Human Aspects of Nuclear Safety
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Human and Organisational Performance in Nuclear Installations

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Human and Organisational Performance in Nuclear Installations

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List of abbreviations and acronyms

CEA	Commissariat à l'énergie atomique et aux énergies alternatives (Atomic Energy and Alternative Energies Commission, France)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat (Federal Nuclear Safety Inspectorate, Switzerland)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HF	Human factors
HFE	Human factors engineering
HMI	Human-machine interface
HOF	Human and organisational factors
HP	Human performance
HRO	High reliability organisation
HTO	Human, technology and organisation
INES	International Nuclear and Radiological Event Scale
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (Institute of Radiological Protection and Nuclear Safety, France)
ISA	Integrated safety assessment
JNRA	Japan Nuclear Regulatory Authority
NEA	Nuclear Energy Agency
OP	Organisational performance
TSO	Technical support organisations
WGHOF	Working Group on Human and Organisational Factors (NEA)

Executive summary

In 2016, the members of the Nuclear Energy Agency (NEA) Working Group on Human and Organisational Factors (WGHOF) conducted a survey concerning their in-house definition of the terms "human performance", "organisational performance" and "human and organisational factors"; the results confirmed wide inconsistencies in both the definition and application of these terms according to the different degrees in development of HOF programmes. It was therefore decided to work towards establishing a common understanding of each term with the help of a simple model. This was further elaborated by using the systemic approach to safety mentioned in the IAEA Safety Standard GSR Part 2 (IAEA, 2016).

The target audience of the report is the personnel of the licensees of nuclear installations and regulatory bodies, including their technical support organisations (TSOs). The understanding and the practical use of the systemic approach is essential for the safe management of nuclear installations and the effectiveness of regulatory practices. This publication will be of particular value for managers at all levels of an organisation, supporting the development and maintenance of an effective management system according to IAEA Safety Standards.

The model, presented in Chapter 3, illustrates the strong inter-relationship between the terms. It shows that HP includes both human activities and the results of these activities. HOF are the factors that have influence on HP in a positive or adverse manner in a given situation. They can be categorised as human-, technology- and organisation-related factors and are themselves in continuous interaction with each other.

The change from a human-centred perspective to a more high-level view makes it possible to apply the model at the organisational level, such as that of the operating organisation of a nuclear installation. The OP is characterised by the ensemble of interacting activities in the organisation (how things are done) and the results of these activities (the outcome of the organisation). The OP is in turn influenced by even more human-, technology- and organisation-related factors that continuously interact in a complex and dynamic manner. Finally, the human or the organisational performance are consolidated in the performance of the human, technology and organisation system (HTO system) as a whole.

The model leads inevitably to a systemic approach to safety – an approach relating to the system as a whole in which interactions between human, technological and organisational factors are duly considered. Chapter 4 gives recommendations for the practical application of a systemic approach.

This is done by evaluating the following topics of the model described in Section 4.2:

Topic 1: Purpose, vision, strategy and objectives of the system.

Topic 2: System boundaries and external context.

Topic 3: Required processes, activities and intended results to achieve the objectives.

Topic 4: Interrelations between processes and activities and key activities identification.

Topic 5: HOF for key activities.

Topic 6: Measurement, monitoring and control of the effectiveness of the activities, processes and performance of the overall system.

Topic 7: Continuous improvement of system performance.

Topic 8: Involvement of humans in the continuous improvement of system performance at all levels of the organisation.

These topics were introduced with guiding questions to be considered in the continuous improvement cycle of the system. In this cycle, robustness and resilience need to be addressed. The environmental context in which the HTO system is embedded also needs consideration. In Chapter 5, the need for the practical application of a systemic approach is demonstrated with various case studies.

As a main conclusion, the report finds that all managers, including senior management, should understand that the continuous application of a systemic approach is required to establish and sustain an effective management system and to foster a culture for safety. Both are essential to achieve, maintain and enhance safety in nuclear installations.

Chapter 1. Introduction

That human actions play a key role in the safe operation of a nuclear installation is out of the question. In the past, the role of humans was mainly discussed in terms of the risk of human error which needs to be minimised. There has, however, been an evolution in the understanding of the role that humans play in the engineered environment of a nuclear installation. In this regard the lessons learnt from the Fukushima Daiichi Nuclear Power Plant accident provide valuable contributions (ENSI, 2021).

Today, there is a well-established view that nuclear installations can be seen as systems influenced by humans, organisations and technology. These three key elements are under continuous and dynamic interaction and affect the performance of the overall system. The fact that such "complex systems" entail a huge number of diverse, interacting parts makes the system performance difficult to predict. The system performance cannot be fully explained by the effects of the individual parts of the system as these parts are strongly interrelated and changes in one might significantly affect others (Dekker, 2011). The conclusion can be drawn that a systemic approach needs to be applied to better understand the nuclear installation as a complex system and to improve its safety.

Furthermore, the nuclear installation as a system is not isolated from the rest of the world but embedded in a context. Stakeholders such as the public, regulatory bodies or suppliers are in continuous interaction and also affect the safety management of the nuclear installation. For example, an equipment modification in a nuclear installation may also require new competencies for equipment maintenance. This could lead to recruiting staff with these competencies, training existing workers or outsourcing particular maintenance tasks. This might also change the way work is carried out and the procedures that describe it.

This publication was developed by the NEA Working Group on Human and Organisational Factors (WGHOF) of the Committee on the Safety of Nuclear Installations (CSNI), which is active in the field of human and organisational factors (HOF). The group works towards an understanding of the use of HOF in the nuclear industry to support the safety of nuclear installations and improve the effectiveness of regulatory practices. In this context, it uses a multidisciplinary approach that considers the complex and dynamic interactions between humans, technology and related organisation(s). This report was developed by a task group consisting of different members of the WGHOF.

The publication was prepared for licensees of nuclear installations and nuclear industry regulators, including their technical support organisations (TSOs). The understanding and the practical use of the presented approach is essential for the

safety performance of nuclear installations and the effectiveness of regulatory practices. People from all levels of the licensee and regulatory bodies, including their TSOs, should make practical use of the systemic approach provided in this document. This entails considering systems and sub-systems and their interactions, including human capabilities and limitations, work organisation and job design, procedures, the design of technology, the design of the physical work environment, the human-machine interface, the management system, and the broader environment, to name only a few. In particular, this publication is for leaders at all levels of a nuclear installation who should consider human and organisational performance and use the systemic approach when establishing and sustaining an effective management system according to IAEA Safety Standards and IAEA General Safety Requirements (IAEA, 2006; 2016).

Chapter 2. **Objective and scope**

Many terms are commonly used when discussing human and organisation topics in a nuclear installation (e.g. HFE, ergonomics), depending on the context. The objective of this document is to provide the basis for a common understanding of the following key terms: human performance (HP), organisational performance (OP) and human and organisational factors (HOF). The strong interrelationship between these elements is explained with the help of a simple model leading to a systemic approach to safety already mentioned in the International Atomic Energy Agency's GSR Part 2 (IAEA, 2016). The scope of this document is to further elaborate on the existing IAEA documents (IAEA, 2016; 2018) to promote consistency in the nuclear community.

According to principle 3 of the IAEA Safety Fundamentals (IAEA, 2006), the organisation of the nuclear installation requires effective leadership and management for safety. All managers are required to establish and sustain an effective management system to achieve, maintain and enhance safety and to foster a culture for safety (IAEA, 2016). This system must integrate all elements of management so that requirements for safety are established and applied coherently alongside other requirements, including those for human performance, quality and security, and so that safety is not compromised by other demands. In this context, all managers are required to advocate and support the use of a systemic approach (i.e. an approach relating to the system as a whole in which the interactions between human, technological and organisational factors are duly considered).

This publication further elaborates on the systemic approach, provides guidance on applying this approach, and demonstrates the advantages of its application. The topics in Chapter 4 and the case studies in Chapter 5 help explain how to apply the systemic approach in different situations and demonstrate the benefit of doing so. The practical application of the systemic approach should address the robustness and the resilience of the system in order to continuously improve it. In the management system, account must be taken not only of its elements (humans, technology and organisation) and their interactions, but also of external influences. These influences can be of an environmental, social, political, economic or cultural nature.

Chapter 3. **Common understanding of terms**

Besides technological factors, human and organisational factors (HOF) also have an influence on the safety of a nuclear installation. However, a common understanding has not yet been reached of the term HOF and other terms used in this context, like human factors (HF) or human performance (HP). The analysis of a questionnaire among nuclear organisations of members represented at the Nuclear Energy Agency (NEA) Working Group on Human and Organisational Factors (WGHOF) reveals that there is no consistent definition of these terms. For example, the questionnaire provided different "in-house" definitions for HF like "all non-technological aspects", mostly understood as a "synonym for ergonomics" or as the "human behaviour in the system".

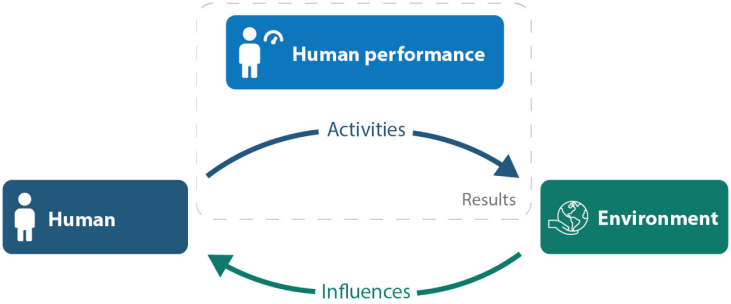
In IAEA-TECDOC-1846 (IAEA, 2018), the aim is to support the development and implementation of a regulatory oversight programme that adequately takes HOF into account to oversee safety throughout the lifetime of nuclear installations. For this purpose, "HOF are defined as the factors that have influence, in a positive or adverse manner, on human performance in a given situation, keeping in mind that safety is the result of the interaction of Human, Technology and Organisation" (IAEA, 2018).

It is important to note that human performance is not only influenced by human- and organisation-related factors but also contextual factors related to the technology as well as the interactions of all these factors.

For a better understanding of the terms and their interrelation, a framework is presented that is developed further with the introduction of a simple model. Figure 1 illustrates how humans are in continuous interaction with their environment. In the same way, personnel have an impact on safety in a nuclear installation, irrespective of their role in the organisation (e.g. workers, managers and contractors).

Human performance refers to *human activities and to the results of these activities*. It is important to mention both, because the way humans conduct their work (the activities), and the output of the work (the results) are equally important to safety. Although the results achieved by an activity may be desirable for the task objective and have value for the organisation, there can be undesirable behaviours (such as deviations from the safe way to carry out the task) that cause negative side effects on safety, such as taking shortcuts to complete a task quickly or achieving the task objective with unwarranted exposure to safety risks.

Figure 1: **Human performance**



Humans are under continuous interaction with their environment. Human performance is both the human activity and the result of the activity. Both affect the environment.

In the past, human performance evaluation often focused on the possible negative impacts, such as from human errors. A broader view of human performance considers that personnel in most cases contribute positively to safety, since people do their best to behave in line with safety and can detect and mitigate adverse circumstances while carrying out their activities. This is important to maintain to improve safety across the whole range of potential work situations. In this sense, the definition of human performance goes beyond the notion of human performance tools for error prevention.

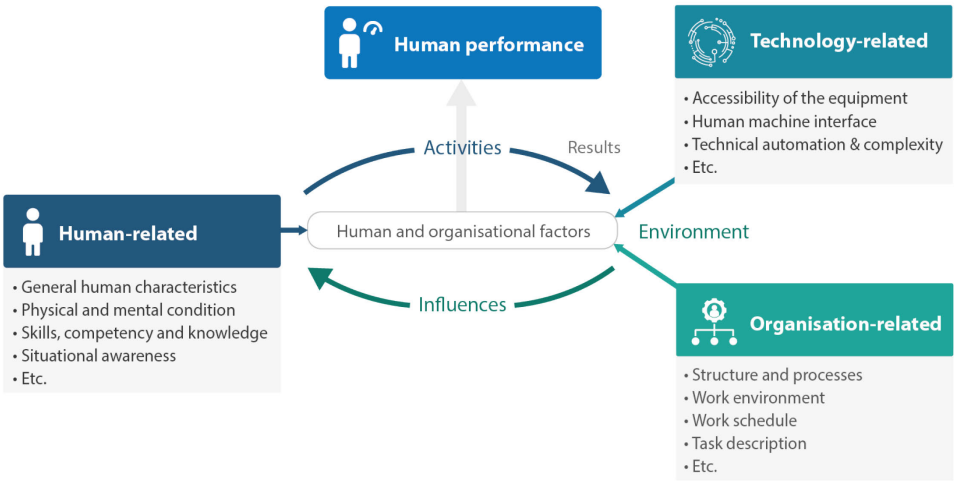
Personnel face many unexpected and unplanned situations for a variety of reasons. Differences between what a worker does (activity, work-as-done) and what a worker is expected to do (task, work as imagined) are often attributed to differences between the actual and expected situation. This is an important distinction. The real-world activities and outcomes of work may be different from those expected by managers or what was intended by the designers of equipment or by authors of the procedures that are used to carry out the work. The idea that it is possible to avoid situations that deviate from design expectations is not realistic. Real-world tasks often require local judgement and adaptations and can be performed successfully in several ways. Even in situations where workers follow a prescribed task exactly, they have to cope with variations in the context of the specific situation, implying deviations with from the task as anticipated and decisions about how to proceed.

As a result, workers may not be able to produce the expected results through strict adherence to the task-related documentation alone. When faced with real-world activities, workers make the necessary adjustments to task prescriptions (processes and procedures) and use their individual perception and understanding of the situation to complete the work. The flexibility and adaptability of humans is necessary to ensure safe operation of nuclear installations. The idea that human errors can be totally eradicated is illusory. Human errors depend both on the variability of human performance and the variability of the environmental situation.

Based on a human-centred view (ISO, 2016) and the influence of HOF on HP a framework has been developed (Figure 2). This model refers to the basic cyclical model (Humbel Haag and Linsenmaier, 2014). People perform activities in the context of an evolving environment. A multitude of factors influencing human performance in a specific work situation create complexity.

It becomes even more complex considering that these factors interact with each other and have a combined influence on human performance. The influence of these many interrelated factors is dynamic and continuously changing. The impact on human performance is therefore hard to predict. To get a task done, the worker always needs to adapt to the real word situation. Humans have the basic ability to do this.

Figure 2: **Human performance influenced by human and organisational factors**



HOF cover this range of factors influencing human performance. Based on the human, technology and organisation (HTO) approach, referred to in paragraph 1.2. of IAEA Safety Standard GSR Part 2 (IAEA, 2016), the factors influencing human performance can be divided into three categories:

- human-related factors;
- technology-related factors;
- organisation-related factors.

For a better understanding, Appendix I of IAEA-TECDOC-1846 (IAEA, 2018) lists several examples of the three categories, which are strongly interrelated.

Changing perspectives to a high-level view of the system allows the described model to become an organisation-centred view.

Organisational performance (OP) is in this respect characterised by the ensemble of interacting activities in the organisation (how things are done) and the results of these activities (the outcome of the organisation). The organisation of a nuclear installation and its performance can be seen as an example of such an ensemble. "Organisational performance" is also influenced by the wider range of human-, technology- and organisation-related factors, which continuously interact in a complex and dynamic way. The same line of reasoning applies to the technological performance if the system is looked at from the technological viewpoint. As a matter of fact, the human, organisational and technological performances are closely linked to each other and consolidate in the performance of the system (Hollnagel, 2016) as a whole.

Chapter 4. A systemic approach to safety

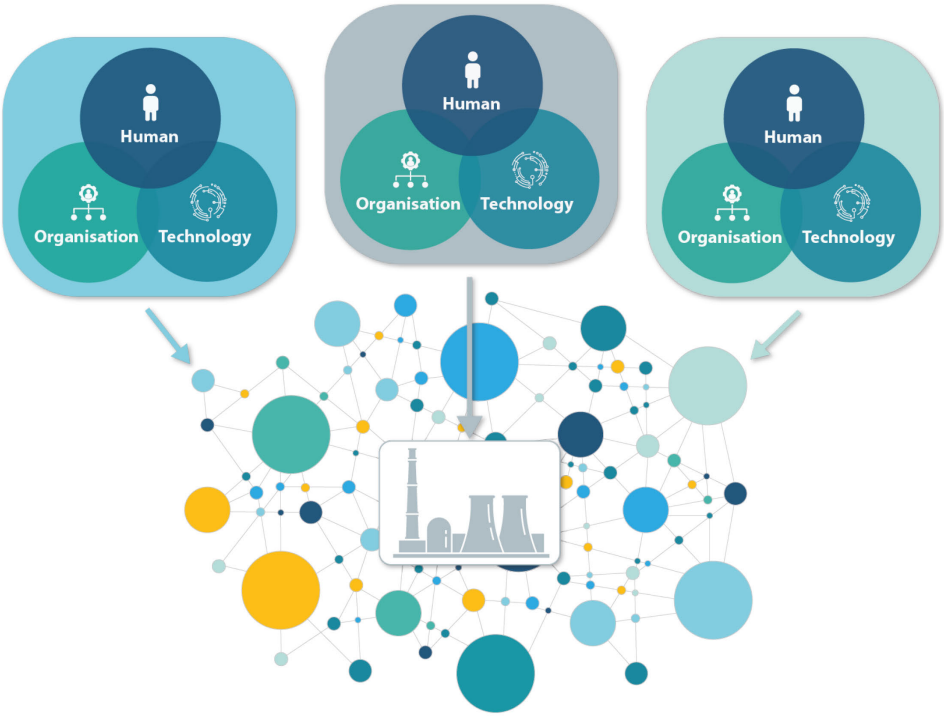
The concepts of "system", "sociotechnical system" and "systemic approach" are widely used in the field of industrial engineering. Nevertheless, the approach taken to address nuclear safety has historically been (and continues to be) to identify and analyse separately the technological, human and organisational factors (Humbel Haag and Linsenmaier, 2014). For example, the causes of events related to these factors are often analysed separately. This approach is not sufficient because the dynamic interaction of humans, organisations and technologies has an impact on safety. This is demonstrated by different case studies in Chapter 5.

In the system represented by a nuclear installation, technical, organisational and human components interact in ways of varying complexity. Ambient conditions such as work environment or work schedule will affect human reliability during the performance of sensitive safety relevant activities. Similarly, human and organisational factors (HOF) such as incomplete operational documents, confined spaces, equipment that is hard to reach, ineffective signage, inefficient communications, or inaccurate representation of the condition of equipment, can increase the risk of human error.

For the nuclear installation as a human, technology and organisation (HTO) system, achieving the intended results (under all foreseen and, to the greatest possible extent unforeseen, conditions) is challenging and requires the reliable performance of many HTO sub-systems related to different levels of the organisation. No matter if the technology, the organisation or the human is the main driver, a reliable execution of a sub-system requires certain preconditions, resources, control and time. Each sub-system is cross-linked with others. This leads to a network of sub-systems in the larger system with strong interactions of human-, organisation- and technology-related factors in all processes and at all levels of the organisation (Figure 3). Changes in one factor may trigger or require changes in other factors. This view enables a deep understanding of how the nuclear installation works that goes beyond the limitations of the isolated consideration of individual technical, human and organisational factors with respect to human performance. This view of the system as a whole is essential (particularly for leaders) to understand how it can support the people working within it.

These interactions generate a high complexity and dynamic behaviour in the system, enabling results that are greater than those of the sum of the parts. According to this "system emergence" it is possible that the results of the entire system behaviour differ from what is expected when looking at the results from the separate sub-systems.

Figure 3: **Network of interrelated sub-systems in the larger HTO system "nuclear installation"**



The performance of each sub-system is influenced by human-, technology- and organisation-related factors.

Because of this uncertainty in system behaviour, the human-centred view should consider that there is a possible gap between work-as-expected in working documents (e.g. procedure, task description, checklists) and work-as-done. Humans need, and are able, to adjust their activities depending on reality. This ability is not only important to achieve the intended results, but also to take care of the dynamic interactions between different sub-systems. This applies in particular to unforeseen or unforeseeable conditions that often occur in emergency situations. In this case, it is not only the better understanding and consideration of the interactions in the system that ensures successful performance, but also the ability to adapt and to cope with unexpected situations (see Section 4.2, system resilience).

4.1. The systemic approach to safety in the management system

The fundamental safety objective of International Atomic Energy Agency (IAEA) SF-1 (IAEA, 2006) is the protection of people and the environment from harmful effects of ionising radiation. This applies to all stages of the life cycle of a nuclear installation.

According to Principle 3 of the IAEA Safety Standards (IAEA, 2006), "leadership and management for safety", safety has to be achieved and maintained by means of an effective management system. Requirement 3 of IAEA Safety Standard GSR Part 2 (IAEA, 2016) emphasises that senior managers shall be responsible for establishing, applying, sustaining and continuously improving a management system to ensure safety.

In leadership and management for safety, the overarching consideration of the system, with the human, organisational and technological elements and their interrelations, must be addressed. Section 3.14 of the IAEA Safety Standards (IAEA, 2006) emphasises that an important factor in a management system is the recognition of the entire range of interactions of individuals at all levels with technology and with organisations. The IAEA Safety Standards (IAEA, 2006) point out at the end that it is the HTO system which ensures nuclear safety. Accordingly, IAEA Safety Standard GSR Part 2 (IAEA, 2016) requires senior managers and all other managers to advocate and support the application of a systemic approach – an approach relating to the system as a whole in which the interactions between technological, human and organisational factors are duly considered – to enhance safety and to foster and sustain a healthy safety culture.

It can be concluded that the application of the systemic approach within the management system is essential to safety. It is already integrated and required in the international regulatory framework.

4.2. Application of a systemic approach

The IAEA GSR Part 2 published in 2016 develops the concepts of the 2006 publication and considers lessons drawn from past events, in particular the accident at the Fukushima Daiichi nuclear power plant. In the context of leadership and management for safety, it emphasises the application of a systemic approach to establish and implement an effective management system (see Section 4.1).

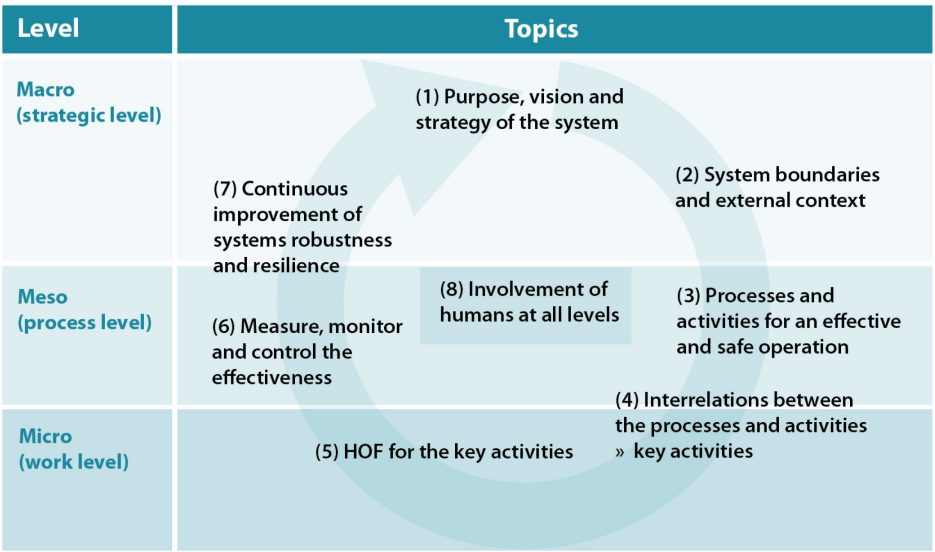
The question of how to apply a systemic approach is not so easy to answer as it concerns HTO systems that are inherently complex and dynamic.

The topics which follow aim to provide guidance for the fulfilment of the requirements from the IAEA GSR Part 2 regarding the consideration of the systemic approach (IAEA, 2016). In the context of management for safety, this refers in particular to the IAEA GSR Part 2 statement that "*A systemic approach relates to a system as a whole in which the interactions between technical, human and organisational factors are duly considered*" with the aim to continuously learn about, understand and improve the system performance.

The topics are introduced to provide guidance on the elements to consider when applying a systemic approach. It is not the intention to prescribe exactly how the systemic approach must be considered because there are different ways and methods to apply a systemic approach, e.g. the Functional Resonance Analysis Method (Hollnagel, 2012). The topics are applicable to HTO systems in general, so they can be applied to every system or sub-system that is "singled out", like a certain process or technological system. As not all topics are of the same relevance for every system, a

graded approach should be considered. Figure 4 describes the arrangement of the topics and the addressed organisational levels. It shows the flow going along the different macro/meso/micro levels with a continuous improvement in feedback loops. For a better practical understanding of the different topics, their consideration is illustrated in the case studies of Chapter 5.

Figure 4: **Topics for the application of a systemic approach in a continuous improvement cycle**



This scheme can be applied to various scenarios, e.g. in operation and maintenance of nuclear installations, in modification or design projects including organisational changes, in event analysis, regulatory oversight, or emergency preparedness (see case study in Section 5.1). It is obvious that the system as a whole to be considered is often the nuclear installation as an HTO system.

However, according to a fractal point of view of organisations (Vautier et al., 2018), it should also be possible to consider just a part of the system, like a technological system, a process, or an organisational unit. It should also be possible to look at a bigger system like the parent company group or even the framework of the national nuclear programme.

It should also be mentioned that the topics are not an instruction to be followed step by step. In fact, the significance of the topics depends on the specific case as shown in Chapter 5. The topic sequence provides an orientation based on the continuous improvement cycle of a management system, but it is not mandatory to follow.

Subsequently, each topic is specified by some guiding questions. Their practical consideration should be described appropriately.

Topic 1: ***Purpose, vision, strategy and objectives of the system***

- Does the purpose of the system defined involve all relevant stakeholders?
- Is there an inspiring vision that can engage all stakeholders?
- Does the vision of the system appropriately consider safety (with an appropriate safety policy)?
- Is a strategy set up to serve the purpose of the system and are appropriate objectives defined without compromising safety?

Topic 2: ***System boundaries and external context***

- What are the outputs and inputs of the system?
- Are the boundaries of the system well-defined considering that the system contains all elements required to satisfy its purpose?
- Are the external stakeholders and conditions that may influence the performance of the system determined and monitored (e.g. in case of a "nuclear installation" HTO system, the interested parties are the regulator, customers, suppliers, support companies, public, and non-governmental organisations)[1]?
- Is the impact of the external stakeholders and conditions on the system considered and addressed when setting up the strategy and objectives?

Topic 3: ***Required processes, activities[2] and intended results to achieve the objectives***

- How are the intended results of processes and activities derived from the system objectives?
- How are the processes established by setting up and sequencing different activities?
- How are responsibilities and resources allocated?
- How is the appropriate implementation of processes and activities ensured?
- How is safety given priority when establishing and implementing processes and activities?

Topic 4: ***Interrelations between processes and activities and identification of key activities***

- How are the (mutual) relationships between the different processes and activities using the identified operational experience feedback?

1. See Section 4.4 "The system in the external context."
2. A process is composed of a sequence of activities. During the setup of processes, the required activities are defined as "work-as-expected" (tasks). The effective performance of activities is the "work-as-done". According to Chapter 3 "work-as-expected" and "work-as-done" can differ from each other.

- Are the types (requests, orders, deliveries, etc.), defaults (delays, desynchronisations, bottlenecks, transmission errors, etc.) and strengths (on time deliveries, quality and reliability of transmissions, etc.) of relationships known and considered?
- How is safety considered when addressing the relationships between the processes and activities and how are new processes or modifications to existing processes designed, verified, approved and applied so that safety is not compromised?
- How are key activities determined based on the number of interactions with other activities and the possible consequences (risks) associated with safety?

Topic 5: ***HOF for key activities***

- What are the technology-, human- and organisation-related factors (HOF) contributing to the successful performance in a key activity?
- What are the interactions between these HOF?
- Are sufficient resources allocated for an effective and safe execution of each key activity based on the contributing factors (technological, human and organisational) and their interactions?
- How is an effective identification, co-ordination and synchronisation of the key activities managed so that safety is not compromised even if unforeseen or unforeseeable conditions and sequences occur?
- How is the variety of situations that could occur when operating in real-world conditions considered regarding sufficient margins for time, resource margins, support tools, as well as regarding the freedom for humans to make necessary adjustments for a successful and safe performance of activities?

Topic 6: ***Measure, monitor and control the effectiveness of the activities, processes and the performance of the overall system***

- How are the results the system performance measured (quantitatively and/or qualitatively), monitored and controlled?
- How are all activities and processes regularly evaluated with special regard to safety?
- How is the effectiveness of the overall system's performance assessed in an integrated way using aggregating information from the network of processes and activities?

Topic 7: ***Continuous improvement of the system performance***

- How does the integrated system assessment consider:
  - safety;
  - internal and external stakeholders;
  - Lessons learnt from operational experience and from successes (good practices);

  - identified potential side effects[3];
  - potential gaps between the documented prescriptions and the real-life performance also coming from unforeseen situations (variety of reality);
  - unexpected system performance related to the multitude of relationships between actors.
- How are the lessons learnt from the integrated system assessment used to continuously improve the system's performance with regard to its robustness and resilience?

Topic 8: ***Involvement of humans in the continuous improvement of the system performance at all levels of the organisation***

- How is humans' contribution to the overall system performance being made aware in the organisation?
- How are humans made aware of how they contribute to the HOF system and how are they encouraged to continuously improve the system performance with attention to safety?
- How is an interdisciplinary approach (diversity in competency) applied to ensure an adequate consideration of different points of view and a common understanding in particular with respect to the interrelations in the HTO system?

4.3. System performance improvement

Because of the high complexity of systems, it is not possible to foresee their performance in every situation. There is a multitude of interactions between processes and activities with all the human-, technology- and organisation-related factors. This is particularly true for rare situations such as emergencies. This is confirmed by the experience of accident investigations where system failure was a cause of an emergent phenomenon (Hollnagel, 2016). Therefore, maintaining awareness of the lessons learnt from significant accidents like the one at the Fukushima Daiichi plant is essential for continuous system improvement.

Improving performance of an HTO system requires both an impetus for continuous improvement and a better understanding and consideration of the interactions of processes and activities, which should be addressed in the frame of an integrated system assessment (system robustness) but also in conjunction with the improvement of the ability to cope with unexpected situations (system resilience)[4]. The resilience of a system depends on its ability to sustain the required system

3 Side effects happen when an activity causes more than just the intended result or at least has an influence on other results (in a positive or negative way).

4. *System robustness* is the ability to sustain the required system performance in case of foreseen events like changes or disturbances; *system resilience* is the ability of the system to cope with unexpected situations.

performance by adjusting its functioning prior to, during or following an event like changes, disturbances and opportunities (Vautier, et al., 2018). Learning, responding, monitoring and anticipating are therefore key abilities in the context of a varying environment.

Both the robustness and the resilience of the system need to be considered in the management for safety. The principles of a high reliability organisation (HRO) include striving for a culture of collective mindfulness (Sutcliffe, 2011). The following principles form the foundation for a mind-set that drives continuous improvement in the robustness and resilience of the system.

- *Preoccupation with failure*: Based on the acceptance that human errors are inevitable and that bigger problems are almost always preceded by smaller problems or anomalies, a culture in which the reporting of events and near misses is encouraged, gathered and learnt from is promoted and implemented ("just culture").
- *Reluctance to simplify:* It will not help to find fast answers in a complex system by simplifying the situation. It is essential to strive for a picture of the system which is as close to reality as possible. Therefore, a consideration of different opinions is required. Keeping in mind that the setting of system boundaries is arbitrary, spanning and looking beyond the system boundaries is also required.
- *Sensitivity to operations:* As front-line workers are close to the work on-site, they know about the real situation and may be in the best position to recognise a potential system failure or identify opportunities for system improvement. Leaders should foster open and frequent communication with those people and be sensitive to their feedback. Leaders should demonstrate their appreciation when workers are involved in the process of system improvement.
- *Commitment to resilience:* This is the ability to anticipate trouble spots and improvise when the unexpected occurs. The system must be able to identify issues like errors or unexpected situations that require correction while at the same time innovating solutions within a dynamic environment. Leaders should be prepared for emergencies and have clear means of communication and control. To foster resilience, leaders should emphasise the importance of working together in multidisciplinary teams and remove barriers to cross-functional collaboration. They should encourage flexibility in team members to accommodate changes in conditions or resources. Teams should be explicitly trained in how to manage unexpected events.
- *Deference to expertise:* Expertise is required when conditions of high-risk with rapid changes occur and sensemaking is difficult. The intervention of experts is essential for an urgent situational assessment and response. In order to defer to expertise, leaders must know who in the organisation has which specialised knowledge and competency.

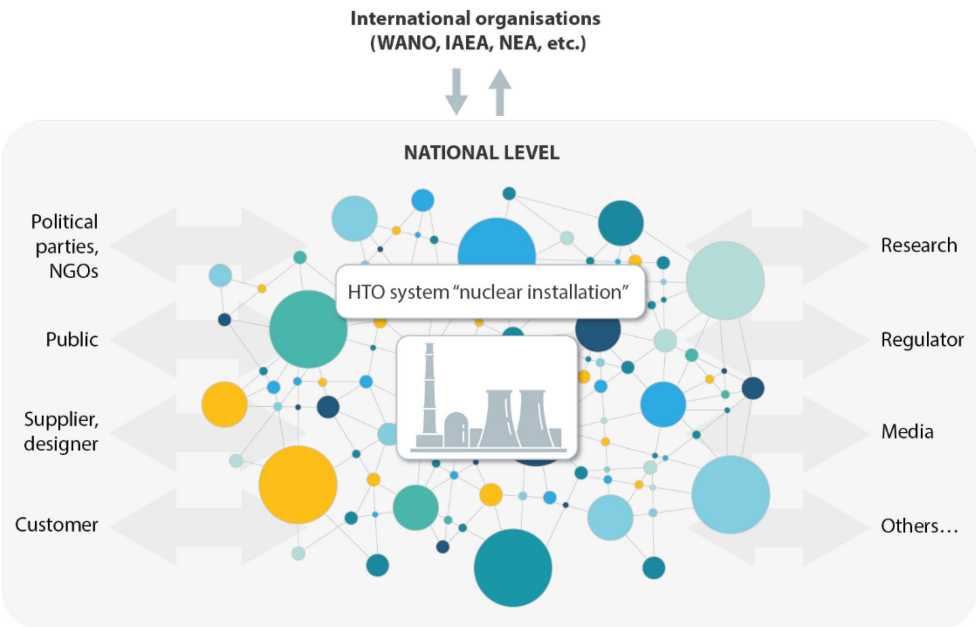
It can be concluded that the application of a systemic approach with the aim to improve system performance needs to address both the understanding and consideration of the interactions (robustness improvement) and the ability of the system to cope with unexpected situations (resilience improvement). Both can be fostered by the practical application of the HRO principles.

4.4. The system in the external context

The external context of a system is defined by drawing boundaries around the system. It should be kept in mind that the system boundaries are arbitrary. Systems thinking is also explained by going "up and out" versus going "deep and narrow", e.g. when looking for the causes of an event (Dekker, 2011). Understanding comes from seeing how the system is configured in a larger network of other systems, tracing the relationships with those other systems, and seeing how these spread out to affect, and be affected by, factors that lie far away in time and space.

For instance, the nuclear installation as an HTO system is not isolated from the rest of the world. It is embedded in an environmental context with many different stakeholders like the parent company (board of directors, ownership, shareholders, licence holder), regulator, suppliers, public, media, government and political actors. All those external stakeholders are under continuous interaction with the nuclear installation system and among each other (Figure 5) (Peloli, 2018). This institutional structure also forms a complex system with broader system boundaries on the national or even international level.

Figure 5: **Context of the "nuclear installation" HTO system and the external stakeholders**



Due to interactions with the external environment, the operating organisation of the nuclear installation must monitor, review and anticipate external issues that may influence the system's performance with respect to nuclear safety. An adequate response should be taken with the overall aim to improve the safety of the system. This should be done in a continuous and dynamic learning and improvement cycle (Espejo and Reyes, 2011). The following examples illustrate external factors influencing the nuclear installation as a system:

- The price for electrical power is a direct external influence on a nuclear installation contributing to electricity generation. A decrease in the price for electrical power leads to a loss of earnings. As a possible consequence, the plant is confronted with cost saving programmes with a direct impact on the resource and investment plans. However, it is not the only impact. The low prices also have an impact on the other players in the market. Less attractive market conditions will increase the risk that qualified external suppliers exit the nuclear business. The loss of these suppliers with their specific competencies will have an indirect impact on the organisational performance of the nuclear installation.
- The political framework influences the nuclear installation system. Political decisions regarding how to progress the national nuclear programme have a strong impact on many different stakeholders such as the public, education system the regulator, etc. For example, the political nuclear phase-out decision in some countries will have consequences on the attractiveness of nuclear as a field of education. This will in turn be felt in the recruitment of qualified nuclear experts by the operating organisation of a nuclear installation (Knissel, 2017).
- The material ageing of a nuclear installation is a key issue for the operating organisation and its performance. It is strongly influenced by external stakeholders. For example, in the current context of technological change, external suppliers would not guarantee the supply of spare parts for an obsolete piece of equipment. The switch to a new technology requires new competency also from external suppliers. Together with the old technology which is still present in the plant, this increases the spectrum of technologies that the operating organisation needs to cope with.

In this context, systems learning is essential because the faster the system runs through feedback loops, the better the system performance is understood and the more the system is able to adapt to changing (external) conditions (Espejo and Reyes, 2011). Going back to human and organisational performance, the drivers of this adaptation are humans.

Chapter 5. Case studies for the practical application of the systemic approach

In this chapter, different case studies illustrate the practical application of this systemic approach. The aim is to show how and when the systemic approach should be applied and the benefits of this approach. The topics discussed in Section 4.2 should help guide through the application.

5.1. Example of the systemic approach used in system engineering (maintenance of systems)

Context

The following practical example illustrates the benefits of using the systemic approach in system engineering. There is a safety system in a nuclear power plant dedicated to cooling the reactor core under high pressure in case of emergency by injecting water into the reactor pressure vessel (high pressure cooling system, topic 2). A high number of mechanical and electrical components interact to make the system work.

A young system engineer from the safety department is responsible for the reliable functioning of the entire system described above. To guarantee the operational availability of the overall system, the numerous sub-functions in the system must be reliable to perform as intended. Personnel from different technological disciplines (i.e. mechanical, electrical, operational departments) are needed for the appropriate maintenance and testing service of these functions according to their respective technical domains. Some of these functions are defined in the technical specification of the system and are key for the operational availability of the system and therefore are essential to operate the plant. In the past, the maintenance departments implemented several modifications to the system to ensure the reliable performance of certain sub-functions in the system. The reason for these changes were specific technological improvements within the original design specifications. The changes were realised mainly by the different technical departments (i.e. mechanical, electrical) without involving the adjacent disciplines.

Issue

After several maintenance-oriented modifications for different sub-systems were implemented, unusually high vibrations occurred during the periodic testing of the system's function. Nobody paid attention to the high vibrations until the first

damage (weld leakage) occurred. As periodic testing of the system was done during the outage of the plant, there was always time pressure to get the tests done. To save time, the specific leakage problem was addressed just through repair welding, without a detailed analysis of the failure mechanism. Subsequently, damage reoccurred several times at different locations of the system. Each time, no more was done beyond just repairing the damage.

The young engineer, who was inexperienced and was responsible for the overall system, raised his concerns about the safety issue to management. Instead of getting support, he was told by senior management not to disturb the outage plan and not to cause any delay in the restart of the plant. His recommendation to conduct a cause analysis was not taken seriously by the heads of the involved technical departments. The operational department was also not concerned about the recurrence of these events since the repairs did not affect the critical path of outage time plan.

This changed when the vibrations caused a weld failure and a pipe break during the periodic testing, just before the planned restart of the plant. The repair and the request of the regulator to carry out a root cause analysis concerning the failure caused a significant delay in the restart of the plant.

Outcome

The senior management recognised that an overall analysis of the problem was needed to understand the cause for the high vibrations in the system (topics 7 and 1). The technical staff in charge of the different system sub-functions started to collaborate on the possible interrelations of the different sub-functions of the system in relation to the repeating failures (topic 4). A communication process started across the different departments, from the mechanical to the electrical, safety and operational departments, and generated important insight regarding the interactions between the different system functions (topic 4). It turned out that it was not a single factor that caused the vibration problem but the combination of different interacting functions (valve opening time, frequency of emergency diesel engine, etc.). Even if past modifications were done within the design limits for operation, they caused a critical interaction leading to the observed vibration problem. The re-adjustment of some key functions in the system helped to effectively solve the problem of high vibrations and no further failure occurred (topics 5 and 6). From there on, regular meetings were organised in an interdisciplinary way where all the people involved in the system maintenance exchanged relevant operational experience (topic 8). The person responsible for the overall system organised and co-ordinated these meetings with strong support from the senior management (topic 1). This now provides an opportunity for continuous learning about the overall system behaviour for all people involved. These meetings developed so that there are not only discussions about specific system problems but also about how to anticipate possible issues and preventive actions to improve the robustness of the system (topic 7).

5.2. Example of a systemic approach in design or modification projects

Context

This second example illustrates the benefits of using the systemic approach in a design or plant modification project. In the main control room of a nuclear power plant, there is a need to record a significant amount of process data during operations. In the original design of this particular example's facility, this was done by pen-recorders. Over time, this was no longer considered state-of-the-art. The electrical department decided for various technological reasons (reliability, ageing effects, measurement accuracy, electrical interfaces, supplier's product support) to replace the old data recorders with new digital data recorders. This modification project was planned and quickly implemented by the electrical department (topic 2). The different technical departments of the organisation used to work more or less separately from each other. The person in charge of the project was a new recruit in the electrical department who proceeded according to the requirements of the management system. There was no consideration of how human and technological factors interact in the process of the required modification.

Issue

During the installation of the new digital data recorders, the operating staff were surprised because they were not informed or consulted about this modification. The head of operations asked the electrical division for clarification and received the answer that there was a strong need to change the data recorders for various technological reasons. The head of the electrical department added that operators should be quite content about the new state-of-the-art data recorders. After a certain time with the new data recorders in service, the operators in charge of the assessment of the process data identified and complained about missing functions for a trend analysis as required by the regulator. The method for data evaluation that was used before, with the old data recorders, could no longer be applied.

Outcome

The main users of the data recorders (the people from operation) reported the lack of functionality to the plant manager. The plant manager decided to deploy an interdisciplinary team to solve the problem (topic 8). The team recognised that the new colleague from the electrical department who led the project did follow the process for modifications in the management system correctly. Nowhere in the planning part of the modification process was the involvement of the users required. As the main corrective actions, human and organisational factors (HOF) checklists were introduced with a different level of detail along the different process stages that establish a user-centred approach in the design and implementation of new systems or modification of existing systems (topics 4 and 5). On the basis of the checklists it could be decided to what extent HOF aspects are concerned and if an involvement of a HOF specialist is required. These checklists were developed in a participatory process with the involvement of representatives from all the different technological domains as well as of the users, and under the lead of a HOF specialist.

It turned out that none of the further modification projects showed any issue with a lack of user consideration (topic 6).

Finally, a solution for the missing data evaluation with collaboration between the supplier and the operations department was found, but this generated a significant amount of extra time and costs.

5.3. Example of the systemic approach in regulatory oversight

Context

The following example illustrates the benefits of using the systemic approach in regulatory oversight. The purpose of the regulatory body is to strengthen nuclear safety through its supervisory work (topic 1). Suppose that a regulatory body performs regular oversight at a nuclear power plant. Information gathering is mostly carried out through document reviews. According to the internal structure of the regulator, the different disciplines traditionally work independently from each other. The exchanges between the regulatory body and the licensee take place between experts in each field, based on a profound common technological basis. The flow of safety relevant information within the regulatory body is more or less limited to the individual sections or fields. The HOF section consisting of people with relevant expertise is not well accepted because of a lack of engineering knowledge and weak cross-links to the different technological fields. Management by the regulator relies very much on its staff's competency in engineering across the entire oversight process. The enforcement process was realised in a single-loop learning mode. This means that when a problem occurred it was solved technologically without any view of the sustainable effectiveness of the corrective actions and there was no integrated assessment for safety.

Issue

One of the regulator's licensees reported frequent events that seemed to involve HOF aspects. These could not entirely be explained by just looking separately at the technological states and conditions of the installation and the results of the technical document review.

The regulatory body wanted to better understand the reasons for the accumulation of these safety relevant events at the licensee and so decided to investigate further (topics 6 and 7).

Outcome

The managers reviewed their oversight processes documented in their management system and determined that they were not appropriate to provide clarity in identifying the causes of the reported events (topic 4). It was decided to redesign the regulatory oversight process in a way that the safety relevant findings were discussed internally and analysed by a dedicated multidisciplinary team (topic 8). The exchange and discussion of findings in this team deepened, especially between the technical and HOF experts. The findings of the different technological fields indicated similarities in

organisational deficiencies. The following lists the findings of the multidisciplinary review (topic 6):

- The findings from the different maintenance inspections indicated that the provision of procedures within the licensee's organisation was incomplete, the maintenance personnel needed to carry out the work under time pressure, and the personnel's training status could not be verified.
- Regulatory inspections of the management system of the licensee showed that the roles and responsibilities of the people involved in the operating experience feedback process were not clearly defined, especially when organisational interfaces were concerned.
- The licensee had also undertaken a lot of improvement measures without finishing them.
- There was no effectiveness control in the corrective actions programme.
- The site inspector provided feedback saying that the management of the licensee seemed to consider the situation was going well, even if there were many minor events reported as well as a lack of leadership and a drop in morale among people in the field.

Next, the interdisciplinary team of the regulatory body used the information to perform an integrated safety assessment (ISA) by duly considering the licensee's whole organisation and interactions between technological, human and organisational factors to identify deficiencies in the overall organisation. For this assessment, the main contributing factors identified in the analysis of the recent safety-relevant events were also considered (topic 5).

The regulatory team identified a series of deficiencies related to HOF in the licensee's organisation, including an unclear strategy and objectives, poor implementation of the processes in the management system at all organisational levels, and a lack of effectiveness control of the management system (topic 6). The causes of the events were often traced back to interfaces between different processes which were not sufficiently addressed in the regulation of the management system (topic 4).

Based on the results of the ISA, the regulator was able to re-adjust its oversight focusing on the management system's effectiveness and the ability of the licensee to work in feedback loops with a clear strategy, corresponding objectives and an effective corrective action programme (topic 1). The management of the regulator requested that the work of the interdisciplinary team continue (topic 8).

Chapter 6. **Conclusions**

The analysis of views held by the nuclear organisations of members represented at the NEA Working Group on Human and Organisational Factors (WGHOF) showed inconsistencies in the definition and understanding of the terms human performance (HP), organisational performance (OP), human and organisational factors (HOF). In this document, a model was elaborated that illustrates the strong inter-relationship of these terms. Furthermore, it provided guidance (topics) and examples (case studies) for the practical application of the systemic approach to safety.

The following conclusions can be drawn:

- The model offers a better common understanding of the terms HP, OP and HOF.
- The model leads inevitably to a systemic approach to safety which is required to achieve, maintain and enhance safety in nuclear installations.
- The introduction of the continuous improvement cycle with the different topics to be considered provides guidance on the practical application of the systemic approach.
- Within the continuous improvement cycle both the robustness and resilience of the HTO system need to be addressed. The same applies to the consideration of the external context of the HTO system.
- Senior managers and all other managers in an HTO system should develop an understanding for the continuous application of a systemic approach and use it to fulfil their responsibility in establishing and maintaining an effective management system and a culture for safety.

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Annex 1. Example for the interaction of human, technology and organisation in everyday life

Imagine the activity of an airport's staff when leaving the passenger areas by doors that have to be opened by entering a PIN, or using an entry card to keep out intruders from areas that require special protection for reasons of safety or security. There are instances where the personnel enter such an area and continue on their way, without looking behind to ensure that they are not followed by an unauthorised person trying to get in. Such intrusions would be easy if the doors are designed in such a way that they close automatically and, importantly, slowly enough to enable an intruder to slip in. "Carelessness" would seem to be a simple and obvious explanation of the personnel's behaviour in such a case and remedies could include like disciplinary action, supervision or sanctions.

A systemic approach to the described scenario comprises the following:

- description of the system;
- description of the personnel's activity in a neutral, factual way;
- an inquiry into the reasons for the observed activity and identification of precautions against unauthorised and undetected intrusions.

Description of the system

A system can be defined by a principle that explains why the system has to be considered as an entity and not as an "aggregate", which is defined as an arbitrary, random set of objects. The underlying principle explains the purpose and the internal structure of a system. For example: the randomly scattered pieces of waste on a square after a public event correspond to the concept of an aggregate. A waste bin is already a system, because it has a structure and location that supports the deposition of things that people want to throw away without spoiling the environment. In the airport example, the principle would be to restrict access to specific areas to authorised people and prevent others from entering these areas. Components of the system would be as follows.

- departure and arrival areas, the areas with access restricted to authorised personnel and the doors between these two zones;
- safety and security regulations that explain why intruders must be kept off specific zones;

- the aforementioned doors and their design;
- entry procedure (PIN, entry card);
- implementation of safety and security regulations by the airport company (instruction, training, control of personnel's compliance with the regulations) including measures to support this implementation by subcontractor companies;
- organisational issues (number of personnel, workload, organisational structures and processes), including those of subcontractor companies;
- issues of corporate culture, respect, acknowledgement, leadership style, teamwork;
- personnel's behaviour;
- airport management's consideration of and preparation for threats and risks.

This is already a long list. But leave out one item and the system will be ill-defined or become an aggregate. Without for example the relevant safety and security regulations, it is not clear why access to a specific area must be restricted to authorised personnel and denied to all other persons in the departure or arrival areas of an airport.

Description of personnel's activity in a neutral, factual way

In the example, at a specific moment a member of the airport staff did not check if someone tried to follow them when they went from the passenger area to an area with access restricted to airport staff. The staffer exited through the door, which must be opened by using an entry card or a PIN and which closes automatically, but slowly enough to enable another person to get into the area with restricted access. Note that this description is free of terms with negative connotations ("carelessness") and unwarranted generalisations like "airport staff does not check if they are followed by intruders …." Such generalisations require suitable, systematic observations of personnel.

Blaming individuals or entire groups is likely to degrade the proper investigation of the activity, of its reasons, and of effective corrective measures. If people are confronted with observations like "you were careless and left the door open", they will try to defend or protect themselves. This could be done by answering investigator's questions vaguely or by emphasising those pieces of information that shed a positive light on their conduct. And if the investigation is prematurely narrowed down to an apparently obvious reason like "carelessness" or "lack of attention", it is likely to miss the true reasons of people's behaviour. A blame-free investigation does not amount to avoiding the term of human error. In safety- or security-relevant areas, there must not be intruders for obvious reasons. Personnel behaviour is thus "erroneous" to the extent that it makes intrusions possible. The term "error" is used to highlight an unacceptable deviation from a desired target state, which must be maintained for objective reasons, and to assist in the development of proper corrective measures.

An inquiry into the reasons of the observed activity and identification of precautions against unauthorised and undetected intrusions

The reasons and corrective measures related to the omission of controls by airport staff members, if an unauthorised person tries to follow a member of staff in protected areas, needs a systemic investigation. A few examples of causes and corrective measures are presented below, together with some hints on the effectiveness of the measures. It should be kept in mind that the causes may be interrelated and consequently require several suitably co-ordinated corrective measures that complement each other and are together more effective than any individual measure. Contributing reasons for the unauthorised and undetected intrusions into the protected area might include:

Human-machine interface (HMI) and technological control measures

Automation must be considered prudently. In this example, it is exactly the slow automatic closing of the door that favours intrusions. Modifications in the HMI design (e.g. automation for door closing) might decrease the likelihood of unauthorised and undetected intrusions.

Error prevention or error detection might be improved by measures like video surveillance, use of conventional keys to lock doors by hand, mirrors showing personnel what is happening in the doorway behind their back, photoelectric barriers with an acoustic signal, if someone tries to enter without prior identification by PIN or entry card, or a system of two successive doors which cannot be opened simultaneously. But there may also be adverse effects or shortcomings in such measures. Video surveillance may lower personnel's attention to intruders (the logic being that "because there is the video device which will detect intruders, there is no need to do it ourselves"). Conventional locks and keys have the disadvantage that a time-consuming replacement becomes necessary if a key gets lost and that immediate measures must be taken to control access during that time. Mirrors will be ineffective to the extent that the intruder manages to hide behind the back of a staff member. Acoustic signals may become ineffective if groups of staff members become used to crossing the photoelectric barrier together after the first person to cross the doorway entered the PIN or inserted her/his entry card. A signal triggered by an intruder might be attributed to a colleague who arrived a few seconds later and is passing the door. Having two doors seems to be quite effective if the door in front can only be opened if the door behind is closed. But it is also necessary to have an arrangement for opening one door before the other is closed in case of fire or other emergencies to enable people to evacuate quickly. Such arrangements might be used to shortcut the entry procedure.

High workload

If personnel must hurry to get their work done, they are more likely to skip tasks or task steps. A decrease of workload by employing additional personnel and/or automating or rationalising certain tasks may increase the readiness to perform the controls in question. An appropriate workload does not necessarily mean high performance in all tasks, but increases its likelihood.

Demotivation of personnel

In an organisation, there may be many sources of demotivation, which can result in less attention and effort when personnel fulfil their tasks. An in-depth analysis is required to uncover the nature of demotivating factors as well as the size and composition of the group of people affected by these factors. Proper corrective actions depend on the outcomes of this analysis and may range from open discussion of issues to the re-composition of teams, leadership-training or replacement of people with leadership tasks. Subcontractor personnel may feel demotivated if their salary and other advantages are inferior to those of staff who are directly employed by the airport company and perform the same work. In this case, the remedy is in principle obvious: equal monetary and non-monetary incentives for the same work and independent of company affiliation. While proper incentives and other factors of work motivation increase the disposition to perform well, they do not causally determine high performance. The change of an incentive is not a deterministic means of changing people's behaviour, but it can increase its likelihood.

Fitness for duty

Fatigue, illness or personal problems may divert attention from the task at hand. There may be underlying reasons why the worker did not report in sick or was unfit for duty. The worker may expect to be blamed or suffer poor treatment from colleagues who will have to do the person's work in addition to their own. Corrective measures may include a rigorous control of the fitness for duty before personnel start to work, to encourage people to report sick/unfit for duty, and to foster personnel's acceptance that a colleague or subordinate reports sick/unfit for duty and that this person's work will have to be done by someone else. These corrective measures will not guarantee a change in personnel behaviour, but will increase the likelihood.

Lack of training

If there is a standing order to airport staff to make sure that no unauthorised people follow them to areas with access is restricted to staff, it is worth considering that the memory of this standing order may have faded due to lack of refresher training. It is obvious that more frequent refreshers will support people's memory of the required behaviour. But too frequent refreshers may have the opposite effect of tiring people of the instructions and increasing reluctance to follow them. An example of this is the attention that airplane passengers pay to the cabin staff safety instructions prior to departure. Changing the medium of the messaging regularly may help staff to keep the message at the forefront of their minds when passing through to areas with restricted access, e.g. training refresher to reinforce why the behaviours are important, engineered door alarms, posted signs.

Supervisory observation

Supervisor observation of the extent to which personnel check for intruders may be considered as a means of promoting personnel vigilance. But unless the number of supervisors is sufficiently high, personnel might expect supervision to be improbable and behave according to their habits. Excessively tight supervision may

be counterproductive because it may be misinterpreted by personnel as a sign of mistrust and degrade the corporate culture of the airport. If this activity is undertaken, it must be with an attitude of positive reinforcement.

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Human and Organisational Performance in Nuclear Installations

This report from the NEA Working Group on Human and Organisational Performance establishes a common understanding around the terms human performance (HP), organisational performance (OP), and human and organisational factors (HOF) through a simple model.

The model presented illustrates the strong inter-relationship between the terms. It shows that HP includes both human activities and the results of these activities. HOF are the factors which have influence on HP in a positive or adverse manner in a given situation. They can be categorised as human-, technology- and organisation-related factors which are themselves under continuous interaction with each other.

The report highlights the need for all managers to develop an understanding that the continuous application of a systemic approach is required to establish and sustain an effective management system and to foster safety culture.

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