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Review

Human and organizational factors in European nuclear safety: A fifty-year perspective on insights, implementations, and ways forward

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ABSTRACT

In this essay we investigate the "lessons learned" within the domain of human and organizational factors (HOF) from operating European nuclear power plants (NPPs) in a fifty-year perspective. Specifically, we consider learning processes at an industry level that aim at promoting human contributions to nuclear safety. This is done by bringing together two main perspectives: (1) a historical perspective on HOF-related institutional and research initiatives is presented by outlining the history of nuclear safety according to three major nuclear accidents, (2) an applied perspective is provided on how HOF are managed in the field. This latter perspective rests on the results of the EU Project *LearnSafe*, conducted in the European nuclear industry between 2001 and 2004, and its re-evaluation 15 years later by means of an interview study carried out with 21 European managers from the nuclear industry. Our results reveal that the European nuclear industry has to some extent encoded the HOF lessons learned into routines, tools and systems. The three accidents have promoted a broadening of knowledge, ranging from simple ergonomics to crucial issues of interactions between major stakeholders in the nuclear domain. As a conclusion to our study, we suggest that academia and industry should search for improved collaboration, especially in terms of including HOF into safety activities and linking HOF issues to technical design factors and associated hazard potentials. Moreover, we conclude that avoiding major nuclear accidents requires a continuous re-invention of HOF, which should aim to involve and harmonize divergent interests of several stakeholders, demanding further research and efforts to translate insights into practice.

1. Introduction

Since the commencement of nuclear power on an industrial scale in the mid-20th century, industrialized countries across the world have embraced nuclear power. To date, 31 countries operate 408 nuclear reactors, of which 270 have been operational for 31 years or more [1]. Due to its hazard potential, the backlash against the peaceful use of nuclear energy has accompanied this industry since its beginnings (and still continues). Besides developing and implementing advanced technological safety controls, the nuclear industry is also characterized by the fact that it gives a special role to human and organizational factors (HOF) in the design and safe operation of its sociotechnical systems. The industry had to learn quickly that human behaviour makes a massive contribution to the safe functioning of nuclear production systems. Consequently, the industry's activities promoted not only individual human capabilities in the operation of these systems (e.g., through training, ergonomics, rules and regulations), but also an intensive examination of (inter-) organizational elements (e.g., management processes, cultural and regulatory influences) to ensure nuclear safety.

This essay considers "lessons learned" from operating European

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nuclear power plants (NPPs) during the last 50 years. It examines learning processes at an industry level that aim at promoting human contributions to nuclear safety, so-called human and organizational factors (HOF). In adopting a multidisciplinary and systemic view of the human contribution to safety [2], we define HOF as safety-relevant influences from the immediate working environment on individual and team safety capabilities as well as influences from organizing and implementing these internal and external performance conditions, which are constituted by (spatio-temporally remote) decisions from plants and their stakeholders aimed at regulating and managing nuclear facilities. Adopting this systemic view rests on the assumption that the influence of HOF is not limited to social systems, but that conditions and capabilities of technical systems are also susceptible to HOF; for instance, through maintenance errors introducing hidden deficiencies in available technical or administrative safety barriers. Therefore, we generally assume that promoting HOF means supporting people, teams and individuals, to do the work they are supposed to do, whether it is based on adjustments to the technical systems or finding organizational solutions that support them in their work.

Our essay focuses on HOF lessons learned only within the European nuclear industry. Our analysis should be taken with caution, especially when cultural, political and economic influences on nuclear safety are considered. Restricting ourselves to European NPPs already presents a large diversity of views, referring, for instance, to the different national high-level policies that present in themselves very different interpretations [3,4]. We feel, therefore, that our restriction is justified. Moreover, we do not intend to provide an exhaustive review of specific HOF issues and implementations, nor do we adopt an all-encompassing view of learning processes in the industry. Instead, we examine how operational and managerial experiences with HOF are converted into safety knowledge, which is retained in institutional and academic repositories, and transferred within and between nuclear organizations. Considering learning processes at the level of the nuclear industry means also that our focus is clearly more on the transfer of knowledge between organizations, rather than on learning dynamics within an organization.

The authors of this essay have different disciplinary and national backgrounds, as well as varying lengths of time dealing with HOF in the European nuclear industry. Nevertheless, all have extensive experience in the applied field and research work in nuclear industries over many years, at national and international levels, and for different nuclear stakeholders. Pooling these resources and personal experiences allows us to reconsider old "facts" and to project new needs, covering observations on the discovery, the development and the promotion of HOF over a period of about 50 years. This is done by bringing together two main perspectives. Firstly, a historical perspective on HOF-related institutional and research initiatives is presented by outlining the history of nuclear safety according to three major nuclear accidents—at Three Mile Island (TMI), Chernobyl, and Fukushima. Each accident triggered a specific view of the human contribution to nuclear safety, leading to specific conclusions drawn about potential causes and countermeasures that were implemented. Secondly, we adopt an applied perspective on HOF concepts in the European nuclear industry; namely, we are interested in how HOF concepts and solutions (i.e., the lessons learned promoted by institutional and academic actors) are implemented in daily operations. This is done by examining the results of the EU Project LearnSafe [5], conducted in the European nuclear industry between 2001 and 2004, and re-evaluating the LearnSafe results 15 years later by means of an interview study with European NPP managers.

Our essay is structured in three sections. The first provides a historical overview of the development and significance of HOF, illustrated by the responses to three major nuclear accidents. It is based on a timeline describing four phases, which trace the identification and development of HOF-related concepts during each period, while paying attention to the nuclear industry's "lessons learned" manifested in scientific conference proceedings and articles, accident reports and institutional publications. The second provides an applied perspective on the implementation of HOF practices in the European nuclear industry during that time period. It presents the results of the LearnSafe project in 2004 and its re-evaluation 15 years later, allowing us to cover the complete period of how the European nuclear industry encodes HOF lessons learned into safety and work routines and practices. The final section brings both perspectives together by contrasting developments and implementations of HOF concepts, both on paper and in practice. Finally, we reflect on how the development and implementation of HOF-related concepts have influenced the nuclear domain during the last 50 years and draw conclusions about learning regarding HOF in establishing nuclear safety.

2. Historical perspective on HOF in nuclear industries

Nuclear is a technology new in the history of mankind. For a general view since its inception, one may use a simplified timeline (Fig. 1). In one flash, the bomb over Hiroshima made the whole world aware of the technology. The event started research activities in many countries, especially connected to weapons development. This also raised concerns about what a proliferation of the new technology would imply for the world. An important response to these concerns was the Eisenhower "Atoms for Peace Speech" before the United Nations in 1953, which aimed to moderate the arms race and open up nuclear technology for civilian use. However, the race between the two superpowers continued and in 1962, during the Cuban crisis, the world was brought to the brink of nuclear war. Fortunately, projections of the consequences of an all-out war persuaded the leaders of the two superpowers (Kennedy, Khrushchev) to listen to reason and the threat was averted. When these events were subsequently analysed, many details illustrate aspects of the importance of HOF issues on chains of events [6].

The first plants for electricity production—in the Soviet Union (Obninsk, 1954), the United Kingdom (Calder Hall, 1956), and the United States (Shippingport, 1958)—were successful enough for a period of rapid design and construction to be started; however, the need for safety became evident in these three countries through accidents in prototype reactors (the Kyshtym accident in 1957; the Windscale fire in 1957, and the explosion and meltdown of SL-1 in 1961) that are not as well documented as the three accidents we discuss below. The civilian reactors that were constructed in these three countries obviously took the technical lessons learned into account, through the application of the safety principle Defense-in-Depth (DiD). This principle is applied through the use of redundancy, separation, and diversity. A systematic application of DiD implies that consecutive safety barriers are independent; otherwise, the plants would be vulnerable to common cause failures (i.e., one single failure could make several of the safety barriers non-functional in situations where they are urgently needed).

In 1979 there were already 225 NPPs around the world trying to fulfil the unrealistic promise of "electricity so cheap that no metering is needed" [7]. That year, the accident at TMI occurred and, later, two more major nuclear accidents: Chernobyl and Fukushima. We discuss these three accidents in more detail below to explore how deficient approaches regarding HOF issues at that time contributed to the sequences of these three events.

2.1. Lessons learned from the TMI accident

The period before the TMI accident was characterized by a building spree, where several new NPPs were put into operation each year. That rapid rate of building also occurred in Europe, with new plants in Belgium, Germany, Finland, France, Holland, Italy, Spain, Sweden, and Switzerland. In the US market, four large companies—Babcock & Wilcox, Combustion Engineering, General Electric and Westinghouse—competed fiercely. Of these, Westinghouse won contracts in Europe. The owners of the new plants in the US were mostly companies with experience from coal-fired power plants, which—according to

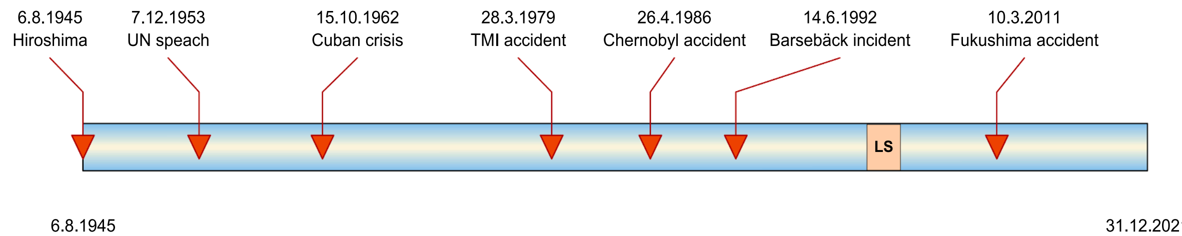

Fig. 1. A timeline of nuclear power. *Note*: LS is the position of the LearnSafe project on the timeline. *Source:* Authors.

some analysts—conceived nuclear power as "a way of boiling water to get steam to turn a turbine". Consequently, that conception did not place much emphasis on HOF issues, besides how humans had to operate machines, and their malfunctions. In Europe, the new plants were commonly national undertakings, requiring investment in research and education. The new plants in the US often recruited personnel from nuclear submarines for their operations, resulting in plant cultures in the US and Europe diverging to some extent regarding technical and, in particular, HOF issues [8].

Two units were built at Three Mile Island near Harrisburg, Pennsylvania. On 29 March 1979, the TMI-1 had already operated for nearly 4 years and was down for refuelling. TMI-2, a sister plant to TMI-1, had entered commercial operation only three months before the accident. A small disturbance (i.e., a postulated initiating event, PIE) at TMI-2 on the secondary side increased reactor pressure and led to the opening of the pressure-relief valve. The accident sequence started when the valve did not close as it was supposed to. The operators did not notice the open valve and large amounts of reactor coolant escaped. The operators could have stopped the sequence of events before its development into an accident, but deficiencies in several systemic HOF issues gradually led to the unfolding accident.

The sequence of events has been thoroughly analysed, not only in official documents [9,10] but also in reports from nuclear institutions [11] and in many academic articles [12]. The verdict is unanimous: the accident was caused by many simultaneous deficiencies regarding control room designs, training, operating procedures and applying lessons learned [9]. In addition, investigations revealed problems with systems that manufactured, operated and regulated nuclear power production including structural problems in the organization, process failures and lack of communication between key individuals and groups [13]. These findings immediately led to much activity in the nuclear industries around the world, in the national regulatory agencies, and in the global research community. We do not want to sum up the massive responses to the accident around the world, but we still want to pick a few to illustrate the level of concern this nuclear accident introduced in various places:

- In the US, the accident led to the establishment of the Institute of Nuclear Power Operation (INPO), which can be seen as an institution located between the industry and the regulator. INPO got the important role in developing organizational approaches to safety within the nuclear industry in the US [14].
- The United States Nuclear Regulatory Commission (USNRC) issued many NUREG documents (i.e., regulatory documents by the US regulator USNRC), which were intended to take care of the problems. Two documents (NUREG-0700; NUREG-0800) are still relevant and are kept updated even today [15,16].
- In Sweden, the accident led to a referendum considering the Swedish nuclear power programme. Three possibilities were put on vote and all assumed a stop to building new NPPs and plans for shutting down the 12 reactors that were operating at that time.

In retrospect, the TMI accident is astonishing because most of the recommendations that were suggested after the accident were not new. There should have been common knowledge and experience to avoid the most obvious problems that were subsequently highlighted. A remarkably similar sequence of events, for example, had taken place in an incident at the Davis-Besse NPP in 1977 but the TMI operators had not been informed or given training of it [9]. Another example is the NATO conference held in Berchtesgaden, Germany [17], where a presentation went through the findings of a forthcoming report [18]. The presentation illustrated several control room deficiencies found at US NPPs at that time. Also, prior to the TMI accident training of operators in various accident sequences using full scope simulators was a standard practice at many power plants around the world.

In the aftermath of the TMI accident, the first probabilistic safety assessments (PSAs) were developed. The PSA methodology provides means to calculate probability estimates for selected sequences of events that may challenge plant safety. Selecting a set of accident scenarios, their combined impact on the core damage probability can be calculated. The methodology has been successfully used for technical improvements and preliminary suggestions for extending the methodology to HOF issues were proposed [19].

The presentations and papers at a conference in Knoxville, Tennessee, in 1986 provide an overview of activities initiated by the nuclear domain in response to the TMI accident [20]. Browsing the sessions and papers one can see—among other things—that control room design, operator support systems, and human reliability were addressed. Additionally, organizational issues were presented in two sessions, with papers on communication, training, and human performance as well as work and organizational structure. It is also notable that members of the international nuclear community were well represented at the conference. The documentary nature of the conference material cannot fully reflect the implementation of lessons learned around the world; however, we can see that at least awareness of the importance of HOF was increasing, taking the first steps.

2.2. Lessons learned from the Chernobyl accident

On 26 April 1986, the Chernobyl accident occurred near the city of Pripyat in Ukraine (i.e., only a few days after the conference described earlier). The first information in the West was received at the Forsmark NPP in Sweden, where radiation scanners reacted on people going home after work. That caused some initial confusion, but investigations showed that the contamination was coming from outside. Assessing the fallout, it rapidly became clear that the likely origin was a nuclear accident abroad. The Soviet authorities tried to cover up the accident to their own citizens for about 36 h and, also, in their responses to the West. When a satellite picture taken on 29 April showed the burning reactor, they yielded and admitted that an accident had taken place.

The sequence of events started with the preparation to make a turbine roll-out test at around noon on the 25 April, which would end in a shutdown state of the reactor. Unfortunately, another regional power unit went offline, and the grid control centre asked the fourth Chernobyl unit to extend its production. The plant agreed but left the emergency core cooling system disabled, which was one of the preconditions for executing the test. Around midnight, the grid control centre stated that the shutdown could resume, and the control room operators started preparations for carrying out the test. Due to an apparent lack of understanding of the reactor's dynamic behaviour, it was brought to an unstable state. The control room operators were presented with indications they did not understand and when they activated the reactor trip, that action determined the fate of the reactor. The reactor went prompt critical and exploded in a power peak a thousandfold larger than the design power of the reactor. This blast in turn caused a steam explosion, the second explosion, which finally destroyed the reactor and its building.

The accident spread large amounts of radioactivity both locally and globally. It left an exclusion zone of about 2600 square kilometres uninhabitable for people. An understanding of the sequence of events together with the suffering of local people can be imagined when you read novels about the accident [21,22], which are based on the opening of old Soviet archives. The design of the reactor was developed from military reactors for plutonium production. The reactor was unstable (positive void coefficient) in low power regions. The NPP site had no emergency plans and everything was handled in a culture of secrecy. Officials were apparently afraid to make decisions that could jeopardise their positions, which meant that almost everything had to be checked with party officials in Moscow.

After the accident, an international meeting was assembled in Vienna on 25–29 August 1986 [23] and the term a deficient “nuclear safety culture” was used as an umbrella cause for many of the issues that are mentioned as more specific contributory causes (e.g., inappropriate design, no preparedness for emergencies, operators’ weak understanding of reactor dynamics). The report caused a lot of additional activity at the International Atomic Energy Agency (IAEA). The second document with HOF content was published in 1988 [24] and the third in 1991 [25], the latter defining how the concept of “safety culture” should be interpreted. Interestingly, this first conceptualization of safety culture also integrates so-called higher levels affecting nuclear plant safety. Besides defining requirements in terms of managers’ and individuals’ commitment, the “highest” level is also addressed: the policy or “the legislative level, at which the national basis for Safety Culture is set” (25:5). Since then, several more of the so-called INSAG reports have been published as well as other reports providing guidance for how to assess and develop safety culture in NPPs [26–29].

It took some time for the introduction of safety culture to settle in the nuclear industry. Without any scientific foundation, this concept was out in the nuclear world; and it was necessary to give life to an ambiguously defined concept, even if one was not even clear about whether culture is meant as “a pattern for behaviour” or “a pattern of behaviour” [30]. Accordingly, the way the concept of safety culture has been considered within the industry depended very much on how corresponding national regulators defined their own requirements regarding safety culture. This, in turn, depended on how they reacted to guidance obtained from IAEA, through direct consulting and the so-called IRRT assessments [31], which is an activity with peer reviews that national regulators are exposed to. A sweeping response was that everything that had some relationship with safety and human behaviour was now seen as a component of the safety culture at a plant.

It is not possible to give a comprehensive account of the HOF improvements that were made at the NPPs in the Western world, but apparently—due to the large differences between the Chernobyl plants and Western NPPs—they were mostly handled in training and written material, which aimed at promoting a broader understanding of safety culture and its practical implications for NPP operations. Nevertheless, we want to collect a few events that can be considered as directly caused by the Chernobyl accident, namely:

- This accident had a global impact on radioactive fallout, which resulted in the forming of the World Association of Nuclear Operators (WANO). The political state of the world at that time forced the establishment of four regional offices (Atlanta, Moscow, Paris, Tokyo) with headquarters in London.
- European concerns for nuclear safety were discussed at an EU level in Brussels, leading to the establishment of the Western European Nuclear Regulators Association (WENRA), which—among other activities—started work on increased harmonization of regulatory requirements in Europe.
- Many plans for new reactors in Europe were shelved.

In addition to these political developments, there have been increased efforts at institutional and academic levels to make the concept of safety culture workable. These initiatives relate primarily to questions of what a safety culture is, how it can be assessed and positively influenced, focusing on safety culture as a somewhat all-inclusive remedy [32,33]. In addition to these efforts, the concepts of organizational learning as well as the management of safety came increasingly into focus: on the one hand, as an important component of safety culture (in the case of organizational learning) [34], and on the other hand, as a means to foster or complement safety culture (in the case of safety management) [35,36], with which a more visible promotion and guidance of developing safety culture was promised. This focus was also triggered by an increasing change in political, regulatory, and economic parameters at the turn of the millennium, leading to the initiation of the EU LearnSafe project (described later).

2.3. Lessons learned from the Fukushima accident

The Fukushima disaster on 11 March 2011 was different as compared with the two earlier accidents because it was caused by an external event: an exceptionally large earthquake and a subsequent tsunami. The height of the tsunami, more than 11 m, was a beyond design basis accident (DBA). This means that although the design of the Fukushima Daiichi plant had considered possible accidents scenarios, which involved earthquakes and tsunamis, the safety precautions installed were only designed for a tsunami about half the height of what struck the plant (i.e., the design base was 5.7 m). Because the event was beyond DBA it is easy to understand that the consequences were far more severe than what had been prepared for. All critical buildings that were inundated by water lost their electric power, as did the buildings housing the emergency diesels that were assumed to power cooling pumps in the event of an accident. The plants were all shut down properly at the earthquake, but the residual heat removal stopped when the tsunami arrived. Without residual heat removal, the reactors and the spent fuel storages at the site overheated. In the reactor vessels, the zirconium in the fuel elements reacted with steam to form hydrogen. During the events, at least three hydrogen explosions were registered, which destroyed the leak-tightness of the containments that should have protected against releases of radioactivity. The seawater flooding the site had its own consequences, spreading radioactivity everywhere—onto the ground, into groundwater, and sea. The inventory of radioactive materials inside the reactor pressure vessels was considerable. A straightforward answer to HOF issues that mattered in this accident can be found in an IAEA report summarizing the results of an international expert meeting in 2013 [37] as follows:

- “The traditional approach to safety should be complemented by a systemic approach that considers not only the human, organizational and technological factors that contribute to safety, but also the complexity of the interrelationships among them.
- Regulatory oversight and assessment of NPP safety should include safety culture.
- The review of the IAEA safety standards should take into account the lessons from the Fukushima Daiichi accident involving human and organizational factors” [37:2–3].

We agree wholeheartedly with these conclusions; however, it may be necessary to go beyond those points, especially to shed more light on the relation of these insights to the event. The critical question in this case concerns the design base applied to the plants on the site. According to our understanding, evidence of tsunamis has been found to indicate about 11 m-high tsunamis in a thousand-year perspective [38]. We are unable to judge whether or not that was known and acknowledged by governmental or TEPCO officials; nevertheless, it would indicate a core damage probability larger than 10^{-3} per year (i.e., one magnitude larger than commonly accepted). The events at the Fukushima Daiichi site may also be considered as violations of the single failure criterion (even though this criterion is usually applied for single systems) [39] because a single external event resulted in core damage for four of the reactors on the site.

With regard to this, the IAEA report [37:14] speaks of the necessity for a paradigm shift, alluding to the need to understand that the more perfect the system that is developed for a specific situation, the more inflexible the system becomes for situations that might occur outside the defined boundaries of that specific situation. One can interpret this to put more emphasis on risk assessments, both qualitative and quantitative, by which the need for improvement also applies to the HOF area. More details, especially for emergency preparedness and responses (such as roles and responsibilities, training and use of operating experience influencing performance), are to be found in the specific presentations at the expert meeting [37], which include many concrete suggestions for improvements. We have selected the following lessons learned from the Fukushima accident, which give a flavour of issues noted:

- WANO abandoned its former gentlemanlike principle not to pay attention to technical solutions at the plants of their member countries.
- The accident was severe enough to cause a political need for large and visible improvements, which were perhaps a subsequent goal and reached with the EU requirements for stress tests.
- It may be noted that the reactors at the Fukushima Daini site, located about 20 km south along the coast, did not experience core damage, the reason being exceptional activities undertaken by their operational staff to build and operate temporary supplies of electricity.

What becomes evident from this is that the Fukushima accident has led to a change in thinking in the nuclear domain, reinforcing the idea that NPPs are open systems. Although the TMI and the Chernobyl accidents forced the industry to take a broader view of a variety of separate and, in the case of safety culture, overriding HOF, the Fukushima accident showed that one single event, the earthquake and the tsunami it caused, led to disaster. One can therefore argue that the plant had no protection against the event when it occurred, i.e., the calculated core damage probability was based on the probability of an earthquake causing a tsunami less than 5.7 m. The reason for this misleading risk assessment goes back to assumptions stemming from the design of a plant, which have their origins in joint interactions between regulation and management. National initiatives, such as the abovementioned stress tests, quickly followed the accident. However, there was also, in the area of HOF, an increased focus on nuclear regulatory processes, risk assessments and emergency planning, which resulted in, for instance, recommending regulatory bodies to reflect on their own safety culture or further developing safety requirements regarding internal and external hazards [37].

In summary, the scope of HOF has been broadened throughout the period considered here. Although the focus at the outset of the nuclear industry was primarily on the human–machine interface involving ergonomic issues with regard to basic human factors, it expanded over time to include the entire sociotechnical system performance with its inherent interactions in terms of a weak regulator, no emergency plans, and the need to go to the top to get approval for suggestions. Most recently, after Fukushima, this industry again had to learn painfully that NPPs are open systems, and safety–critical influences also overcome the boundaries of a single plant illustrated by a deficient understanding paired with helplessness with regard to external influences on nuclear safety.

In the next part of this essay, we trace and evaluate how the lessons learned on HOF illustrated above have been transferred and applied in the field. This is done by outlining the results of an EU nuclear research project, LearnSafe (conducted from 2001 to 2004), and the re-evaluation of the results and implementations made at European NPPs 15 years later.

3. Investigating the implementation of “HOF lessons learned” in the field: The LearnSafe project

The overarching goal of the LearnSafe project was to provide a snapshot of managing safety in the nuclear industry in 2004, and to “translate” an integrative perspective on the management of safety and safety culture into practical approaches with special emphasis on methods and tools supporting organizational learning. The project was based on the lessons learned from the TMI and Chernobyl accidents and had a focus on the operation and management of NPPs. It involved five European countries, several plant owners and one international organization, the WANO Paris Office. It drew on an earlier EU project ORFA, which was a cooperation project between seven partners investigating the impact of organizational factors on nuclear safety [40].

The participants in the research were senior managers at NPPs and at corporate level, who were responsible for strategic choices and the allocation of resources. Based on the “lessons learned” from Chernobyl and the (looming) academic spotlight on cultural and managerial factors at that time [41], it was intended to investigate the ways senior managers viewed and approached nuclear safety and, consequently, to create methods and tools supporting processes of organizational learning at NPPs. At this time, organizational learning was becoming increasingly important for the nuclear industry—as an important element of a plant’s safety culture—in its adaptation to changes in the political and economic environment, in regulatory requirements, in the ageing workforce, and in the technology in the plants [42:14]. It was commonly recognized that safety problems, real or perceived, always pose a risk to the business of the utility or corporation. Serious cases would mean regulatory intervention with the threat of licence revocation, loss of production income, remedial investment costs and potential or actual damage to their reputation, all on a massive scale.

The project proposal with the undertakings of the consortium was filed and accepted in 2001. The research examined (a) senior managers’ perceived challenges to nuclear safety, (b) their general assessment of functional activities promoting nuclear safety and (c) the most common hindrances to and facilitators of organizational learning. This focus rests on four parameters, which were identified as main drivers of change at that time, i.e., ageing plants, the generational change, increasing competition in the market, and changing political and societal requirements.

The close involvement of several NPPs in the project made it possible to benchmark approaches to managing nuclear safety, promoted by the collection, analysis, and utilization of operational and managerial experiences between the project partners (including peer-review processes providing insights and potential issues for organizational learning as reviewers and as being reviewed). These experiences were empirically derived, mostly in the form of recommendations, suggestions, and good practices, which were assigned to specific areas of managing nuclear safety. Information about LearnSafe has been publicly available since the beginning of 2019,[1] providing an integration of the results of the project and details on good practices as identified in the project.

3.1. The LearnSafe project: Perceived challenges and practices of managing nuclear safety in 2004

Based on a refined list of safety related activities, which was derived

[1] https://www.bewas.fi//learnsafe.html.

from the earlier ORFA project, it was decided to investigate the managers' perceptions of emerging challenges, functional safety activities, and hindrances and facilitators of organizational learning. For that purpose, so-called Metaplan sessions were conducted with senior and middle management groups as well as in interviews with corporate vice-presidents and groups of managers at the participating plants. All collected statements were coded and grouped using two methods: content analysis [43,44] and clustering analysis (using the Metafuzz method) [45,46].

An overview of the results obtained is presented in Table 1 with regard to the three main categories identified. The statements were clustered into eight main challenges for managing nuclear safety at that time, ranging from external factors such as economic pressures, finding suitable recruitment bases (i.e., maintaining nuclear know-how), dealing with national authorities or building up public confidence and trust, to more internal challenges such as conducting training and succession planning (i.e., human resource management), establishing a sound safety culture and climate, providing adequate safety resources (i.e., focus and priorities) or protecting the assets represented by the technical condition of the plants.

Eleven general clusters of functional safety activity areas promoting nuclear safety were identified. All are areas that focus on optimizing the impact of human and organizational contributions to nuclear safety such as risk analysis, operational decision-making, or management and quality systems. Finally, statements on facilitators and hindrances of organizational learning were collected and structured around eleven clusters. Depending on its manifestation, in each cluster there were statements on both facilitators and hindrances for organizational learning processes in NPPs.

We do not want to go too deep into the results of LearnSafe[2] but we would like to reflect here, on a higher level, the main results obtained based on the focus of this essay, i.e., on the understanding and handling of HOF in the field at that time. The results illustrate that even in 2004, HOF issues played a crucial role in managing nuclear safety and organizational learning. Although the results rely on perceptions of managers and their assumptions about how to manage nuclear safety (without any verification as to whether these practices are actually applied and successful), they show that the "HOF lessons learned" from nearly four decades of operating NPPs were present in the mindset of managers, considered to be important, and manifested in strategic planning of day-to-day operations at that time. This is particularly true for some of the functional activities implemented in European plants at that time, where human factors issues and organizational factors (to a lesser degree) play a crucial role (e.g., conducting human reliability assessments or formalizing operational decision-making). Moreover, the concept of safety culture had permeated all the plants. It was gradually accepted and offered a way to bundle HOF-related issues under one umbrella, resulting in a broad range of safety initiatives associated with the promotion of safety culture in the NPPs. Thus, managing nuclear safety already included the understanding of NPPs as open systems, but the primary targeted influence was on HOF within the plants (e.g., due to political framework conditions, or international initiatives of WANO and IAEA).

Table 1
Summary of results of the LearnSafe project regarding perceived challenges, functional safety activities and organizational learning promoting HOF. Source: Authors, adapted from [5].

Challenges to manage nuclear safety	Areas of functional activities promoting safety	Facilitators and hindrances of organizational learning
Economic pressures	Risk analysis	Objectives, priorities and resources
Human resource management	Design for safety	Formal systems and practices
Nuclear know-how	Feedback of operational experience	People's attitudes and orientation
Rules and regulation	Operational decision making	Corporate culture and traditions
Focus and priorities	Management and quality systems	Communication, guidance and appraisals
Ageing, modernization and new technologies	Safety performance indicators	Maintaining touch and focus
Public confidence and trust	Surveys of organizational climate	Openness and trust
Organizational climate and culture	Self-assessments	Work community
	Safety committees	Encouragement and rewards
	Organizational structure	Adequacy of means and methods
	Work practices	Networking and cooperation

In addition, the LearnSafe results also revealed a gap between theory and practice when attempting to understand how humans and organizations influence nuclear safety. Academic research was quite theoretical at that time, whereas practical guidance in the field had a poorly grounded scientific base. Consequently, one of the most prominent demands resulting from the project was to stimulate multi-disciplinary research in nuclear safety, potentially improving the prevention of minor events that may lead to nuclear accidents.

3.2. *Reflecting and evaluating the LearnSafe results 15 years later*

The results of the LearnSafe project provide a snapshot of the "lessons learned" on human and organizational contributions to nuclear safety implemented during a period of approximately 35 years. Fifteen years later (and 8 years after the Fukushima accident), we were interested in the current state of the European nuclear industry related to the challenges and practices once identified in the LearnSafe project. Our goal was to explore how managing the human and organizational contribution to nuclear safety is seen today with regard to actually perceived challenges, and the benefits of functional safety activities and organizational learning promoting HOF. Specifically, we were interested in finding out what has changed in the management of HOF since 2004, and what are the current problems perceived in dealing with HOF today.

Therefore, we conducted a focused in-depth interview study with senior nuclear managers and experts (n = 21) from five different European countries. Almost all of them had been working for more than 20 years in the nuclear industry and were selected based on earlier contacts with the plants in consideration. The interviews were designed as being inductive and exploratory. The goal was to access managers' in-depth perspectives on managing HOF today. Being aware of the limitations of such an approach, such as the rather small country and respondent sample sizes and further biases inherent in interview formats per se [47], we would like to point out to the reader the drawbacks regarding the generalizability of the results of our interviews. On the other hand, we believe that our experts provide a rather robust representation of the state of HOF in European NPPs, because all have built up long expertise in HOF, and were active participants in numerous collaborations on HOF within the nuclear community during their professional career.

Based on the LearnSafe results, we developed a semi-structured interview guideline,[3] which lists all three areas (challenges, functional safety activities and organizational learning) and associated clusters described above, with corresponding definitions and good practices. Our

[2] In the supplemental material we have provided a more detailed descriptions of the results obtained with regard to the three areas.

[3] A more detailed description of the implementation of the interview study and the materials used can be found in the supplemental material.

interview partners were asked for each cluster to evaluate their actual systems with regard to the good practices and challenges put forward by their colleagues 15 years ago. In addition, they were asked to quantify their evaluation by filling out a 4-point rating scale (ranging from commendable, excellent, good to acceptable systems in place) for each of the 30 clusters. At the end of the interviews, managers were asked whether they had additional suggestions for good practices and challenges to be added.

The interviews were conducted by telephone, Internet or face-to-face and lasted between one and two hours. In total, four interviewers conducted the semi-structured interviews and took notes of the conversations with the 21 managers, which were compiled together with the obtained ratings. Because the sample was too small to draw any significant statistical conclusions, the ratings were used to provide initial indications of certain practices and challenges that would subsequently guide the analysis and interpretation of the expert assessments. This procedure was followed by the four interviewers, first alone and then in a team context, by an exchange of questioning and developing ideas about and insights into the material obtained. The results were fed back to the managers, asking them to assess our interpretations and conclusions. Based on their feedback, we have been strengthened in our assessment that we have credibly represented the results from the perspective of our respondents, even though we have to accept cutbacks in terms of the generalizability of our results to the whole European nuclear industry. In presenting the results, we would like to start with aspects of nuclear safety management (in terms of perceived challenges, safety activities and organizational learning) that have—more or less—changed in the perception and handling of HOF since 2004, before we come to perceptions of actual HOF problems.

3.2.1. What has changed in the perception and handling of HOF since 2004?

In addressing the challenges of European nuclear safety management, our interview partners consistently agreed on the continuing influence of the four main drivers of change challenging nuclear safety management (i.e., ageing plants, the generational change, increasing competition in the market, and changing political and societal requirements). However, it also became apparent that these main challenges have evolved differently over the past 15 years, and accordingly have a much more nuanced impact on managing HOF today. In particular, the political, economic and regulatory conditions in the national locations of our interview partners fundamentally differ. For instance, in Finland new plants continue to be built whereas interview partners from Germany were confronted with the governmental decision to phase out the country's use of nuclear energy. These differences clearly become evident in the interview material, especially when it comes to economic constraints and the influence of corporate headquarters on the plants' operation and resources, which are perceived to be more salient in countries phasing out nuclear power production. However, economic pressures on nuclear safety management were perceived to be less intense, in particular not affecting investment in technological upgrades of the plants. Moreover, compared to 2004, public trust toward nuclear power operations is perceived as less of a challenge, attributed primarily to the creation of various forms of collaboration with the local community, encouraging visits to the facilities and information centres, and ensuring timely and open communication with the public. On the other hand, it has become more difficult to arrange visits to the sites and their information centres due to restrictions in allowing access inside the fences (due to security concerns).

A broad agreement among our interview partners can be found in perceptions of the need to preserve nuclear competencies, which was seen to be a challenge of utmost importance. Although a major generational shift in the majority of plants took place about 10 to 20 years ago and is perceived as somewhat under control (although some concerns still exist related to "non-critical" positions), the lack of attractiveness of the nuclear industry as an employer is becoming apparent, particularly in countries where the phase-out of nuclear energy supply is being carried out or, at least, is being considered. This has implications not only for internal processes (e.g., implementing a calculated succession planning maintaining nuclear know-how), but also for the nuclear know-how of external organizations such as contractors, regulators or research institutions. Especially challenging is the generational shift related to contractor companies. Due to the (sometimes) increasingly aggressive policy of budget-cutting and uncertainty about future markets, contractor companies are less willing to invest in the development of human resources to remain competitive.

In addition, our interview study revealed further challenges that go qualitatively beyond those collected in 2004. One prominent topic in the interviews was the perceived need for a paradigm shift triggered by the lessons learned from the nuclear accident in Fukushima. The insight that "everything might happen", the obvious dysfunctional dynamics between management and regulatory actors, and the need to guard against complacency with respect to nuclear safety led to the realization that it also requires multiple und adaptable resources beyond the boundaries of the organization to handle those hazards in the future. This also applies to the strong focus on the management of emergencies, leading to more participative roles of involved actors in the event of emergency situations. Finally, we conducted some interviews during the COVID-19 pandemic, which was considered as a new challenge for managing nuclear safety. During the pandemic first wave, prioritization of essential work and rescheduling of some non-essential work was possible with the available resources and thanks to employees' commitment. However, the situation evidenced that some processes need to be more flexible (e.g., procurement of materials and services), and uncertainty makes it necessary to plan work (e.g., refuelling), taking into consideration different potential scenarios derived from the pandemic situation.

Regarding the effectiveness of functional safety activities, our interviews revealed a broad consensus in terms of significant improvements in the management of HOF since 2004. Implemented practices of operational decision-making received the highest effectiveness ratings from our interview partners, such as ensuring the existence of instructions on all organizational levels addressing normal operation and disturbances or discussing events and operational experiences with personnel from operations, maintenance, technical support and safety. It seems that besides the continuously strong focus on the formalization of safety procedures and approaches (supporting decision making in normal and critical situations), the institutionalized exchange of different disciplinary perspectives in detecting and solving safety problems (e.g., due to the introduction of safety committees) has become clearly more pervasive during the last 15 years. Another trend can be seen in the implementation of human performance programmes aiming at optimizing individual and team safety behaviour and associated leadership processes (mainly promoted by industry associations such as the WANO). Although these programmes primarily focus on individual error-reduction techniques, some elements (e.g., manager-in-the-field programmes) are seen as facilitating the communication between management and the workforce and are perceived as important building blocks of fostering safety culture in the plants nowadays. Correspondingly, regularly conducted self-assessments of safety culture and related HF programmes, as well as safety indicator systems and peer reviews, are taken-for-granted initiatives to evaluate HOF issues on a regular basis.

When it comes to organizational learning and its antecedents, our interview partners perceived significant progress compared to 2004 in terms of the implementation of supporting systems as well as the cultural conditions surrounding organizational learning. The attitude and motivation of employees, in line with corporate culture and tradition, are perceived as highly conducive to organizational learning, i.e., HOF concepts are commonly understood and seen as important for establishing nuclear safety. Moreover, systems for feedback of operational experience have clearly improved over the years. Present systems provide good support for the analysis part of both own and external experience. People feed in data, which is stored in easily accessible formats. However, it has shown to be more difficult to move from the analysis to efficient and persistent modifications and changes (e.g., in plant systems and procedures), which will be discussed in more detail in the next section.

3.2.2. What are the actual problems perceived in handling HOF today?

Finally, we looked at our interview data to examine with which problems nuclear managers are confronted nowadays when it comes to HOF. Although identifying, analysing and retaining HOF issues has clearly improved since 2004 (e.g., due to training, implemented systems and tools) some of our interview partners perceive a major difficulty in drawing the right conclusions from all the data obtained due to self-assessments, analyses of operational experiences and safety performance indicators. For instance, event analysis methods provide HOF checklists, where users are explicitly asked to question a broad variety of HOF factors in relation to the event being analysed. Safety management systems provide indicators that allow conclusions to be drawn about the safety climate or the work satisfaction of the workforce. However, predicting how interrelated dynamics between HOF factors—within the plants and "outside"—develop over time and, most importantly, finding ways to influence them in a targeted manner is seen as one of the most crucial tasks in managing nuclear safety today. The lessons learned from the Fukushima accident reinforce this view, as they have led to the realization that HOF transcend the boundaries of organizational systems, methods and tools. For instance, being confronted with political decisions in terms of (not) supporting the technology in the future and associated economic dynamics has to some extent "changed the game" for managing European nuclear safety, at least in the plants that are going to be phased out [48].

The difficulty of promoting HOF in a targeted manner also becomes obvious in the interview results evaluating the progress in supporting organizational learning since 2004. Whereas several systems that provide a closer examination of HOF are now in place (such as reporting systems, formal safety management systems with indicators or human performance tools), our interview partners provided only mixed evidence about the operational benefits of these systems. Some of them were satisfied with learning from operational experiences and reported examples of good practices (e.g., a book with external and internal operative experience related to refuelling). Others were more critical, suggesting that the loop of organizational learning is not completely closed. Issues are analysed, solved, and registered. However, drawing the "right" HOF lessons learned, transferring them, and observing performance benefits is still seen as a difficult project. Specifically, when HOF-related implementation decisions are to be based on cost-benefit analyses, the question of how safe is safe enough seems to be especially crucial and hard to answer. This also aligns with recent findings that methods and tools to facilitate the future of HOF in nuclear safety are needed [49,50].

In addition, some of our respondents referred to the limits of the PSA framework when it comes to the consideration of HOF issues. The PSA was introduced at most NPPs for technical issues well before 2004 and the methodology has also been used successfully for identifying systems and sequences that may challenge plant availability in addition to its safety. The PSAs have also proved beneficial for evaluating and improving safety when technical plant modifications are pondered. The general view, however, appears to be that the consideration of human errors and organizational deficiencies in PSA is still almost on the same level it was in the year 2004. Human errors and corresponding (immediate) performance-shaping factors are covered by PSA. However, credible tools modelling the impact of the temporal and interrelated dynamics of organizational factors on nuclear safety have not yet reached the plants. In this regard, some interview partners expressed a need for finding methods that are practical enough to separate important and less important issues that may be considered necessary to improve training, control room design, and operational procedures.

Similar to the situation in 2004, less academic support is perceived. Concepts such as resilience engineering or system thinking clearly help to "frame" problems; however, they still fail to prove their practical benefits in the field (we come to that point later). Safety culture is somewhat important and is in most countries regularly assessed, but still perceived as something "intangible" [26] or "tacit" [51]. Behaviourally focused interventions (such as human performance programmes promoted by the WANO) pay tribute to the invisibility of the psychological elements of the interventions' target because they transfer "unobservable" dynamics into observable manifestations, which can to some extent be judged. However, considering only human performance tools [52] is not taking the broad and deep view the systemic nature of HOF issues would warrant for understanding the full potential (positive and negative) of human contributions to nuclear safety.

Next, we contrast, and reflect upon, the outlined historical development of the HOF concept with the applied experiences in dealing with HOF in the field.

4. Contrasting and reflecting HOF lessons learned and their implementation

As stated at the beginning of this essay, we aimed to look at the fifty-year-old learning process promoting HOF lessons learned in the European nuclear industry. We have done that by outlining two long-term perspectives on HOF developments and solutions: one providing institutional and academic access in terms of "HOF lessons learned", illustrated by the responses to the three major nuclear accidents; the other describing perceptions of European nuclear managers about how to manage HOF in establishing nuclear safety. Although this subjective selection of both perspectives leaves out many important aspects of the organizational learning and the safety science literature (e.g., plant- and team-level learning), we hope to draw some important lessons for both scholarship and practice by contrasting the two and, therefore, to derive assumptions about how to strengthen the interface between applied research and the industry. This will be done by answering three questions that lead through the following section; namely, whether the industry has learned at all from its operational experiences concerning HOF; if so, what it has learned in terms of HOF; and what recommendations can be derived to promote HOF in the future.

4.1. Has the industry learned at all from its HOF experiences?

Firstly, we asked ourselves how to contribute to the question of whether the industry has learned by operating European NPPs for 50 years, or more specifically, whether our perspective and findings on HOF in nuclear safety justify the existence of the industry's learning process. Several empirical studies have already shown that it has learned from previous accidents within the global nuclear industry [53],illustrated by, for instance, a significant reduction in the frequency of operative events after the Chernobyl accident, and suppression of moderately large cost events after the TMI event [54:99]. However, our qualitative perspective is restricted to the HOF lessons learned in European nuclear safety, not to global technical lessons learned. Moreover, even though analyses of the three accidents have brought to light different HOF issues, all accidents have in common that they show how HOF can defy the technical safety barriers of these systems.

However, based on the information we have compiled in this essay, we believe that learning in terms of HOF exists when contrasting the occurrence of these three accidents with their estimated probability of occurrence at that time. Therefore, we refer to the PSA framework providing a method for calculating core damage probabilities for selected scenarios [55]. It should be noted that PSAs cannot be used for predicting plant safety because this would imply that all possible scenarios with the end state of core damage would have been included in the calculations. However, importantly, the PSA—if used as a design target—can give an assessment of safety improvements that have been achieved over a certain period of years [56]. In retrospect we may use operational data to make a qualitative assessment as to whether the commonly used design target applied before the turn of the millennium of 10^{-4} per year (later 10^{-5} per year for new plants) has been reached.

Our historical outline reveals that the Fukushima Daiichi plants were damaged by a single event, an earthquake causing the tsunami, from which it can be concluded that the probability of such an accident was significantly underestimated at that time (see Section 2.3). Even in hindsight, the impact of not taking HOF into account is obvious here. What about the two earlier major accidents? The TMI accident showed that one plant had not considered the very basics of HOF issues. In 1979 there were 225 plants around that may have experienced the same type of problems or, in the case of the incident at the Davis-Besse NPP, had gone through a similar sequence of events. If each of them had one magnitude larger probability of core damage due to HOF-related scenarios, we would have something like a 20% probability of core damage each year, and the TMI accident could be seen in a somewhat different light. We do not argue that this calculation is realistic, but it points to the fact that at that time there were apparently not many plants that had the same problems with HOF as TMI-2.

Considering the Chernobyl accident in the same way, there were 15 RBMK reactors in operation in 1986. The Chernobyl accident demonstrated that there was at least one sequence of events caused by a deficient safety culture that destroyed the reactor. If Soviet experts believed that the probability of core damage was 10^{-4} per year and with the same assumptions as above, one could expect a similar accident to occur once in about 66 years. With the 15 reactors of this type operating, in 1986 there were 85 plant years of operation, indicating that the Chernobyl accident can be seen to have happened within a range that could be expected.

If one relates this argument—underestimation of probabilities of major nuclear accidents due to not taking HOF issues into account—to a time span of about 50 years of nuclear electricity production, one may conclude that the occurrence of major nuclear accidents is higher than suggested by today's commonly used design target of 10^{-5} per year. However, if we believe that the three accidents were caused by outliers with problems with their HOF issues, we may conclude that the nuclear industry has learned in terms of dealing with HOF [18,25,57], provided that safety management systems have given these factors the attention they deserve. To make a fair calculation of the core damage probability it would, in principle, be necessary also to credit HOF issues for successes in avoiding accidents, but regulatory bodies are perhaps not likely to accept this type of argumentation. Based on this thinking, we want to tackle next the question of what has been specifically learned with regard to HOF.

4.2. *What has been learned about HOF (and what not)?*

Both perspectives of our analysis show the special importance given by the nuclear industry to HOF, which is reflected in the constant differentiation and associated efforts to establish nuclear safety through promoting HOF. Although our study focus ignores many other important influencing factors (e.g., business pressures, socio-economic issues, scientific lessons learned), the interview results show how insights gained from operational experiences have been integrated into daily work. Analysis of the institutional and academic initiatives demonstrates—in a rough before/after comparison—that the lessons learned from all three accidents have increasingly broadened the industry's scope on HOF, from operator-specific safety activities to safety-related activities on an organizational and regulatory level. After the TMI accident significantly more attention was paid to the human operator, ergonomics, control room design, symptom-based procedures and operator training. The Chernobyl accident led to the understandability of HOF in a (larger) organizational context in terms of, for instance, procedures, responsibilities and cultural mindsets. Lessons learned from the Fukushima accident triggered a focus on emergency planning and the need for emergency drills as well as the handling of external resources. This is complemented by the painful insight that HOF can also act outside the boundaries of a single plant and may have dysfunctional influences on the safe operation of nuclear reactors. Also, the beyond planned emergency operations at the Fukushima Daini plant in response to the tsunami proved what can be done by insightful and committed staff, i.e., pointing clearly to the benefits of HOF issues.

One important mechanism in coping with these challenging HOF insights is organizational learning. Our interview study revealed that systems that support learning in terms of the identification, analysis, storage and dissemination of safety knowledge have now been implemented in the plants. Incident analysis seems to be functioning well at the plants and within the whole industry, and it is a commonly accepted way of learning from operational experiences. However, there were also some problems with these systems, especially when it comes to the proper integration of HOF lessons learned into safety activities. For instance, one symptom of this problem manifests itself in long HOF to-do lists in which various initiatives that one would like to take on later are laid down and these lists have the sad habit of growing. It seems that when it comes to initiating HOF activities, the question “how safe is safe enough?” becomes increasingly relevant. The general uncertainty about the effectiveness of HOF interventions and how to verify them makes it difficult to prepare and make decisions, in particular, in terms of investments of human and financial resources. Interestingly, this opens the window for the regulators exerting strong influences on these open questions and decisions regarding the need for and scope of HOF interventions.

These degrees of freedom become especially apparent in the case of promoting safety culture. The concept has been embraced by the NPPs and its understanding includes roughly all possible human activities that may have an influence on safety. However, the specific conditions for a safety culture to be good or bad are hard to define, especially in the case of a deficient safety culture, where means for improvement on such a finding are not easily derived. Our interviews reveal that regularly conducted safety culture peer reviews are important countermeasures in this respect. They provide an additional perspective to the still dominant more external view of somewhat idealistic nuclear safety cultures put forward by national regulators and global institutions.

The lessons learned from the Fukushima accident also address the need for a harmonization of thinking and acting upon HOF, especially when it comes to regulation. The interviews reveal differences with regard to the influences of national regulators on promoting HOF in European plants. This is also illustrated by a recent OECD/NEA (Organisation for Economic Co-operation and Development/Nuclear Energy Agency) report [58]. Although focusing on the whole package of regulatory requirements, the report suggests a price of +30% of plant costs (5-10G$) if the plant vendor has no experience with the national regulatory system, showing the specificity of these national systems.

Relatedly, the question arises as to what has been learned with regard to a suitable degree of independence in regulation? Clearly, regulators living in complete isolation from the industry (e.g., not hiring people with industrial background, not allowing inspectors to meet the industry anywhere) are not conducive to establishing nuclear safety. On the other hand, regulators prescribing solutions for the plants, or, in turn, plants that ask regulators what to do or whether something should be done, are observed tendencies in the industry that suffer from the many degrees of freedom in interpreting HOF and its influences on nuclear safety. Although the relationship between national and international requirements varies, international systems get stronger, but they are far from a situation where requirements of national regulators can be mapped “one to one” onto international requirements.

Finally, we want to look at what has been learned with regard to assessing the resources and risks of HOF. Our impression is that the methodology, models and tools used in the PSAs have been taken into efficient use, particularly for technical failures, in providing necessary databases that can be assessed and updated continuously with respect to modifications both in plant and in instructions. For instance, our experience is that several plants have been able to decrease their core damage probability ratings by one magnitude, which—regardless of the uncertainties in available data—indicates large and sustainable improvements. However, the inclusion of HOF issues into risk assessments seems still to be on nearly the same level as in 2004. Human interactions with event sequences can be introduced to assess available support to operators in making correct decisions in critical situations, but making the connection between them and more general characteristics of a social system (e.g., its culture, its systems or structures and associated processes) is still not possible.

4.3. What can be done to improve HOF in establishing nuclear safety?

Our historical analysis revealed that all three major accidents could have been prevented if the information about their precursors—which was already available—had been taken into account. There may be many reasons for this non-use (e.g., financial or political pressures, or insufficient understanding of HOF). In our view, this is also a consequence of insufficient attention being paid (a) to implementing HOF concepts into practice—without considering concrete technological designs and associated hazard potentials—and (b) to safety critical influences of divergent stakeholder interests on establishing nuclear safety. We believe that there is still room for improvement in these two areas, which we will discuss in more detail below.

Wahlström and Rollenhagen [59] have claimed that hazard potentials and corresponding risk assessments are often not addressed in the safety culture literature. Also, our impression from the interviews was that managing HOF is more focused on compliance to predefined—cultural—mindsets and safety activities within social systems (e.g., reporting behaviour, leadership behaviour, or assessing safety culture) rather than on their potential impact on concrete technological risks (i.e., dysfunctional sociotechnical system dynamics leading to accidents). Moreover, contrary to safety performance on individual and team levels, which can to some extent be predicted and attributed to work tasks, goals, planning and procedures in terms of concrete hazard potentials, the same does not apply to organizational factors. These factors constitute the work conditions (i.e., work tasks and processes) and are based on other risk parameters, goals, means, intentions and ideas. Organizational factors develop their effects over longer periods of time, stemming from fluctuating goals and interests of different stakeholders, which makes it hard to directly relate them to technological hazard potentials and to apply concrete standards to them, especially when common event-based perspectives on potential accident sequences are taken.

Moreover, our general impression is that in the past, behavioural and social sciences have primarily tackled HOF issues, which were identified as blind spots after analysing major nuclear accidents, such as human machine interaction after the TMI accident or safety culture after the Chernobyl accident. Consequently, the obtained scientific knowledge is solely added in a way that new requirements for social systems operating NPPs are developed and implemented. Surprisingly, as mentioned above, these HOF concepts hardly refer to the design of a technical system and seem to be "detached" from technical issues, concrete hazard potentials, and operational decisions to be made. Certainly, one could argue that promoting HOF (e.g., fostering safety culture) supports the resilience of an organization; for instance, in a way that operators and maintainers are better (mentally) equipped to handle unknown disturbances. On the other hand, Rollenhagen [60:268] showed that a strong focus on safety culture, although pursued with the best of intentions, could lead to an increased risk for downplaying the importance of technical designs such as control rooms.

When looking at actual developments in the safety science field, there are threads where our guess is that they have not been seriously investigated by the industry for possible introduction into daily practices. This may imply that there are new blind spots connected to unknown unknowns, where the nuclear industry has not yet implemented proper barriers against sequences of events that may have an unacceptably high core damage probability. Our second guess is that, if such are found, they are simultaneously associated with technical and HOF issues that go beyond present PSA tools and methods. In order to search for new openings that would aim for proper reflections of how organizational development, group management procedures and technological issues may influence nuclear safety, we propose increased collaboration between academia and industry. However, even when theoretical ideas are desired, they may not be practically feasible. Concepts such as Resilience or Safety-II [61,62] are certainly good, but it does not help in looking at successes if you do not know what to protect against.

We believe that risk assessments or more general, safety management systems offer a fruitful way to improve our understanding of the relation between HOF and technical design factors (and associated hazard potentials) in advance. For instance, the PSA methodology could be used to identify critical HOF decisions through a sensitivity analysis and thus give directions for improvements to be considered. This gives clear directions for future work. Because the PSA already offers powerful tools for analysing technical safety issues, considering HOF issues might improve these methods and, therefore, challenge safety engineering when, for example, sequences with a high core damage probability are found. Bringing HOF issues broadly into risk assessments (e.g., one may look at people and organizational systems and ask for necessary conditions for safety regarding possible hazards [63]) might also foster a deeper understanding of the interactions between technical risks and social system performance. This could mean that the plant, its personnel and organization would have continued capabilities to react to unexpected events in a proper way, and, if necessary, generate control responses adapted to new situations at short notice.

As a second area of improvement, we also want to stress the importance of regulators in the nuclear industry. Coming back to the question of why nothing was done before these three accidents, a simple answer seems to be: the regulator did not give an ultimatum "shut down until the deficiency is corrected". Even though such decisions are not easy to make and it is open as to who is supposed to make them, we think that this is important to give HOF issues the attention they need. To illustrate this argument, we take the strainer incident on 15 June 1992 in Barsebäck-2, Sweden. In the incident, there was a small break in a steam line, which caused insulation material from the piping to be transferred to strainers that are intended for circulating water in a loss of coolant accident (LOCA). The incident did not lead to any danger at that time, but the regulator's experts became seriously concerned, because a clogging of the strainers could in such a case prevent the circulation of water to provide cooling of the reactor (a violation of the single failure criterion). The result was that five reactors were shut down for about 6 months, until the reactor owners could provide proof to the regulator that this deficiency had been removed (e.g., by modifying insulation materials, installing larger strainers, installing systems for backflushing and issuing instructions for this type of situations). In our mind, the Swedish decision was commendable and should be applied whenever such scenarios are identified. From this follows that a part of the responsibility for the accidents moves to the regulators and, consequently, one can cautiously conclude that in a way regulatory capture can be considered as a common contributory cause for all three major accidents.

It becomes evident that HOF influences exceed the limits of individual plants, whether it is the influence of policy makers and regulators on the operation of individual plants or learning from the operational experiences of other plants. The long lifecycles of the NPPs present a high demand to develop and foster knowledge and experience. We also think that nuclear power generation is somewhat unique compared to most other high-risk industries because it is a primarily political technology, is characterized by military and political interests, has a high damage potential and because "everyone" has an opinion. It has been demonstrated that any major accident in an NPP around poses a risk to the survival of the whole industry. As a consequence, establishing nuclear safety means that a broad range of stakeholders have to be committed when it comes to the promotion of HOF. One may well question whether these fluctuating and sometimes divergent interests make it even possible to establish nuclear safety as a top priority at all. However, we believe that nuclear history has clearly shown that harmonizing regulations with regard to HOF on both international and national levels (also put forward in the aftermath of the Fukushima accident) is a worthwhile endeavour [37].

5. Conclusions

In this essay, we have investigated the "lessons learned" within the domain of human and organizational factors (HOF) from operating European NPPs in a fifty-year perspective. First of all, we hope to have made a strong argument for considering HOF in the context of establishing nuclear safety (defined in the broadest sense). Next, we here summarize and discuss what we think is the essence of conclusions that we have reached in our analysis, as listed in the following two bullets:

- Understanding and establishing nuclear safety requires a continuous questioning, re-imagining and re-inventing of HOF, which should aim to take into account and harmonize divergent interests of several stakeholders (e.g., military, political, economic, or public stakeholders)
- The industry and the academic community must find fruitful collaboration in developing theories, methods and tools that can support a better inclusion of HOF issues into safety activities; specifically, with regard to linking HOF to technical design factors and associated hazard potentials

With respect to our first conclusion, we think that our essay has made clear that safety–critical influences of HOF have the potential to overcome the boundaries of a single plant. HOF are not only relevant on an operational level for the safe functioning of NPPs. They are also pertinent at a strategic and regulatory level for providing resources and boundary conditions for operational safety and across the board for any human activity involved in the planning, design, implementation, operation, maintenance and phase-out of NPPs. Our conclusion of continuously questioning, re-imagining and re-inventing HOF pays tribute to this open system nature of establishing nuclear safety, which has partly shared and partly conflicting interests of the stakeholders involved. Nuclear safety is an overarching goal and a plant that is not safe should not be allowed to operate. However, the conclusion that a plant is safe has to be derived based on factual evidence and it is not always clear how this evidence should be compiled. It is certainly not enough that it fulfils regulatory requirements because these were thoroughly modified after the three accidents we have discussed. For the plant owners an important goal is that an NPP is profitable, because if it is not, it has to be closed. An NPP cannot operate in an atmosphere of secrecy, because that will hamper possibilities for organizational learning, which seems to be one of the most promising mechanisms in coping with HOF risks. We have also seen that NPPs depend on societal trust, where a growing distrust may trigger premature closures. We think that there is a need to harmonize these divergent interests of stakeholders involving an open and honest mindset, and also requiring that parties take critical opinions seriously and meet them with thoughtful arguments in establishing nuclear safety [64]. A continuous re-invention of HOF also implies that there is no reason to believe that we have now reached the final frontier of averting HOF risks. New challenges perceived by our interview partners, such as the COVID-19 pandemic or unstable political and economic conditions, harbour a multitude of unknown unknowns and underscore our call for continuously reinventing HOF.

With regard to our second conclusion, our snapshot of managing HOF has shown that the understanding of HOF has been increasingly expanded, and has also manifested itself in the operational processes of European NPPs. However, according to our interviews, difficulties are perceived in proactively dealing with these interrelated dynamic mechanisms between HOF, and in finding ways to influence them in a targeted manner. In our view, this calls for a stronger collaboration between the industry and the academic community. Specifically, our analysis has shown that many of the HOF systems and concepts implemented in European NPPs lack reference to technical design factors and associated hazard potentials, especially when it comes to the impact of organizational factors (e.g., cultural or economic influences). This, in turn, may have implications for the acceptance and effectiveness of HOF interventions, resulting in, for instance, difficulties to evaluate their benefits. We believe that a stronger collaboration between the industry and the academic community provides promises of improving the situation. For example, collaborative activities could start by updating models of nuclear safety, describing both necessary and sufficient conditions for safety in the interplay between technological hazard potentials and associated HOF issues, as well as taking into account and combining many of the things we have seen discussed in the academic literature. This could perhaps also make it possible to give credit to HOF issues in safety assessments, which regulatory bodies need for establishing their belief in plant safety.

Finally, we would like to reiterate the lack of generalizability of the data we have presented. The focus on the European context as well as weaknesses of the methods used do not allow a full transferability of our arguments to the global nuclear industry (and even to the European industry to some extent). Nevertheless, we think that there is learning potential within our smaller focus that merits discussion. HOF's contributions to establishing nuclear safety are indispensable because there are always possible situations that can render automation or procedures non-functional. It is then up to operators and maintainers to handle those disturbances locally, and to obtain outside support for the analysis and the selection of control actions in situations that are beyond their own capabilities. Implementing HOF as an established part of both proactive and reactive safety management processes including audits, risk assessments, safety and quality training, and operating experience reporting, analysis, corrective actions and learning should then be assured [65]. The ultimate goal is to ensure that major nuclear accidents are made almost impossible.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplemental material

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