safety-related systems, in particular the E/E/PE system or SIS. The CCF contribution in the PFD_{avg} or PFH is often incorporated using a modified β -factor method in probabilistic modelling of redundant system considered [8], [24].

If diagnostic tests run in each channel that can detect and reveal only a fraction of the failures, it is justified to divide all failures into two categories: (1) those that lie outside the coverage of the diagnostic tests (can not be detected) and (2) those that lie within the coverage (detected by the diagnostic tests). The overall failure event probability per time unit of the subsystem dangerous (D) failure due to potential failures including CCF, is a function of parameters to be included in the formula below [24]

$$PF_D^{CCF} = f(\lambda_{Du}\beta, \lambda_{Dd}\beta_D, \dots) \quad (2)$$

where:

- λ_{Du} is the rate of dangerous (D), undetected (u) failure in a single channel, influencing the probability of failures that lie outside the coverage of the diagnostic tests; β is the common cause failure factor for undetectable dangerous faults, which is equal to the overall β -factor that would be applicable in the absence of diagnostic testing,
- λ_{Dd} is the rate of a dangerous (D), detected (d) failure in a single channel, influencing the

probability of failures that lie within the coverage of the diagnostic tests, β_D is the common cause failure factor for detectable dangerous faults; as the repetition rate of the diagnostic testing is increased, the value of β_D falls below β .

In probabilistic modelling of given subsystem the value of β is determined for the score

$$S = X + Y$$

to be evaluated for factors specified in the standard IEC 61508 and the value of β_D is evaluated for the score

$$S_D = X(Z + 1) + Y$$

as it is presented in *Table 2*. These scores are evaluated respectively for the logic subsystem, and for the subsystem of sensors and actuators (final elements), respectively. In evaluating scores for X and Y following factors should be taken into consideration [8]:

- (1) Separation / segregation,
- (2) Diversity / redundancy,
- (3) Complexity / design / application / maturity / experience,
- (4) Assessment / analysis and feedback of data,
- (5) Procedures / human interface,
- (6) Competence / training / safety culture,
- (7) Environmental control,
- (8) Environmental testing.

Each of these factors is divided into several sub-attributes with specified sub-scores to be added to obtain final score, respectively for X and Y , and finally for S and S_D . The value of Z in calculating S_D depends on the diagnostic test interval and a diagnostic coverage (DC). For instance, in case of the subsystem of sensors or actuators, if $DC \geq 99\%$ and the diagnostic test interval is between 2 hours and 2 days, it is suggested: $Z = 1.5$. If the test interval is greater than 1 week, then $Z = 0$ [8].

Table 2. The values of β or β_D for subsystems suggested in the standard IEC 61508 [8]

Score for S or S_D	Values of β or β_D for the logic subsystem	Values of β or β_D for the sensors or actuators
≥ 120	0.5%	1%
[70, 120)	1%	2%
[45, 70)	2%	5%
< 45	5%	10%

Thus, the values of β and β_D parameters used in the probabilistic modelling of safety-related subsystems depend significantly on factors specified in IEC 61508 and the expert opinions collected during the functional safety analysis of the E/E/PE system or SIS. In publication [24] two examples are presented of the SIL verification for given SRCS architecture using the probabilistic models of subsystems including the CCF analysis. The architectural constrain issue in relation to the HFT and S_{FF} determined for subsystems are considered below. It seems to be justified to assume that some categories of factors specified above are also relevant for the cybersecurity analysis.

4.2. Case study of SIL verification

An example of the reliability block diagram of the E/E/PE safety-related system will be considered for the hardware architecture as shown in *Figure 5*. It consists of three subsystems of following configurations: (A) 2oo3 for sensors, (B) 1oo1 of logic device, and (C) 1oo2 for actuators. The potential common cause failures (CCF) is included in the system analysis for redundant subsystems: A and C. In the CCF analysis the β -factor method is applied in evaluation of probabilities: PFD_{avg} and PFH .

It was assumed that channels of j -th subsystem are periodically tested with an interval T_{Ij} . The average probability of failure on demand $PFD_{avg}(T_{Ij})$ and the danger failure per hour $PFH(T_{Ij})$ for consecutive subsystems are evaluated according to the formulas as below that include relevant β and β_D factors for representing relevant CCF.

The probabilistic measures of the system shown in *Figure 5* have been calculated according to formulas (3) and (4) respectively for low and continuous mode of operation [9]:

$$PFD_{avg}^{Sys} \cong PFD_{avg}^{A,2oo3} + PFD_{avg}^{B,1oo1} + PFD_{avg}^{C,1oo2} \quad (3)$$

$$PFH^{Sys} \cong PFH^{A,2oo3} + PFH^{B,1oo1} + PFH^{C,1oo2}. \quad (4)$$

Below some formulas are presented for calculations of these probabilities [8], [24].

Subsystem architecture 1oo1

$$PFD_{avg}^{1oo1} \cong \lambda_D t_{CE} \quad (5)$$

$$PFH^{1oo1} = \lambda_{Du} \quad (6)$$

$$t_{CE} = \frac{\lambda_{Du}}{\lambda_D} \left(\frac{T_I}{2} + \tau \right) + \frac{\lambda_{Dd}}{\lambda_D} \tau \quad (7)$$

where: T_I is the proof test interval [h], and τ is the mean time to restoration, t_{CE} is the channel equivalent mean down time (in hours) for 1oo1, 1oo2, and 2oo3 architectures (this is the combined down time for all the components in the channel of given subsystem).

Subsystem architecture 1oo2

$$PFD_{avg}^{1oo2} \cong 2[(1 - \beta_D)\lambda_{Dd} + (1 - \beta)\lambda_{Du}]^2 t_{CE} t_{GE} + \beta_D \lambda_{Dd} \tau + \beta \lambda_{Du} \left(\frac{T_I}{2} + \tau \right) \quad (8)$$

where: t_{GE} is the voted group equivalent mean down time (in hours) for 1oo2 and 2oo3 architectures (this is the combined down time for all the channels in the voted group) to be evaluated from the following formula:

$$t_{GE} = \frac{\lambda_{Du}}{\lambda_D} \left(\frac{T_I}{3} + \tau \right) + \frac{\lambda_{Dd}}{\lambda_D} \tau \quad (9)$$

$$PFH^{1oo2} \cong 2[(1 - \beta_D)\lambda_{Dd} + (1 - \beta)\lambda_{Du}]^2 t_{CE} + \beta_D \lambda_{Dd} + \beta \lambda_{Du}. \quad (10)$$

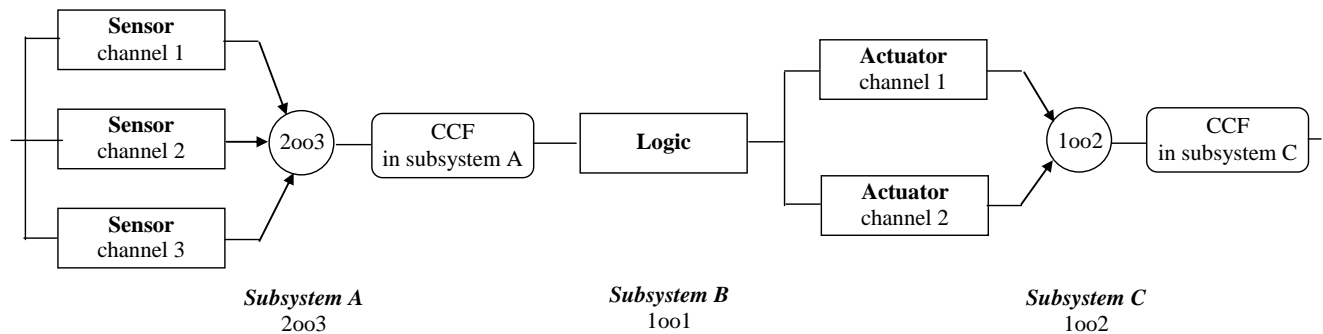


Figure 5. Hardware architecture of safety-related system used for verifying the safety integrity level

Subsystem architecture 2oo3

$$PFD_{avg}^{2oo3} \cong 6[(1 - \beta_D)\lambda_{Dd} + (1 - \beta)\lambda_{Du}]^2 t_{CE} t_{GE} + \beta_D \lambda_{Dd} \tau + \beta \lambda_{Du} \left(\frac{T_1}{2} + \tau\right) \quad (11)$$

$$PFH^{2oo3} \cong 6[(1 - \beta_D)\lambda_{Dd} + (1 - \beta)\lambda_{Du}]^2 t_{CE} + \beta_D \lambda_{Dd} + \beta \lambda_{Du}. \quad (12)$$

The component reliability data and other parameters for calculations of probabilistic measures according to formulas as above for determining the safety integrity levels (SIL) are presented in Table 3.

Table 3. Parameters verified by experts for probabilistic modelling of subsystems

Subsystems → Model parameters ↓	A	B	C
DC [%]	60	90	60
λ_D [h ⁻¹]	$2.5 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$
$\tau = MTTR$ [h]	8	8	8
T_1 [h]	4380	360	4380
β [%]	3	–	2
β_D [%]	1.5	–	1

The results of calculations for subsystems A, B, C and the entire system are presented in Table 4 for the low demand mode (LDM) of the system operation (see explanations of S_{FF} below this table).

Table 4. Results of SIL verification for the LDM of system operation

System / Subsystem / Channel	KooN	PFD_{avg}^{Sys}	SIL	[%] of PFD_{avg}^{Sys}
Sys	–	$13.6 \cdot 10^{-5}$	3	100
A	2oo3	$6.6 \cdot 10^{-5}$	4/3^a	48.5
1	–	$2.2 \cdot 10^{-3}$	2	–
2	–	$2.2 \cdot 10^{-3}$	2	–
3	–	$2.2 \cdot 10^{-3}$	2	–
B	1oo1	$2.6 \cdot 10^{-5}$	4/3^b	19.1
C	1oo2	$4.4 \cdot 10^{-5}$	4/3^a	32.4
1	–	$4.4 \cdot 10^{-3}$	2	–
2	–	$4.4 \cdot 10^{-3}$	2	–

^a SIL reduced due to architectural constrains ($S_{FF} = 90\%$, HFT 1)

^b SIL reduced due to architectural constrains ($S_{FF} = 99\%$, HFT 0)

When the failure rates are treated as constant the *safe failure fraction* (S_{FF}) of an element or channel, treated as a serial reliability structure, is to be evaluated from the formula [8], [24]:

$$S_{FF} = \frac{\lambda_s + \lambda_{Dd}}{\lambda_s + \lambda_{Dd} + \lambda_{Du}} = 1 - \frac{\lambda_{Du}}{\lambda} \quad (13)$$

where: λ_s is the safe failure rate, λ_{Dd} the dangerous failure rate, which are detected by the diagnostic tests, λ_{Du} the dangerous undetected failure rate, and λ is the overall failure rate of the channel considered.

Considering probabilistic criteria given in Table 1 the safety integrity level of subsystems A, B and C is at the level SIL4. The system is almost balanced as regards percentage of contribution of these subsystems in the system PFD_{avg}^{Sys} , which ranges from 19.1 to 48.5%. However, if the architectural constrains will be included in the analysis, then the safety integrity level for these subsystems is decreasing to SIL3.

A final conclusion can be drawn that this SRCS contributes to the risk reduction approximately with a coefficient of

$$PFD_{avg}^{Sys} = 13.6 \cdot 10^{-5},$$

i.e. the risk evaluated for hazard considered is about

$$1/PFD_{avg}^{Sys} \cong 7.3 \cdot 10^3$$

times lower when the safety function considered were implemented.

The probabilistic models described above include several parameters in formulas from (3) to (12). The results obtained from the model described for configurations of subsystems 1oo2 and 2oo3 are most sensitive to β -factor related parameters: β , β_D , and the danger failure rates: λ_{Du} , λ_{Dd} , as well as a diagnostic coverage

$$DC = \lambda_{Dd} / \lambda_D,$$

that is included indirectly in evaluations.

The testing interval T_1 contributes also significantly to the results obtained. In determining of this interval, it is necessary to consider experience of the users of E/E/PE system and restrictions regarding the operation of given industrial installation. In case of the subsystem C, the partial tests of actuators can be also proposed to be performed more frequently than overall tests.

Thus, the parameters of the model developed should be carefully evaluated in the modelling process,

considering verified sources of information, careful aggregation of the expert opinions concerning the β and β_D factors (Table 2). In some cases, also opinions of specialists responsible for the design of the E/E/PE systems or SIS, and experienced engineers supervising operation of these systems in industrial critical installations could be useful in the probabilistic evaluation of the safety-related systems. The results of probabilistic modelling and the model sensitivity analysis could be undoubtedly useful in developing operational procedures for safety related systems [25].

5. Cybersecurity of safety related control systems

The security related remote attacks are becoming increasingly important threats to the IT and OT systems, especially the IACS operating within industrial networks of hazardous plants [9], [12], [16]. The internal or external threats can initiate in the IT and/or OT security-related incidents with the potential to adversely impact the SRCS and safety critical installations. Their vulnerability is understood as a security related weakness of the IT and/or OT systems and related networks that can be exploited by various threats to trigger hazardous events having significant potential to make losses [12], [21]. The cyber resilience of such systems and networks [2] is an important issue to be adequately treated also in the BCM [14].

A threat may be either passive or active. In case of the passive threat the agents usually gather information by casual communications with employees and contractors. Examples of active threats are as follows [12]: database injection, spoofing and impersonation, phishing, malicious code, Denial of Service (DoS), escalation of privileges, physical destruction, etc. As it was mentioned the security-related analyses should be carefully carried out to identify the SRCS vulnerability that can be exploited by various threats, potentially impacting the reliability and safety of the entire production installations.

The IT security risks shall be mitigated through the combined efforts of component suppliers, the machinery manufacturer, the system integrator, and the machinery end user [11], [26]. Generally, the potential responses to the security risks should take following steps [12]:

- eliminate the security risk by design (avoiding vulnerabilities),
- mitigate the security risk by risk reduction measures (limiting vulnerabilities),

- provide information about the residual security risk and the measures to be adapted by the user.

The standard IEC 62443 [11] proposes an approach to deal systematically with the security-related issues of the IACS. Four security levels (SLs) are defined that are understood as a confidence measure that the IACS is free from vulnerabilities and it functions in an intended manner (see Table 5). In the standard IEC 63074 [12] these levels are also proposed to deal with the SRCS security of manufacturing systems.

The SL is related to seven foundational requirements (FRs):

- FR 1 – identification and authentication control (IAC),
- FR 2 – use control (UC),
- FR 3 – system integrity (SI),
- FR 4 – data confidentiality (DC),
- FR 5 – restricted data flow (RDF),
- FR 6 – timely response to events (TRE),
- FR 7 – resource availability (RA).

Thus, instead to express the SL as a single number, it is suggested to apply a related vector of seven FRs specified above. Such vector is proposed for describing the security requirements for a zone, conduit, component, or system. This vector may contain the integer numbers of SL from 1 to 4 or 0 to be assigned to consecutive FRs. A general format of the security assurance level (SAL) to be evaluated is defined as follows [11]:

$$\begin{aligned} & \text{SL-? ([FR,] domain)} \\ & = [\text{IAC UC SI DC RDF TRE RA}] \end{aligned} \quad (14)$$

where: SL-? = (required) the SL type: possible formats are: SL-T = target SAL, SL-A = achieved SAL, and SL-C = capabilities SAL vector; [FR,] = (optional) field indicating the FR that SL value applies; domain = (required) is applicable domain that SL applies – this may be procedure, system or component, when applying the SL to a system; it may be for instance: Zone A, Machinery B, Engineering Workstation, etc.

For instance, according to the standard [11] it can be written as follows:

- SL-T (Control System Zone)
= [2 2 0 1 3 1 3],
- SL-C (Engineering Workstation)
= [3 3 2 3 0 0 1],
- SL-C (RA, Safety PLC) = 3; in this example only the RA component is specified, instead of a 7-dimension SAL vector SL-C.

Thus, three type of vectors describing SL_i for consecutive FR_i of the domain are distinguished:

- SL-T (target SAL) – the desired levels of security,
- SL-C (capability SAL) – the security level that device can provide when properly configured,
- SL-A (achieved SAL) – the actual level of security of a particular device.

The SL numbers are related to a qualitative information addressing relevant protection scope of the domain or zone considered, for instance, for the IACS or SRCS as its part, as presented in *Table 5*.

Table 5. Security levels and protection description of the IACS domain [11]–[12]

Security levels	Description
SL 1	Protection against casual or coincidental violation
SL 2	Protection against intentional violation using simple means with low resources, generic skills, and low motivation
SL 3	Protection against intentional violation using sophisticated means with moderate resources, IACS specific skills and moderate motivation
SL 4	Protection against intentional violation using sophisticated means with extended resources, IACS specific skills and high motivation

For instance, in the case of FR 1 – identification and authentication control (IAC) – the security levels shall be interpreted in a following way "Identify and authenticate the SRCS users by mechanisms against" [11]:

- causal and coincidental access by unauthorized entities (SL 1),
- intentional unauthorized access by entities using simple means (SL 2),
- intentional unauthorized access by entities using sophisticated means (SL 3),
- intentional unauthorized access by entities using sophisticated means with extended resources (SL 4).

For improving the SRCS security it is suggested to elaborate guidance (the instruction handbook) for the end user that includes the following issues [12]:

- restriction of logical/physical access to the IT systems with potential influence on safety, for instance using internal IT systems with risk reduction measures, such as firewalls, antivirus tools, etc.; providing authentication and access control mechanisms, such as card

readers, physical locks, according to specifications of manufacturer or integrator; disabling all unused external ports/interfaces and services, etc.,

- detection and reaction on IT-security incidents with potential influence on safety, for instance checking regularly means for detecting failed IT system components or unavailable service according to the specifications of the machine/component manufacturer; being responsive for vulnerabilities resulting from a new IT security threat and potential attack,
- in case of remote maintenance and service, for instance using provided means for setting up and ending a remote access session according to the specifications of the component manufacturer; using encryption means for initiating a remote service according to specifications of the machine/component manufacturer; watching any remote access session with a restriction of duration for remote access, etc.

Such topics should be included and carefully treated in a security information and event management (SIEM) to be developed and used proactively in practice according to requirements given in ISO/IEC 27001 [17], and supported by the information security risk management as suggested in ISO/IEC 27005 [18]. Its specific requirements to be formulated should include the target SAL (SL-T) and then verified as achieved SAL (SL-A) considering the capability SAL (SL-C) of technology applied. Defined system requirements (SRs) and specific requirement enhancements (REs) for consecutive FRs to be fulfilled at relevant SLs from 1 to 4 are specified in the IEC 62443 standard [11] and a recent publication [26].

6. Integrated functional safety and cybersecurity analysis and management

The IEC 62443 [11] standard consists of 14 parts. Some of them are still in development. The main objective of this series is to cover important topics of the IACS security entirely. In the second edition of the generic functional safety standard IEC 61508 [8] it is suggested to use the IEC 62443 standard to deal with the cybersecurity issues at the design stage and operation of the programmable safety-related control systems. Up to now, though, the IEC 61508 and IEC 62443 standards have been rather loosely linked [1]. As it was mentioned, also in case of the SRCS of manufacturing systems there is a need to deal more systematically with security issues, as it has been lately emphasized [12], [26].

It is worth to mention that the SRCS security level to be achieved depends strongly on the quality of an information security management system (ISMS) established in industrial practice. The objective of the ISMS might be also to monitor, continuously control, maintain and, wherever justified, improve the IT and OT security.

The IEC 62443 standard is based on general requirements and stipulations of the ISO/IEC 17799 and ISO/IEC 27000 series, especially as regards basic security requirements [17]. Due to complex and dynamic internal and external conditions making technical specifications related to the IT and OT security solutions for implementing in industrial practice is quite challenging.

An important task to be undertaken is the risk evaluation and management, as it is postulated both in ISO/IEC 27001 [17] and ISO/IEC 27005 [18]. It includes the consideration of all functional components of the information system including the hardware (HW) and software (SW), communication conduits and relevant human/organizational factors, especially those related to the IT and OT safety and security. Opinions are expressed that the quantitative evaluation of security-related risk is difficult due to the complexity of the IT and OT system and many influencing factors involved. The credibility of such evaluation depends on a framework adapted and availability of data, and expert opinions concerning specific domain to be evaluated.

Opinions are also expressed that the CIA triad (confidentiality, integrity, availability) is a justified order of requirements in the IT network security analysis, but in case of the OT system a reversed triad, namely AIC (availability, integrity, confidentiality) is more appropriate.

As it was mentioned above the domain SAL defined in IEC 62443 is to be evaluated using the vector of seven FRs, as explained by the formula (14). So, there are some doubts how to match these two kinds of requirements in the security related analyses. It seems to be reasonable that the fundamental requirements IAC, UC, SI and TRE should be mapped to integrity (I), RA to availability (A), and DC, RDF to confidentiality (C) [1], [26].

Additional issue, worth to be explained in context of the cybersecurity evaluation, is related to the definition of seven evaluation assurance levels (EALs) in so-called common criteria standard (IEC 15408) [16] that usually are to be applied in defining the IT security requirements.

As it was explained above only four SLs are defined in IEC 62443. This issue was discussed in the publication [6], [26] in the context of generic functional safety standard IEC 61508 [8], in which

also four SILs are distinguished (see Table 6). So, the problem is encountered how to treat these concepts in an integrated functional safety and cybersecurity analysis.

In the publication [6] the correlation between SIL and SAL is proposed as it is shown in Table 6. Similar correlation can be proposed for the SRCS of manufacturing systems, however remembering that in the machinery sector the highest SIL to be assigned to the safety-related systems is SIL 3 [10].

Table 6. Proposed correlation between SIL and SAL [6]

Safety integrity level (SIL)	Security assurance level (SAL)	Explanation
SIL 1	SAL 1	SAL assignment is based on asset owner's assessment
SIL 2	SAL 2	
SIL 3 & SIL 4	SAL 3	Reserved for total system failure
	SAL 4	Reserved for loss of life

In view of the above we propose an approach for integrated functional safety and cybersecurity analysis based on a framework of existing concepts and accepted models suitable to apply the quantitative and qualitative information available, similarly as in the knowledge based systems [22]. We start from defining the safety functions regarding hazards and threats identified and then evaluate required risk reduction regarding the risk criteria defined as it was described above. It allows to determine: the safety integrity level required SIL_r according to IEC 61508 [8], or the safety integrity level claimed SIL CL regarding IEC 62061 [10].

As it is known, the levels: the safety integrity level required SIL_r (1, 2, 3 or 4) or SIL CL (1, 2 or 3) are related to the required risk reduction with regard to relevant individual or social risk criteria [8], [10]. For instance, the average probability of failure on demand PFD_{avg} is related to the risk reduction measure as its reciprocal.

The SIL_r or SIL CL determined for given safety function must be then verified using probabilistic model of the SRCS of architecture proposed at the design stage. Such architecture includes generally the hardware configuration and requirements concerning software [8]. Parallely, the security related evaluation is to be carried out as it is shown in Figure 6 for cyber security evaluation. The integrated functional safety and cyber security analysis are repeated when justified to enable

a rational management of the SRCS domain in life cycle regarding the SIL and SAL.

Additional issue to be considered is associated with expressing SAL as a single number to be assigned to the security level achieved SL-A for given domain, as it is outlined below the formula (14), according to the standard IEC 62443. It would lead to sometimes disputable requirement that the security levels SL_i would be the same for each FR_i . However, confidentiality can play in some cases a minor role for safety related control system and encryption of all data might lead to complications in testing and the time response longer than required. So generally, different levels of SL_i may be assigned to seven consecutive elements of the FR vector.

This problem was noticed by Braband and discussed in the publication [1]. Only in simple cases of equal levels SL_i for consecutive FR_i (i from 1 to 7)

determining SAL of domain of interest (e.g. IACS) is straightforward, for instance $SAL\ 1 = [1\ 1\ 1\ 1\ 1\ 1\ 1]$. Generally, the SL_i can be different depending on the security technology applied or FR_i relevance for the domain considered. So, he suggests using some security profiles, for instance for zones of interest. However, it might also lead to many profiles, difficult for evaluation and security related decision making.

In our earlier publications [20] it was assumed that resulting SAL for the domain considered can be determined based on dominant FR_i and some common sense rules, in a similar way as in the methodology outlined in the IEC 15408 (common criteria) [16]. In this methodology seven evaluation assurance levels (EALs) are distinguished, related to classes of the security assurance requirements (SARs) and defined scope of fulfilling relevant requirements.

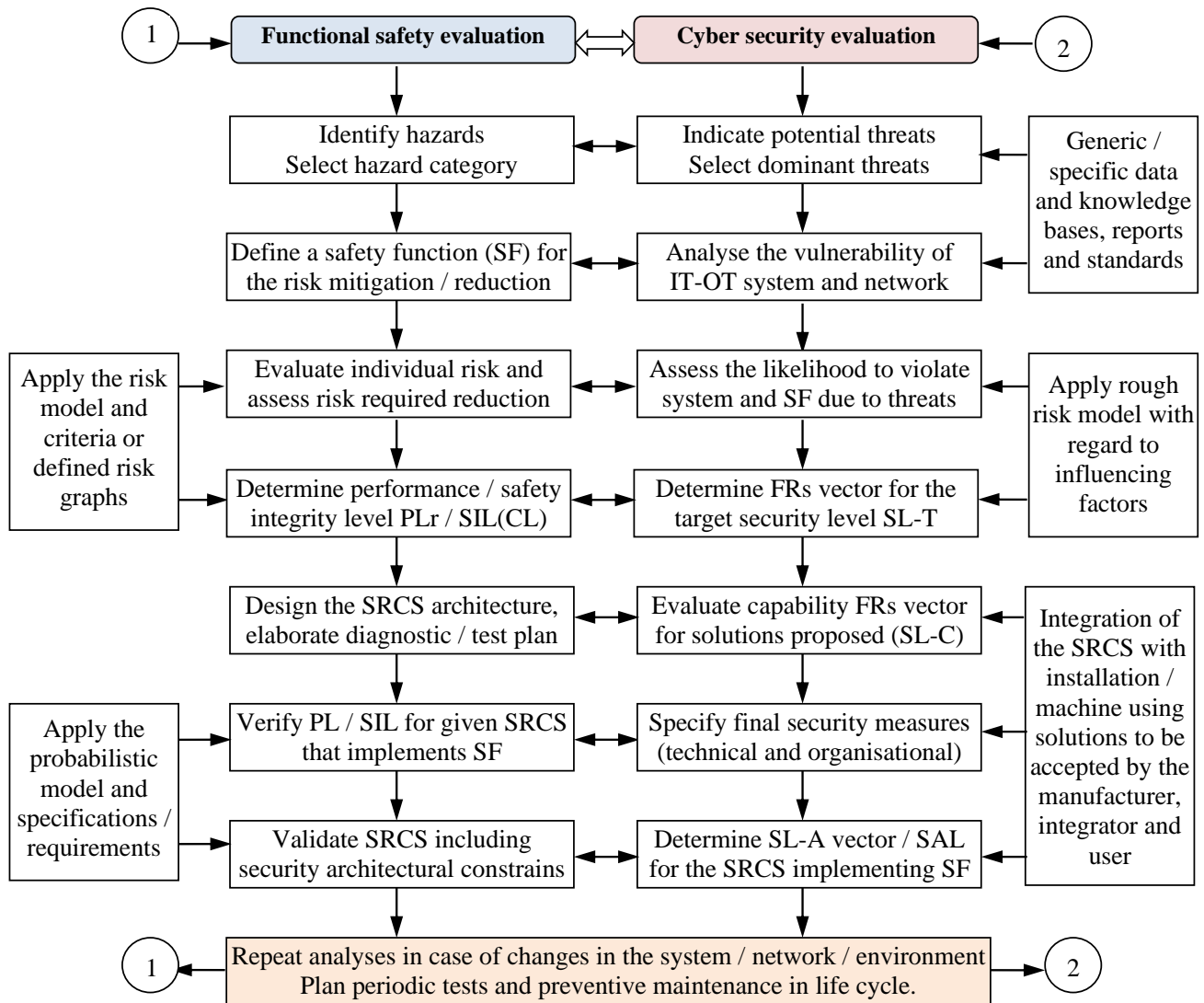


Figure 6. Integrated functional safety and cybersecurity analysis for the SRCS domain

We propose below another method for determining the security level achieved SL-A (SAL) for the domain considered if the weights w_i of security levels SL_i for consecutive (and relevant) FR_i are evaluated by experts. These weights can differ in general due to diversified importance of FR_i for the domain considered. The method includes cases in which not all fundamental requirements FR_i are relevant to the domain considered. It is suggested in the IEC 62443, as explained below the formula (14). There are cases that only one relevant FR_i is relevant [11].

Thus, instead of determination of SAL for given domain based on dominant FR_i we propose alternatively to evaluate a domain security index SI^{Do} and then to assign an integer number (1, 2, 3, or 4) to the SAL as it is proposed in first column of *Table 7*. The importance I_i of FR_i is evaluated by experts for specific domain, for instance indicating an integer number on the scale from 1 to 5 (or 1 to 10), and 0 if FR_i is not relevant. Then, the weight w_i of given FR_i is calculated according to following formula

$$w_i = \frac{I_i}{\sum_{i=1}^7 I_i}. \quad (15)$$

The security index SI^{Do} for the domain (Do) and determined security level SL_i (the integer number from 1 to 4, or 0 if FR_i is not relevant) for relevant (Re) fundamental requirements (FR_i) is to be calculated as follows

$$SI^{Do} = \sum_{i \in \text{Re}} w_i SL_i. \quad (16)$$

Four intervals of the domain security index SI^{Do} (from SI^{Do1} to SI^{Do4}) are proposed in first column of *Table 7* for assigning the category number of SAL from 1 to 4. Such approach corresponds with attributing SAL for the domain in our earlier publications, based on dominant SL_i for relevant fundamental requirements FR_i .

Proposed correlations between security index to be assigned to the domain SI^{Do} or SAL and final SIL attributing to the SRCS in hazardous installation are presented in *Table 7*. It was assumed that SIL has been verified according to IEC 61508 based on results of probabilistic modelling as described above, regarding CCFs and human factors, and the architectural constrains for evaluated S_{FF} and HFT of consecutive subsystems.

Thus, the verification of the SIL requires probabilistic modelling of the SRCS of proposed architecture regarding S_{FF} and HFT of subsystems. In the case study as above (results in *Table 4*), the safety integrity level SIL 3 was obtained. Considering the domain of SRCS in which the safety function is implemented including the communication conduits, the SL-A vector was evaluated as follows: [3 2 3 2 2 3 2]. Assuming that weights of all SL_i are equal ($w_i = 1/7$) and using the equation (16), the result obtained using the formula (16) is $SI^{Do} = 2.43$, to be interpreted as SAL 2. Looking at the column 3 of *Table 7* the final safety integrity level, validated regarding the security requirements, is SIL 2, lower than required SIL 3.

Table 7. Proposed correlation between SI^{Do} or SAL for evaluated domain and final SIL to be attributed to the SRCS of safety critical installation

Security index SI^{Do} / SAL	SIL verified according to IEC 61508*			
	1	2	3	4
$SI^{Do1} \in [1.0, 1.5) / \text{SAL 1}$	SIL 1	SIL 1	SIL 1	SIL 1
$SI^{Do2} \in [1.5, 2.5) / \text{SAL 2}$	SIL 1	SIL 2	SIL 2	SIL 2
$SI^{Do3} \in [2.5, 3.5) / \text{SAL 3}$	SIL 1	SIL 2	SIL 3	SIL 3
$SI^{Do4} \in [3.5, 4.0] / \text{SAL 4}$	SIL 1	SIL 2	SIL 3	SIL 4
* verification includes the architectural constrains regarding S_{FF} and HFT of subsystems				

Therefore, the security of the domain should be improved (its vulnerability decreased). For instance, in case of the SL-A vector [3 3 3 3 2 3 2], $SIL^{Do} = 2.71$ and relevant SAL for such domain could be indicated as SAL 3. In this case finally validated SIL will be equal SIL 3, and the process of the SRCS in designing may be stopped, if required SIL, obtained from the risk assessment, SIL_r was also evaluated as 3.

7. Conclusion

Traditionally, the industrial production installations include the information technology (IT) and the operational technology (OT). Lately, using the cloud technology (CT) is often considered as an external network that is more and more important for distributed manufacturing and business management. Advanced automation and control systems are also in dynamic development based, for instance, on the OPC UA and AutomationML concepts. They offer advanced manufacturing solutions and production flexibility. However, it causes some problems to be solved that include the reliability, safety and security issues, crucial also for the business continuity management (BCM) to mitigate the risks of outages, abnormal situations and major accidents contributing to high losses.

Selected design and operational aspects of the OT and IT networks have been overviewed and discussed in this chapter in the context of functionality and architectures of the industrial automation and control systems (IACS) to be designed and operated in life cycle. Emphasis was put on the functional safety and cybersecurity of the industrial control systems and networks. These issues are becoming crucial, because the IACS that includes the safety related control system (SRCS) plays a key role in innovative high-quality manufacturing, especially in modern industrial plants of Industry 4.0, and safety critical industrial installations.

In this chapter a method is proposed for integrated functional safety and cybersecurity analysis, regarding the concepts outlined in the generic functional safety standard IEC 61508 (7 parts) and the cybersecurity standard IEC 62443 (14 parts). To limit the vulnerability of the IT and OT systems and networks, and the SRCS to be designed and operated to reduce relevant risks, a set of security-related fundamental requirements (FRs) defined in IEC 62443-1 is considered in the analyses and evaluations.

The method proposed uses the individual and/or societal risk graphs for determining the safety integrity level required (SIL_r) of consecutive safety

functions to be defined and analysed. These levels are then verified to indicate that the required SIL is achievable in the designed SRCS of architecture proposed, in which given safety function is to be implemented.

For that purpose, relevant probabilistic models of the SRCSSs are to be developed regarding potential common cause failures (CCFs), when a hardware redundancy in its subsystems should be applied to increase their dependability. Then, the verified SIL is validated regarding determined SAL of the domain of interest, for instance the domain of SRCS in which safety given function is implemented, including internal and external communications that can be vulnerable to potential threats.

The dependability of the SRCS performing the safety functions can be influenced both by technical factors, including requirements concerning hardware (HW) and software (SW), and the human and organizational factors [22]–[23]. These aspects require further research, especially in the context of the design and operation of high complexity industrial installations, including the functional safety and cybersecurity aspects regarding the defense in depths (D-in-D) concept and related strategy to be elaborated and applied in particular industrial plant.

Industrial plants are characterized by the venture capital, production capacity, existing or emerging hazards and threats that influence various risks in changing environment. To deal systematically with such challenging and interrelated issues the systems engineering offers a general framework to be adapted for using in life cycle of given critical installation.

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