FOOD FOR THOUGHT

Industrial safety in the age of "living with"

Uncertainty, complexity and rising expectations

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TOPIC

Risk management

Les Cahiers de la sécurité industrielle

FONCSI
Fondation pour une culture de sécurité industrielle

The *Foundation for an Industrial Safety Culture* (FonCSI) is a French public-interest research foundation created in 2005. It aims to:

- undertake and fund research activities that contribute to improving safety in hazardous organizations (industrial firms of all sizes, in all industrial sectors);
- work towards better mutual understanding between high-industries industries and civil society, aiming for a durable compromise and an open debate that covers all the dimensions of risk;
- foster the acculturation of all stakeholders to the questions, trade-offs and problems related to risk and safety.

In order to attain these objectives, the FonCSI works to bring together researchers from different scientific disciplines with other stakeholders concerned by industrial safety and the management of technological risk: companies, local government, trade unions, NGOs. We also attempt to build bridges between disciplines and to promote interaction and cross-pollination between engineering, sciences and the humanities.

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Abstract

Title	Industrial safety in the age of "living with": Uncertainty, complexity and rising expectations
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Climate change, digital transformation, political, economic and geopolitical tensions, an increasingly arms-length relation to work: can industrial safety (and in particular, its management) continue to be conceived of, modeled and practiced in the same way as in the past, despite the major changes that have arisen over the past decades? The FonCSI invites interested stakeholders to join a debate on this question, which will involve critical analysis at the academic, industrial and practical levels.

To kick off this debate, the current document provides an overview of the significant changes that have occurred since the beginning of the century and analyzes their potential impacts on safety management. These impacts are analyzed at both the conceptual (are the hypotheses and principles that underlie most safety models still valid?) and the practical (what are the implications for safety management professionals?) level. This exercise leads us to propose a number of possible paths forward for reflecting upon and managing safety in our changing world. We will be working with the academic community and interested stakeholders to discuss, improve and develop more practically oriented suggestions for reimagining safety management as a way of living with uncertainty and complexity rather than a commitment to ensuring control.

About the authors

This document is a product of ongoing discussions and disagreements between the team of safety experts at FonCSI, who cumulatively hold several centuries of experience working as researchers, advisors and experts in safety management.

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Contents

Introduction

Context

A number of significant developments in the world, both recent and forthcoming — including climate change, rapid digitalization, political and economic tensions, geopolitical issues, and shifts in work relations — could profoundly impact the future of industrial safety. Over the past two decades, high-hazard industries, as well as the broader environment in which they operate, have undergone extraordinary transformations.

"Industrial safety" as used in this document

Definition

The term "industrial safety" is often used to encompass both operational safety (major accident hazards) and occupational safety. However, the interest of FonCSI, like many academics, is primarily the prevention of major accident hazards. In the interest of clarity, we would like to note that the remainder of this document is mainly focused on operational safety and the prevention of major accident hazards, even if this includes an overlap in practice with occupational safety considerations.

The primary application areas for the ideas discussed in this document are high-hazard industries (transport, energy, the process industries) and critical infrastructures, but many concepts are also applicable in areas such as healthcare **[Vincent and Amalberti 2016]**.

The conditions under which safety is ensured today, from the front line to the governance frameworks, have significantly evolved compared to the 1980s/1990s and even the 2000s, when major safety models and practices were developed. Similarly, the ecosystem surrounding industrial safety has been transformed in numerous ways. Particularly noteworthy is the increasing concern regarding climate change at all levels, along with threats to security and cybersecurity that are heightened by political and geopolitical tensions. Additionally, the digital transition has disrupted and will continue to revolutionize many aspects of work, altered the level of autonomy of front-line workers, modified the way in which stakeholders express their concerns and the relative weight of their voices, and induced new vulnerabilities.

Key issue

In this context, in which industrial accidents have (fortunately!) become increasingly rare, industrial safety tends to fade into the background for citizens, policymakers, and to some extent, industry professionals, in favor of issues that are perceived as being more prominent and pressing in the current news cycle.

Nevertheless, industrial safety should not be taken for granted. The convergence of these multiple evolutions across different spatial and temporal scales challenges several of the assumptions that underlie classical safety management models. For instance, heightened uncertainties related to climate change, cyber threats, and organizational complexity undermine the foundational paradigm of safety management based on *a priori* controllability, especially through predetermination and uncertainty reduction[1]. We need to move beyond the classical approach of identifying and eliminating the causes of "anomalies" and the unexpected, by developing an approach that allows us to learn to "live with" unplanned deviations and contingencies as safely as possible. This raises questions concerning industrial practices, but also concerning the social contract between high-hazard industries and citizens, legal

[1] The controllability paradigm is based on the anticipation of all possible hazards, the definition of a safe operating zone, and the implementation of barriers to maintain the system within the boundaries of safe operations. In addition to being the basis for safety management activities in industry, this controllability paradigm is the foundation of the social contract between high-hazard industry and citizens. In practice, it also underlies the regulation and governance of the safety of hazardous industrial activities, as well as the attribution of responsibilities and liabilities when things go wrong. This intellectual construct is deeply embedded and difficult to move away from.

responsibilities. It also challenges the traditional conceptual and methodological frameworks used in these areas.

Some theoretical models or schools of thought developed at the end of the last century (such as High Reliability Organizations) or the beginning of this century (such as Resilience Engineering) already acknowledge the complexity and unpredictability of the industrial world and advocate for learning to live with them safely. Some of the concepts and terminology developed by these scholars have partially been incorporated into industrial practice, but have rarely penetrated official outward-facing communication on safety (the safety case, the safety management system, the slogans and public messaging used in discussions with the safety authority, the justice system, the media, the general public).

Objectives of this document

The observation of a potentially widening gap between current theoretical models and practical safety management approaches on one hand, and the reality of current and future situations on the other, leads the FonCSI to question both the **future legitimacy** of **currently dominant conceptions and approaches**, and the **epistemic and societal reasons for their enduring presence** in the market of ideas and of practices. We aim to stimulate and facilitate the necessary reflections and debates on the future of safety management and the prevention of major accident hazards. These reflections occur at both academic and industrial/practical levels and aim to propose paths forward that allow the development of new perspectives on safety management, better suited to today's realities and, most importantly, to those of tomorrow.

Structure of this document

The first chapter describes the **ongoing changes** that affect or will affect industrial safety, safety management and its ecosystem. These include climate change, the digital transition and in particular the disruptive capabilities of AI models, international geopolitical tensions, long-term demographic trends and the ongoing change in our attitudes to work.

The second chapter then discusses a number of **challenges** to the way in which safety and major accident hazard risks are conceived, modelled, and developed or managed in practice. These challenges and questions are triggered by the fact that industrial safety tends to fade into the background when faced with a widening scope of other challenges that are more present in societal perceptions and individuals' preoccupations. A second family of challenges arise from the gap between the development of auditing practices to document and certify conformity to documentary standards as a basis for most safety management activities, the increasing organizational complexity and fragmentation of the structures where work is carried out, and pressures on resources which in practice often lead to suboptimal conditions. These threaten the paradigm of controllability that underlies safety management as-designed and as-explained: the assumption that all events can be anticipated, operating conditions controlled, uncertainties reduced, risks reduced (though often true, the number of cases in which this paradigm is no longer fully applicable is growing).

Given these challenges, chapter 3 proposes a number of **new ways forward** for thinking about safety management and better aligning it with the way safety is produced in practice. These include opening up the perimeter of safety management and the arenas occupied by safety management professionals in order to take onboard new problems, such as cybersecurity, environmental risks and well-being at work. Managing these issues may involve a shift towards governance including new stakeholders and more care given to the ecosystem in which high-hazard activities evolve.

An atypical document that aims to stir up debate

This document is not a standard research report. It combines observations drawn from the scientific and technical literature with more **provocative** and **forward-looking thoughts** and hypotheses, presented as boxed exhibits.

The authors of the document have some points of disagreement concerning the conclusions to be drawn from the observations made. For example, some authors argue that the dominant safety demonstration model (based on total and *a priori* control of risks) is so deeply entrenched, not only within industries but also within their ecosystems (public perceptions, the legal framework), that deviating from this model is not straightforward, and the path to do so remains to be determined. Others contend that the integration of concepts from the science of complexity is already well underway, though to a greater extent in local practices than in the facades presented by high-hazard industries when they talk about safety to outside stakeholders.

The spirit of the document is that differences of interpretation and even disagreement should be seen as a source of richness rather than a weakness. The authors welcome reactions (by email to `contact@FonCSI.org`) that bring further nuance to the debate on possible consequences of existing trends and new strategies, or even paradigms, for managing safety in the next decades.

1

Changes affecting safety management and its ecosystem

Four main sources of change are discussed in this chapter: climate change and its impacts, the digital transition, geopolitical tensions and demographic changes, and evolutions in our relationship with employment and work. These factors are obviously interconnected, but we will not attempt to analyze their dynamic interactions in this document.

1.1 Preoccupations related to climate change

The increasing visibility of the impacts of **climate change**[1] and the **growing pressure exerted by civil society and the political world** to on one hand combat this phenomenon and limit the environmental impacts of human activities, and on the other hand to prepare our societies for the looming radical adaptations, lead to multiple transformations within hazardous industries:

- The **environmental impacts of industrial activity** are becoming a **major issue**, which must be treated in parallel to — but also sometimes in competition with — operational safety [Bieder et al. 2024a].
- **New environmental threats** (in terms of nature and/or intensity) potentially challenge normal operation (e.g., prolonged drought affecting sources of cooling water) as well as the safety of installations (Natech risks).
- Certain **industries** are being **discredited** while others are promoted due to their more favorable environmental footprint, leading to:
  - Injunctions to dismantle or, conversely, rapidly develop new facilities[2].
  - Potential recruitment difficulties or situations where employees lose their sense of purpose.

The **growing demand for public debate and citizen participation in decisions** associated with these environmental issues extends, mechanically, to industrial projects and risks [Bieder et al. 2024b].

[1] See for example the Intergovernmental Panel on Climate Change AR6 Synthesis report on climate change, 2023.

[2] A illustration is given by nuclear power, currently promoted as a low carbon energy source and pushed to expand in France, whereas Germany made the decision, which can now be considered paradoxical, to abandon this industry for reasons including safety concerns following the Chernobyl accident.

1.2 The digital transition and breakthroughs in AI

The widespread adoption of **digital technologies** is leading to significant changes at all levels, which may impact industrial safety, whether in terms of its perception or management modalities.

At the **societal level**:

- **Digital information and communication tools** open up **new arenas for expression regarding safety**, but more broadly it **elicits societal expectations**. The widespread use of social networks and their algorithmic filters considerably amplifies phenomena of attraction, polarization, and distortion of information. Anyone can instantly express themselves on any subject, such as safety, without risk. Alternative voices and legitimacies to institutional discourses and established "truths" have the potential to mobilize massively (particularly through influencers), amplify controversies, and thereby influence, or even "manufacture" (through "social engineering"), **public perceptions and opinions**, including on safety and its importance.

- **AI** elicits ambivalent and changing reactions from the public, **between myth, magic, and mistrust**. It has begun to introduce completely disruptive transformations of the role of humans in an increasing number of professions. It is likely to cause significant sociotechnical revolutions in the coming decade.

- The **"industrial" players in the areas of tech and AI become extremely powerful** *vis-à-vis* society. Their revenues exceed the GDP of average-sized countries, and their influence on behaviors and lifestyles equals that of governments.

At the **industry level**:

- Digital transformation opens the door to new vulnerabilities through **cyberattacks**, particularly in a world where warfare is resurgent (Ukraine, the Middle East) [Hansen and Antonsen 2024].

- The use of AI-based systems in operations raises the question of **trust**, whether from operators, safety authorities, or society as a whole. Indeed, learning systems are difficult to shoehorn into the current (and historical) paradigm of safety governance based on **certification** and surveillance.

- The use of AI raises **new questions of responsibility** [de Boisboissel 2022; Laroche and Reuzeau 2022]. Legal responsibility, first and foremost: it is often separate companies that develop the algorithms used in software components, prepare the datasets used for learning, assemble the software components into a critical system, and operate the system. Conflicts of responsibility can be expected in case of malfunction. Societal responsibility, then: machine failures are not interpreted and judged like human failures [Hidalgo et al. 2021]. Machines are judged on the magnitude of harm caused, while humans are judged on their intentions. Spontaneous attributions of responsibility (especially by public opinion and the media) in the case of systems combining human actors and AI will therefore follow cognitive logics that are difficult to anticipate.

- Industrial sectors that would like to delay the introduction of these technologies until they are more proven, a classic conservative strategy for critical systems, risk reducing their ability to attract technical specialists, whose skills are already scarce.

At the **safety management level**, in conjunction with the use of **big data**, AI opens up both **new opportunities for operations analysis** and identification of previously ignored problems, and new risks, notably that of a **narrowing of the prism through which safety is managed** to only those aspects for which data are collected in large numbers.

1.3 Economic, political and geopolitical tensions

While over the long term, indicators of geopolitical conflict appeared to be decreasing [David and Rapin 2018], the world has evidently entered a phase of major instability and the return of high-intensity warfare in recent years. Geopolitical "tectonic plates" and climate change are mutually reinforcing. UN services estimate that the climate changes predicted by 2050 will render vast subtropical regions uninhabitable and cause the migration of 250 million. **Migration flows** due to war and climate change are expected to increase significantly in the current decade.

Economic and political tensions in today's globalized social context are leading to transformations in the industrial domain.

- At the organizational and strategic levels, there is an obscuring of medium and long-term vision within companies, leading to a short-term dictated conduct, with more abrupt decisions, and sometimes reversals of direction, a search for resilience oscillating between **agility** strategies (product diversification, supply-chain diversification, outsourcing, transition from selective outsourcing to co-sourcing) and strategies of overcontrol and **bunkerization** (standardization, conformity, auditism [Størkersen 2024], downsizing, core business focus, closure, etc.).

- At the environmental level, whether national or transnational, adaptive responses to climate change take the form of emergency development programs for industries deemed critical for national/regional independence, or conversely, abandonment of activity areas with no turning back.

- **Deregulated employment** becomes a key variable for **adjusting workforce tensions** within the company, with the proliferation of new low-cost business models, contingent and platform work, multitasking, or self-employed entrepreneurs [Balliester and Elsheikhi 2018; Nilsen et al. 2022].

- On the technical systems side, the boundaries of high-hazard industrial systems also become blurred with the use of "off-the-shelf" systems designed without particular consideration for safety or cybersecurity. This trend towards the use of "generic" components is increased for digital/algorithmic systems.

Current political and geopolitical tensions exacerbate perceptions, by civil society, politicians, and industry, of **risks** related to malicious activities (e.g., sabotage, cyberattacks, military targeting of civilian installations and infrastructures at risk of major accidents).

Moreover, immigration and cultural confrontations occupy an increasingly prominent place in societal concerns. They are present on a daily basis in the environment, a source of multiple tensions. **Within work collectives** in at-risk industries, the diversity of cultures and languages practiced leads to **unprecedented situations of misunderstandings**, including safety instructions.

Finally, the rise of extremes, the distrust of certain political or citizen movements towards the European Union, and further economic liberalization constitute factors of economic instability. For instance, the previous Trump administration threatened some of the gains in occupational safety in the USA [Waring 2019].

1.4 In Europe (at least), a demographic deficit and an evolution of attitudes regarding work and the employer

Europe is expected to experience a significant **demographic deficit**. The labor pool will decrease and age, and the skills training system (vocational schools, universities, etc.), structured by traditional trades and focused on youth, will face great difficulty in providing the industry with the necessary skills for jobs and professions whose lifespan continues to decrease [Laroche et al. 2022].

This will likely result in a major shortage of skilled personnel[3], further exacerbated by the declining attractiveness of industrial work, and by cultural dimensions such as the general deficit in guiding girls towards technical careers in the industry.

The future — and already the present — of "normal" work could become **chronic understaffing**, coupled with aggravated skill shortages in less attractive sectors. These difficulties are likely to lead to an increasing reliance on outsourcing, the platform economy, automation, and robotization, causing other impacts on safety, potentially more critical than those related to understaffing.

Furthermore, the relationship to work is evolving. Quality of work life is becoming an essential element for employees. However, industrial jobs are not the best placed on this criterion. They also offer little opportunity for remote work, which is now a widespread expectation. These factors further diminish the attractiveness of sectors which are already at risk of staff and skills shortages.

Finally, for employees and especially those in "telecommutable" roles, the relationship to work, collectives, and employer is more distant than before.

The industrial world is changing

- ▷ Globalization, deregulation, corporate restructuring with a focus on core competencies
- ▷ Climate change
- ▷ Rapid digitization
- ▷ Geopolitical tensions, cyber threats of all kinds
- ▷ Tight markets in a world dominated by Sino-American antagonism
- ▷ Consequences of deregulation, gig economy, and low-cost trends
- ▷ In contrast to a reinforced demand for Quality of Work Life, at least in Western countries

[3] In her State of the Union address in 2023, Commission President von der Leyen highlighted the deficit of workers and skills as one of the main economic challenges for businesses and the top priority to be addressed for the European Union in the coming year.

2

The main questions concerning the future of industrial safety

These developments challenge the management of safety as it is conceived, practiced, or modeled. They affect two major aspects: the current position of industrial safety within a growing field of issues competing for priority in societal concerns; and the reality of the conditions under which high-hazard industries operate today. These aspects are addressed in detail in the following two sections.

2.1 What articulation between industrial safety and other increasingly pressing issues?

Security (the prevention/management of malicious acts) and environmental protection have emerged as major issues within most industries, coexisting with industrial safety and workplace safety. To meet these new challenges, some industries have created dedicated new departments, while others have more recently integrated these aspects into a single department, under banners such as HSE or One Safety. At the governance level, some regulatory bodies and public authorities formerly dedicated to safety have seen their scope expand, notably to include security, requiring a more or less explicit and thoughtful articulation of the two issues. However, regardless of the definition of boundaries and the distribution of areas of responsibility, the articulation between security, industrial safety, occupational safety, quality, environmental impacts, industrial hygiene, and psychosocial risks (at a minimum) is not always thought of as such, and translated into explicit decisions and frameworks.

However, real-life situations ignore the artificial divisions between the various issues that high-hazard industries try to address, overseen by partly distinct bodies of regulations and authorities. These different issues **coexist in context**, and sometimes appear if not in contradiction with each other, at least not always in synergy. **Trade-offs** are made, sometimes entrenched in integrated management systems, sometimes implicit and unconscious. At the sharp end, these trade-offs place operators in front of difficult choices to make in the absence of clear directives or explicit frameworks when multiple issues prove to be conflicting in context and call for different actions.

In summary, practices reflect an insufficiently conscious and concerted articulation at all levels.

The role that industrial safety plays in these trade-offs, and that ways in which it is conceived, discussed, decided, remain open questions both in terms of field practices and transversal governance modes, across various organizational levels. This reality, in which all issues converge, is only partially described and scientifically analyzed to date in its mechanisms of operation, its strengths, and its limitations. Indeed, theoretical models remain specific to a single dimension, a single issue: security model, safety model, environmental impact model.

2.2 Under what operational and organizational conditions is production carried out today and will be carried out tomorrow?

At the governance level of safety in industry, several difficulties arise from the dual evolution of environmental threats[1] and the emergence of systems that learn during operation. We have already mentioned the challenges associated with the safety certification and regulatory oversight of machine learning systems.

At the industrial level, one of the observed reactions to rising uncertainties and societal expectations — with its legal responsibility issues — is the rise in formalization, standardization, and **auditability**. Under the impetus of major Western industrialists in particular, standards are multiplying and are sometimes integrated by reference into regulations by authorities that adopt co-regulatory principles and move towards state disengagement. This standardization ignores the importance of the professionalism of frontline actors, and values generic risk management expertise at the expense of the contextual and situated expertise on which many at-risk activities rely **[Almklov and Antonsen 2014]**.

At the level of at-risk organizations themselves, this standardization is adopted in the form of processes and procedures, and industrial safety (like security, workplace safety, or the environment) is managed through indicators that feed into a formal management system.

But on the ground, reality is less smooth than in the "paper" frameworks (standards, regulations, management systems) mentioned earlier:

- Organizational and technological boundaries are blurred **[Weil 2014]**, as are responsibilities.
- Work collectives are fragmented, with multifaceted employment statuses (employees, subcontractors, temporary workers, platform workers) and skills.
- Understaffing and/or lack of equipment become more frequent.
- Co-activity becomes the rule, without really organizing the necessary coordination for the simultaneous activity of several companies with different statuses, responsibilities, logics, structures, cultures, constraints, and practices.

This complexification of the conditions under which work takes place, combined with new uncertainties, especially environmental and digital, raises many questions concerning safety management at all levels, from governance to field practices.

[1] Industries also impact the environment, inducing a circular relationship of influences between the two.

Industrial safety as it has been developed is being challenged

- **Increased complexity and instability**: the world of work becomes less predictable, planning more uncertain, yet stability (of regulations, trade, labor, the context) is a historical condition of safety. These trends affect different industry sectors, as well as areas such as healthcare [Amalberti and Vincent 2020; Page et al. 2023].
- **Relative loss of priority in public opinion**: the level of excellence achieved in the safety of industrial operations is seen as an acquired asset rather than as a result of continuing ongoing investment. Other risks which appear more frequently in the news take a larger place in citizens' and firms' preoccupations, at the expense of efforts in favour of industrial safety.
- **More challenges to the integrated global governance of safety** (which refers to the concept of One Safety), in a context of increasing divergence of the risk management requirements put in place for different risk categories.
    - With industrial safety subject to the loss of authority linked to organizational fragmentation and the immense variety of sizes of the actors involved, and to the increasing interdependence of all these companies gathered on the same site in temporary networks for work management.
    - With the increasing importance of psychological aspects in occupational safety, and the limits of training for "new" management styles required to respond to these issues.
    - With ever more constraints related to cybersecurity, which imposes requirements and limitations that often conflict with the openness and data sharing which are embedded in the professional culture of safety experts and which contribute significantly to the production of safety.
    - And with increasingly pervasive environmental requirements, which have their own rules and which put pressure on industrial safety governance to open up to the expectations of new players external to the firm: citizens, pressure groups and NGOS, local and national governments.

3

What paths forward for the future of safety management?

3.1 A new landscape that challenges classical safety models

An important feature of the new landscape outlined in the previous chapter is the increasing complexity of the "world": contexts, interaction networks, organizations, processes, and operations. It is characterized by unprecedented uncertainties and instabilities (geopolitical, environmental, economic, operational). It challenges a **foundational paradigm of safety management**, namely that **operations can be anticipated and their safety controlled**, in particular by **reducing uncertainties** (for example through risk analysis, regulation, certification processes, procedures, management systems). While this paradigm of complete anticipation, predetermination, and *a priori* control has been amended by some more recent approaches (e.g., HRO, Resilience Engineering), these have not, as previously mentioned, truly found their way into practices [Dwyer et al. 2023; Gilbert et al. 2018] and are constrained by existing regulatory and legal frameworks.

Thus, the foundational paradigm of deterministic control as the basis of safety management remains extremely prevalent in businesses and in society (public, the media, the legal system…), particularly in demonstrations of "control" over safety. These analytical and prescriptive models on which safety cases are based rely on a set of assumptions, most often implicit, which the current and future landscape challenges.

Indeed, this foundational paradigm of safety management further assumes that:

- Safety results from effective control over the hazards generated by the activity.
- Total control is possible through "rational" and "safe" design, maintenance, and operation of systems.
- Effective control assumes a scientific understanding of the reliability of human operators and a proper consideration of this understanding in the design and implementation of interactions between them and the technical system.
- "Effective" control requires adequate organization, which combines effective transmission of operating rules and procedures and attentive listening to implementation difficulties.
- Accidents are exceptions to the normally safe behavior of sociotechnical systems. They result from combinations of latent or event-based anomalies in the "system" — failures, errors, violations, made possible by a failing organization. "Every accident is an organizational failure".
- Accident probability can thus be reduced via a continuous improvement loop that detects and corrects anomalies (both patent and latent) before they recur and develop.
- However, the goal of zero risk would be economically unrealistic. There is a level of risk, and therefore of safety, that is acceptable for a given type of industrial activity in a given country. This level results from a trade-off between the perceived benefits of the activity for society and the anticipated and observed statistical harms, measured against the value of a prevented fatality in the country considered.

- Safety can therefore be assimilated to the proper management of anticipated hazards (exploring the realms of the known and the knowable is sufficient). In other words, the complexity of the world can be mastered, in particular through quantification and the drastic reduction of uncertainties.
- Insurance is the complementary strategy to safety management.
- The historical governance framework based on regulation and oversight by an authority is *the* appropriate framework for safety.
- Safety is an absolute priority for high-hazard organizations as well as for civil society.

Key issue

Four observations emerge from the previous sections:

1. Major changes are already underway and will accelerate in the years to come, profoundly affecting high-hazard industries and the ecosystem in which industrial safety is situated.
2. Due to their nature, a majority of these changes will weaken, relativize, or even contradict the characteristics of the world — stability, continuity, linearity, predictability, etc. — that are taken for granted in the design of existing strategies for controlling and managing major accident hazards.
3. Therefore, it is unlikely that the industry will be able to continue to maintain a sufficient level of coherence between its control of industrial risks and society's expectations by extending current strategies, even by evolving them marginally or by doing more and better what it already does.
4. The history of the evolution of industrial safety thinking has not yet produced an alternative paradigm that has been integrated into the management of industrial safety.

3.2 Conceptual evolution paths for thinking and acting on industrial safety management

As mentioned in the introduction, these observations have lead the FonCSI to question both the future legitimacy of the currently dominant approaches and the epistemic and societal reasons for their persistence. They have also triggered an ongoing brainstorming process aiming to explore new perspectives on safety management.

3.2.1 Opening up the current scope of industrial safety management along two axes

Safety practitioners and researchers will need to explore issues and work with partners beyond the historical "frontier" of topics traditionally included in the "safety" scope. Two axes seem important in this expansion in scope:

- **The interfaces between industrial safety and other issues that have become major for industries and society**

  The perceived competitive arrival of new risks to manage in parallel (cyber, ecology, and new concerns about workplace safety, especially psychological) will require **thinking of industrial safety not in isolation but in an environment where other risks and safety-related objectives will also be perceived as priorities**. More generally, safety models should extend beyond the current artificial scope that isolates industrial safety from the rest to address and **include critical interfaces** (both between risks, and with the context).

  To what extent should we move towards **integrated management** (and if so, at what level(s)) of these different safety objectives, naturally diverging from each other in our

current organizations, and managing their respective priorities in context? Are there **other thought patterns** to reconcile, as far as possible, these different objectives by thinking about them together without integrating them?

▷ **To new stakeholders whose voices matter in the effective governance of these various issues and the place that industrial safety occupies** (e.g., NGOS, policy-makers, associations, media/influencers) in order to think more realistically about safety governance in the ecosystem in which it operates [Bieder et al. 2024b].

Extending the scope of safety management

▷ At the interfaces with other salient safety-related issues and the context in which it operates.

▷ To new actors who might contribute effectively to its governance.

What if?

... the reasons for the persistence of control models for managing safety were to be sought elsewhere than in the absence of more "realistic" models?

Some safety management models developed since the 1980s (e.g., HRO, Resilience Engineering) adopt a more realistic approach to the integration of uncertainties and the complexity of operations than that assumed by deterministic control models. However, though these schools of thought which embrace some aspects of the complexity of operations do provide a clearer way of thinking about complexity and its impacts, they remain largely ignored by industries, safety authorities, and society. Why?

Several hypotheses can be formulated for this lack of takeup:

H0: Advocates for considering complexity have not succeeded in deducing measurable, controllable, and integrable safety principles and conditions from models of complex systems that are compatible with the constraints of liberal capitalism.

H1: Theoretical models of complexity are unsuitable for the subject of industrial safety, which relies on "approvals" or "certifications" issued on the basis of rigorous demonstrations. For example, one could argue that considering "unknown unknowns" from Rumsfeld's framework or non-probabilizable uncertainties prohibits a rigorous demonstration of safety in the strict sense.

H2: Considering complexity is an unnecessary and counterproductive refinement, in the same way as the general theory of relativity is a dangerous and entirely unnecessary complication for flying an airplane or firing a canon: Newton's law is sufficiently accurate and more suitable for these situations.

H3: The industrial world has not reached a level of complexity that justifies the introduction of untested paradigm and strategy changes to account for it. We would lose more than we would gain by doing so because the negative collateral effects (e.g., an increase in disorder in simple and predictable contexts) would outweigh the potential gains (better management of the unknown).

H4: It is not about seeking "maximum objective safety" because this notion is meaningless. It is about minimizing the component of the social rejection function of industrial activity caused by accidents. This involves a narrative which can be understood by all (accidents have causes, they are analyzed and corrected) but which has little to do with scientific rigor. The frequency of accidents matters less than the fact that the frequency is decreasing. Moreover, conventional approaches are (currently) very effective in reducing the frequency of non-catastrophic accidents.

H5: Reasons for the rejection of industrial activities are multiplying (pollution, contribution to climate change, etc.), and it is certainly not the right time to announce that, in fact, our control of safety is limited.

H6: In the field of industrial safety management, where anticipation and control have always been the watchwords, transitioning to a new framework of thought and action involves deconstructing at least part of the existing one. This generates methodological and organizational difficulties, as well as insurmountable institutional, political, legal, and societal ones.

A question then arises to avoid reproducing a significant gap between theoretical models attempting best to account for the reality of safety management in the field and auditable models of legitimization/demonstration of safety management: **what are the implications for high-hazard industries and beyond, for safety authorities, policymakers, the judiciary, or citizens, of abandoning or *at least* transcending the control model?**

3.2.2 A reflection on refounding models of industrial safety management to integrate complexity and uncertainties

The complexification of operations and of the context in which they occur means that several new features must be recognized and integrated into safety management models:

- The existence of irreducible uncertainties that we must be able to live with, where previously there was an attempt to control everything by claiming to reduce or even eliminate all uncertainties.
- Organizational and operational conditions (existing today or expected in the future) in which resources do not always correspond to what is planned on paper (e.g., a deficit of qualified labor partly compensated by contingent workers).
- The new cybersecurity and terrorist threats to industrial installations, whether they come from outside or from within.
- The new natural threats to industrial installations, whether new in nature, intensity, duration, or combinations thereof.
- The blurring of organizational and sectoral boundaries and the multiplication of interfaces, or the heterogeneity it induces in terms of knowledge of and attention to industrial safety.

Learning to "live with" identified problems

Traditional hazard elimination strategies are not applicable to many of the problems and challenges identified earlier in the document. Indeed, several of them are not even amenable to a "risk reduction" approach.

- Industrial safety has been built on the identification and assessment of risks, understanding their causes, and eliminating these causes.
- Reality increasingly challenges this approach:
  - We do not (any longer) know how to eliminate all causes, or incidental problems (the result of these causes), particularly issues related to the availability of human resources, both in quantity and quality (training). Understaffing, poorly supervised workers due to a lack of skills, is unfortunately becoming the norm in many countries and industries.
  - We do not (any longer) know how to plan activities as close to reality as possible. It is becoming increasing apparent that we do not, and cannot, fully control the context in which work is carried out. Even adjustments from one day to the next become very approximate.
  - **In these conditions, we must accept the opening of a new field of reflection on industrial safety and its conceptual models** which must help companies and stakeholders **to live safely with** it. A new approach opens debates on the substance (how to do it) and on the practical acceptance by all parties (the *de facto* abandonment of eliminating causes), including the legal systems.

This new field is unploughed. This document opens this debate to the relevant communities, both practical and academic. The FonCSI hopes to contribute to moving this debate forward.

A first approach to defining this new model(s) consists of:

- Exploring what can be "saved" from the founding paradigm.
- Exploring what can be rethought from more elaborate existing models, notably HRO, resilience.
- Exploring what, among the ideas currently being developed, could make sense in the field of industrial safety considered in its ecosystem.

▷ Exploring what new technologies (e.g., AI) can bring to industrial safety management.

What if?

...the scientific framework to describe what is happening already existed?

The evolutions mentioned in the first chapter of this document increase the complexity and instability of the world. Complexity has been apprehended theoretically and conceptually for many decades. An abundant literature on the subject exists, though it has seen limited takeup in the area of industrial safety.

The concepts and methodological tools to address complexity appeared more than half a century ago and are numerous today **[Hardin 1968; Morin 2007; Le Moigne 1995; Progigine 1997; Taleb 2007; Heath-Carpentier 2022]**. Some developments in the field of industrial safety management have drawn inspiration from these theories **[Rasmussen 1997; Dekker et al. 2011]**, especially High-Reliability Organization (HRO) theory, Normal Accident theory **[Perrow 1984]**, and the Resilience Engineering approach **[Hollnagel et al. 2006]**.

However, these applications of the notion of complexity to industrial safety do not constitute a single and coherent message in theoretical and practical terms. Perrow declares that complexity is inherently uncontrollable and deduces that risk management requires us to limit the complexity of high-hazard industrial systems. The HRO school responds that the complexity of the organization (redundancies, slack, coupling the organization to reality as much as possible, sufficient autonomy of frontline staff, empowerment, sense-making capacity, etc.) can control the complexity of processes. The Resilience Engineering school is divided into several approaches. Hollnagel describes resilience as generated by an anticipation-monitoring-reaction-learning loop, which is a classic control model and does not refer to robust control theories. He also proposes to model control losses as resonance phenomena between the "vibrations" of different critical parameters for safety, and to study them using a neural network (FRAM). Woods relies on the theory of adaptive complex systems to model the safety of sociotechnical systems through notions such as the adaptive capacity, optimality-brittleness tradeoffs, decompensation mechanisms, and graceful extensibility **[Woods 2019]**. Leveson uses complex system modeling by loops of amplification and inhibition on "sociotechnical" functions (reliability, trust, risk aversion, etc.) and develops computer simulators quantifying these dynamics. Dekker builds on the HRO approach by overemphasizing the spontaneously stabilizing and securing role of frontline actors' autonomy and advocating for an an-archic (less bureaucratic, horizontally rather than vertically coordinated) safety framework **[Dekker 2017]**.

What if?

...the increasing role of AI in safety management pushed HOF into the shadows?

Current models reserve a predominant and historical place for humans in the organization and management of risk: the "noble and intelligent" part of safety (risk analysis, preventive barriers, safety cases, certification and so on). Today, the technological approach to safety hardly covers this management aspect; it is limited to machines, their design, their reliability, and the quality of their interfaces. What if tomorrow opened a **new logic** with **risk management and operational tasks gradually transferred to "intelligent" machines** (or at least, more capable of managing systems by reconciling safety and other objectives than an average operator)? Industrial safety would gradually move towards an "all technology" approach, deeply questioning the current attention paid to the human and organizational factors (HOF) of safety.

The implications of putting industrial safety management evolutions on the agenda

The involvement of stakeholders in high-hazard industries (especially local communities and civil society) in activities related to industrial safety is not self-evident in a context where safety is a silent issue, much less salient than others in the daily lives of the population, policymakers, and industries. In terms of visibility, further thought may be needed to present industrial safety not necessarily as a concern in itself, but at least in relation to the concerns of industries, individuals, and societies (e.g., environment, health, cybersecurity, security).

Furthermore, the proposals outlined and those emerging from discussions with academics as well as with stakeholders in high-hazard industries are not all of the same nature. Some amend existing practices at the margin (e.g., integrating certain climatic phenomena into risk analyses). Others question more fundamental aspects, organizational, institutional, legal, etc. (e.g., integrating civil society into the governance of high-hazard industries). However, anticipating the conditions that would favor these changes or the impacts of these changes is not easy. For example, while integrating new climatic or cybersecurity threats into risk analyses may seem relatively easy to achieve in the short term, this could highlight risks for which it is difficult (for economic or political reasons) to envisage reasonable reduction measures.

What if? ...we tried to imagine a timeline for the forthcoming changes to industrial practices?

1. In the next 5 years, under pressure from the sharp end, the establishment of **training programs on "living with" uncertainty and the unexpected** as a **more official and formally acknowledged component** of safety management activities. These training programs would be accompanied by the development of various modes of "online debriefing", briefings tailored to the needs of the activity's rhythm, more adapted to the local context of the moment, and aimed at improving the consideration of contingencies. Absolute red lines and "no-go" zones would be more heavily employed to adjust hour-by-hour management to unforeseen circumstances, and would be more readily endorsed by the managerial chain. New operating strategies for dealing with emergency situations would be developed, such as the "state-based scenario-independent" operating procedures in the nuclear power sector, or symptom-based procedures in emergency medicine. Positive lessons learned would be developed to better take advantage of opportunities related to the unexpected. A more comprehensive reflection on the responsibility of actors would limit the organizational hypocrisy which is currently too often used to ignore the effects of uncertainty and operational constraints. These developments presuppose that safety authorities, regulators, the legal system, and society gradually evolve their perspective on this issue of "living with".

2. Within 5 to 10 years, to address the prevalence of other issues (social, environmental, related to malice), the emergence of a **new "One Safety" generation of Safety Management Systems** managed within a single department. The integrated management system provides a framework and procedures for managing interfaces and frictions between these different risks and the safety-security needs that arise from them.

3. Within 10 years, under the pressure of the digital transition, the progressive integration of **"all-technology" system management solutions**, replacing human-supervised control-command systems. Accidents in these large technologized systems will become rarer, but their consequences more severe. An irreducible portion of industrial activity (with lower added value, less easy to automate, less socially valued, more clandestine) will still be conducted by underprivileged humans, who will bear the risks that society prefers not to acknowledge.

4. Within 20 years, a **redefinition of safety solutions**, including in the parameterization of full technological integration. The objective of avoiding accidents would naturally persist, but another aspect of management would gain importance: managing during and after accidents, as accidents will be rare but much more dramatic in their consequences. The social perception of these very rare and very serious residual accidents would depend as much on the effectiveness of managing the consequences as on their avoidability and lack of anticipation.

Adaptation or revolution?

This debate will necessarily require the participation of two interconnected spheres:

- ▷ The academic world, that will likely enrich and advance the notion of resilience and the management of complex systems by highlighting current incompatibilities between dominant safety strategies and real-world characteristics, and hence a need for a paradigm shift.
- ▷ The industrial world, which thinks, above all, in terms of compatibility with the requirements of economic competitiveness and the expectations of the society in which it operates, for demonstrating its total risk control.

The authors of this document have different points of view concerning the terms and the agenda of the articulation between these two spheres, which may explain certain nuances and diversity in the ideas put forward.

Some believe that the industrial world may entertain the premises of the aforementioned models within private deliberative circles, but in practice, will think in terms of adaptation rather than revolution. No one will readily relinquish tangible benefits for speculative improvements. Indeed, abandoning the existing framework that has led to current success in favor of a potentially better alternative, would require immediate and substantial sacrifice for a reality projected beyond individuals' careers and the practical horizon of businesses (rarely greater than 15 years).

Others think that the transition from a "simple, predictable, and totally controllable" world to a "complex, partially unpredictable, and mostly manageable" world would certainly constitute a paradigm shift that would be difficult to digest by the laws of liberal economics and current societal beliefs. But in practice, it would not constitute a speculative jump into the void. It would not mean an abandonment, but rather an extension of current safety approaches, adding strategies adapted to the unexpected and to outside-design-envelope situations. Some are already explicitly addressed and others are present in real safety practices, but are "tolerated" rather than being assumed in safety demonstrations (and therefore do not benefit from wider understanding and improvement).

Another point of ongoing debate between the authors is whether progress on the problems discussed in this document will result from more widespread adoption of the concepts and strategies already developed in the complexity literature and the resilience engineering community, or from a simplification of these concepts to make them more digestible by practitioners, or from a significant change in the paradigm used by regulators, safety authorities, the legal system, and more broadly, societal expectations concerning anticipation and compliance in high-hazard systems. We hope to prolong these discussions with other interested parties.

4

Living with...

The trends described in this document concerning industrial safety and its future will require us to live with climate change, the digital transition and autonomous machines, geopolitical disruptions, demographic shifts, evolutions in individuals' relationship with work and employment, and changes in societal expectations concerning industrial activity, a smörgåsbord of what some commentators refer to as "civilizational changes". These disruptions will be served concomitantly; a management paradigm based on the assumption that total control is feasible is likely to lead to indigestion.

This document gathers reflections on a wide array of dimensions concerning industrial safety and its future. It explores both theoretical aspects through models and approaches found in the literature, as well as practical aspects of safety management and its societal dimensions. Furthermore, it considers the current situation as well as potential developments, some of which may already be underway, all of which have or may have a direct or indirect link to industrial safety and the prevention of major accident hazards.

The objective of this analysis of current and future conditions, and the implications they have or may have on industrial safety, is to share these reflections with other stakeholders in order to enrich them, **encourage debate and criticism**, and collectively **develop various ways of moving forward**, possibly building on some of the ideas sketched out in this document. By combining elements of scientific analysis with more provocative inserts that push certain ideas or hypotheses beyond the confines of polite academic discourse, the FonCSI, as a think-tank, aims to stimulate a global and collective reflection on the future of safety management, in particular in high-hazard industry settings. This document is intended to serve as a starting point for this endeavor, which will continue through discussions with various communities, particularly academics and experts, as well as with other stakeholders concerned by this societal issue that every industrial disaster brings back into the spotlight.

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