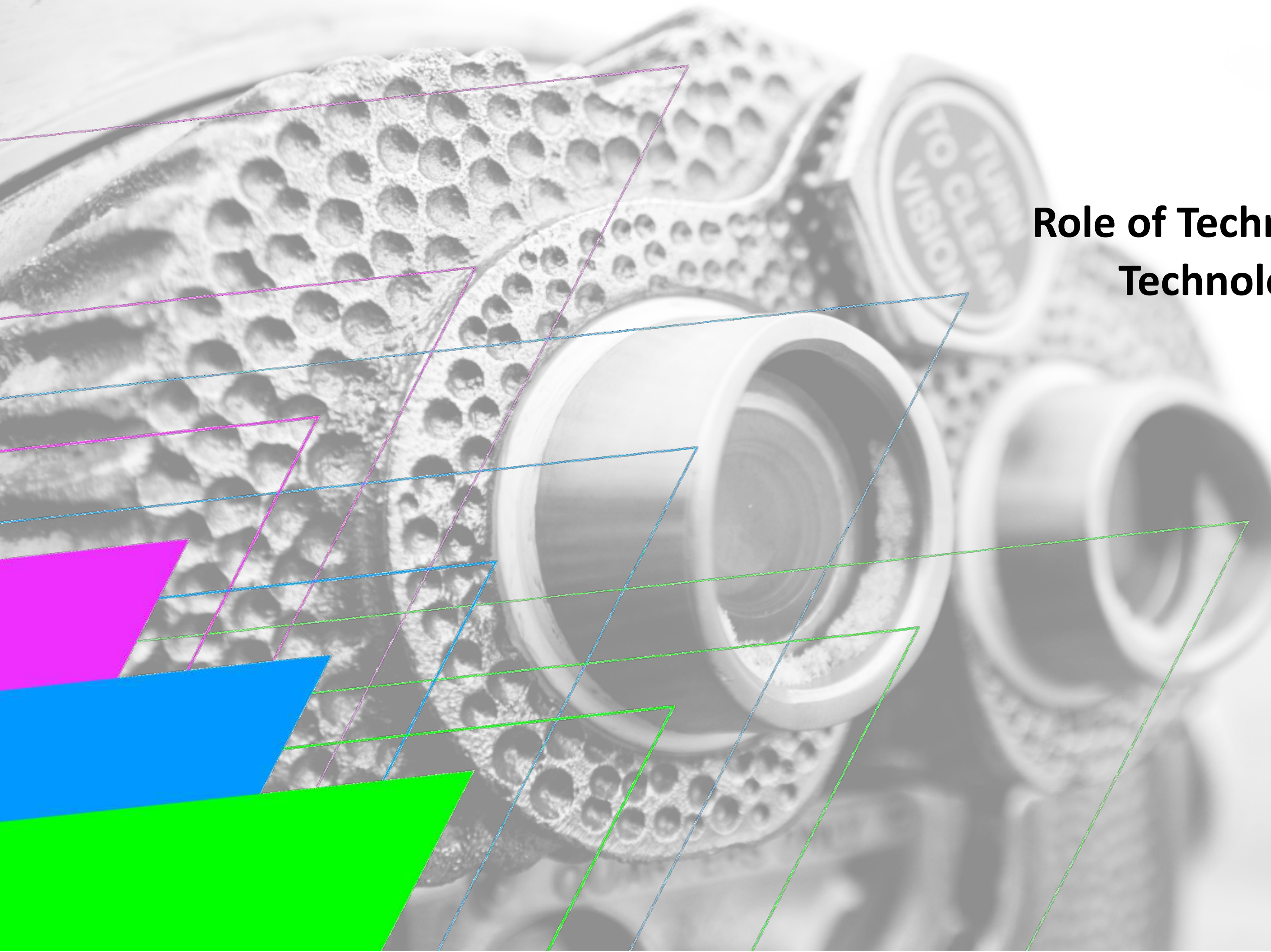
Enhancing Safety: The Challenge of Foresight

ESReDA Project Group *Foresight in Safety*



Chapter 12

Role of Technology in Foresight for Safety — Technological potentials and challenges to enhance foresight in safety

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Executive Summary

This chapter identifies the major existing and emerging technologies relevant for foresight in safety, based on a systematic literature review. The chapter presents technologies, domains and applications in use to improve safety directly and by enabling the use of foresight. The review identifies potentials, limitations and difficulties associated with the application and the use of advanced technologies for enhancing safety and enabling foresight in safety.

New technologies are mainly based on the availability of advanced sensors and growing computing power, communication bandwidth and storage capacity. These basic technologies are improving software and hardware solutions and allowing the use of more advanced technologies like computer aided hybrid development, real time modelling, advanced simulations and artificial intelligence.

Technological advances are useful for all stages of the life cycle of safety related systems, i.e. design, verification, validation, production, testing, commissioning, operation, maintenance, emergency response and decommissioning. Improved designs assure system safety with an optimised use of resources.

The use of realistic simulators for the training of operators increases both performance and safety.

Monitoring and predictive diagnostics also improve availability and reduce the risk.

The use of technology for enhancing safety and foresight is scalable and widely applicable to many domains (e.g. transportation, power generation, construction, process industry, etc.). Different applications allow for the optimisation without compromise in safety. Advanced risk modelling with big data analytics and knowledge management allows for the integration of foresight in safety with conventional approaches. Simulations and virtualisations are improving the design, operation, safety and planning, while creating more realistic accident management. Improved realism, extended scope (with scenarios and time coverage) and easy use are together enabling foresight in safety.

The role of technology in enabling foresight in safety is to complement conventional approaches with the wider consideration (including less likely events and scenarios for long-term time horizons) as well as with means for a wider participation.

Some of the problems associated with the use of advanced technologies are related to the increased technical complexity and required connectivity. The problem with complexity is that software and digital instrumentation and control is more challenging to verify and validate. The necessary connectivity, wireless and over internet, increases both privacy and cyber security related risks.

The potential benefits from the use of new and emerging advanced technologies are continuously increasing. This is especially important for safety related applications where optimisation should not compromise safety. Foresight in safety is easier to apply with advanced technological tools like modelling and simulations over the whole life cycle of the system. It is important to assure that these benefits are greater than the threats coming from the use of many new technologies.

12.1 Introduction

Modern life is more and more changing because of the ongoing and increasing digitalisation of the world. The change to society is mainly digital (new software and more powerful hardware) but it is also complemented with the development of novel and inexpensive sensors, networks and communication systems. When combined, these technologies enable connectivity and base for many new applications, i.e. wide band global communication systems, affordable remote data storage, global positioning system (GPS), cloud computing power and internet of things (IoT). The resulting development is generally improving everyday life, the economy and society as whole but is also causing serious unintended consequences and issues.

The role of technology in safety and foresight is of special importance because technological advances can potentially influence safety related systems through all stages of their life cycle. The design and operation of safety related systems can benefit significantly from technology, with a potential for continuous safety assurance through the application of advanced hardware and software solutions with optimised use of resources. A more integrated life cycle of safety related systems allows for example the use of advanced risk assessment modelling and the easier inclusion of complementary foresight thinking.

A specific example of a framework for an integrated nuclear digital environment, in [1] illustrates the potentials. The UN Sendai Framework for Disaster Risk Reduction (DRR) 2015-2030, on the other hand, emphasises the general use of science and technology, **Error! Reference source not found.**.

This chapter portrays a systematic review, which aims to identify major existing and emerging technologies with tangible potential safety benefits applicable to different life cycle phases (i.e. design, verification, validation, production, testing, commissioning, operation, maintenance, emergency response and decommissioning) of various systems.

The goal is also to identify domains of application and to provide typical examples of potential safety benefits emphasising the relevance for foresight in safety.

New technologies, while solving many problems, also introduce new challenges related to the use and safety (e.g. with unintended consequences). This duality raises many questions about the optimal development, regulation and implementation of new technologies.

The relevance of new technologies for the foresight in safety will be measured by how the conventional approach to safety can be extended and enhanced in relation to the inclusion of less likely and long-term scenarios proposed by a multidisciplinary team.

Foresight in safety can potentially greatly benefit from different new technologies (e.g. advanced simulations, visualisations and virtualisations). It is important to note that the development, use and valorisation of new technologies could also benefit from the foresight thinking and approaches.

The chapter is organised in the following way: the first section describes the approach and the scope of this systematic review; the following section presents findings and discussion; final section contains the concluding remarks.

Life cycle where technologies for foresight in safety are used
The role of technology is key for foresight in safety during all phases and related systems' activities – concept development, design, production, commissioning, operation, and decommissioning; validation, verification, testing, monitoring, education and training.

12.2 Approach

The role of technology in safety and foresight is inherently connected to both the use of technology in general and to the safety related systems specifically. This results in many different safety applications and related approaches to the development and use of regulations. Learning about the safety related use of technology and understanding the value of numerous applications in many different domains is a significant challenge.

A literature review was selected as an approach to define the systematic multi-domain role of technology in safety and foresight. Considering the author's background and the specific importance of safety the review is more focused on nuclear power. Many other fields are also included in an effort to make the review more comprehensive and to illustrate the generic value of many technologies that are useful for safety and foresight. Similar examples from different domains are used in order to illustrate common approaches and solutions. Reviewing different domains is also valuable in identifying different issues and potential limitations.

Google Scholar (scholar.google.com/intl/en/scholar/about.html) online search tool was used to access a list of related literature. The tool gives simple and flexible open access to most comprehensive cross-domain literature databases. References from many disciplines and sources are included, i.e. journal articles, theses and books from academic publishers and other online repositories like societies, universities and libraries. Google Scholar ranks articles based on the content, the publisher, the authors and the citation. The location of documents (in publishers and other repositories) and different versions are also available. Based on some estimates Google Scholar is the most comprehensive academic search engine with 389 million records [3].

Performing a literature search with Google Scholar is as easy as doing a regular web search with additional special functionalities. The search for chosen key words can be applied for selecting a time range. Search results contain a total number of references ordered based on the relevance. Every reference contains a number and the access to the searchable list of cited by articles. Additionally, search results provide a list of related articles. This is all web browser based and conveniently hyperlinked. With a Google account, it is possible to save interesting references.

The search for this chapter was made mostly for recent years, with only a few exceptions for some domains, in order to capture the broader development. The initial search was made with the key-words "technology" and "safety". Based on the titles and an abstract review the most relevant references were selected from the list as pointers for a further, more refined search and review. Over 100 papers were initially selected for further review. The selected references were then grouped in domains including "miscellaneous". A special group was related to "issues" from all domains.

The findings from this review are presented in the next section covering six dimensions as follows: domains where these general technologies are used; general groups of available technologies; list of specific applications; identified parts of life-cycle with related activities where technologies are used; technologies especially related and useful for the foresight in safety; identified issues related to preventing use of technologies or issues with potential to introduce new safety problems.

The selection and review are representative for the role of technology in safety and foresight. However, this is far from the most representative or comprehensive review considering rapid developments, as well as the number of domains and applications.

Domains where technologies for foresight in safety are used
Technology is used for safety and foresight everywhere: transport, power generation, medicine, construction, mining, military, industry, food, meteorology, security, communication, internet, research & development, smart cities, disasters risk reduction and society in general.

12.3 Findings and discussion

The present findings about the role of technology in safety and foresight are based on the more detailed review of 60 references. The presentation is divided into three subsections. The first subsection presents the fundamental technologies with example applications in different domains. The second subsection presents the major issues related to safety and foresight from the use of technologies. The final subsection covers the role of technology in foresight for safety.

The total yearly number of English articles resulting from the search of the term "technology safety"[116] has increased to the point that it doubled during the last ten years to over 300 thousands in 2019. This illustrates the increasing importance of technology for safety. The yearly number of publications including the term "safety foresight" is steady over time at about five thousands (and it is similar when the term "technology" is added). Perhaps this is an indication of a constant, if not strong, interest for the foresight in safety.

12.3.1 Findings about the role of technology in safety and foresight

The role of technology in safety and foresight is reviewed through examples from literature in nuclear power and several other domains. The findings are presented as short explanations of the technology used, the specific application, the part of the life-cycle in which it is used and how it contributes to the foresight in safety. Applications are usually combining several technologies and the grouping of technologies selected in this review emphasises the role of computing power and software.

Technologies useful for foresight in safety
Computing power, software, cloud computing, sensors, laser scanning, radars, machine learning, artificial intelligence, smartphones, social networks, internet, internet of things, global positioning system, geographic information system, virtual reality, augmented reality, 3D printing, big data analytics, knowledge management and blockchain.

[116] *These numbers were derived using Dimensions online tool (www.dimensions.ai/). This resource is similarly big to Google Scholar with a functionality for generating yearly statistics of publications.*

12.3.1.1 Computing power and advanced software

Computing power is an enabling factor for many other technologies and applications, e.g. safer and affordable design needs the fastest possible computing in order to explore numerous alternatives and test them against multiple hazards. A nuclear power plant (NPP) design, for instance, requires both the highest level of safety and economic competiveness. High performing computing with advanced modelling and simulation is necessary to include multi-physics "core simulation" (e.g. radiation transport, thermal-hydraulics, corrosion chemistry, etc.), which requires algorithms for robust numerical solutions and uncertainty quantification [4]. The access to enormous computing is significantly improved with so-called *cloud computing*. Significant and affordable computing power enables the application of many other technologies including advanced software technologies.

Advanced software consists of algorithms and the necessary hardware. The hardware is usually a combination of high computing power, sensors and some other peripherals. Several advanced software technologies are presented here, both specific (i.e. simulators, building information modelling and virtual and augmented realities) and general (i.e. visualisation and knowledge management).

Plant simulators are proven tools allowing for a better training of operators of complex systems like airplanes, NPPs and process plants, [5]. Methods for designing a human system interface evolve together with the development of technologies and include more than just an improved user interface, [6]. Simulators improve in two different directions in order to make them fully realistic and affordable. So-called full-scale simulators can not only present the full operational characteristics of the plant but also the accident conditions and the development of related scenarios, [7]. Simplified simulators can run on a single personal computer and still represent most of the plant operation, including emergency conditions. This improves both the education and training of plant engineers and operators, [8]. Plant simulators enable foresight in safety with a wider involvement and engagement of staff and stakeholders for the evaluation of different plant conditions and for testing various what-if conditions.

Virtual and augmented realities (VR and AR) are the most advanced software developments with the potential to improve education, training and operation. Both VR and AR could be applied independently or combined with other technologies like simulations. For instance [9] and [10] suggest a virtual environment and simulation as means to improve the safety during both the work and the decommissioning of an NPP. In [11] the use of augmented reality is evaluated for safety signs in the working environment. The use of AR for generating safety awareness and enhancing emergency response for construction, earthquakes and driving is reviewed in [12]. VR and AR have a potential similar to plant simulators (and especially in combination with simulators) for enabling foresight in safety with a wider participation and the consideration of less probable plant conditions.

Visualisation and *multimedia* are demonstrated to be beneficial, for example in the construction industry (e.g improved safety management and training, hazards identification, monitoring and warnings, [13]), and hospitals (e.g. preventing surgery mistakes, [14]). The *Building information modelling* (BIM) framework is used in construction design, implementation and operation for different domains (e.g. for nuclear [1] and general waste [15]) and many applications like construction risk management [16] and fire protection [17]). BIM is also used for the planning and building of the first high-level radioactive waste final disposal facility by Posiva in Finland, [18]. The risk management potentials for BIM are further enhanced with ontology and web semantic technologies, [19]. Visualisation and multimedia enable foresight in safety by allowing a wider participation and safety deliberation. BIM is therefore important for foresight in safety because it enables a long time consideration.

Knowledge management (KM) is increasingly important for complex systems during the whole life cycle. KM has the potential to improve the safety economy with a better design and efficient operation and decommissioning, with a better use of accumulated knowledge and experience, [20]. Successful KM relies on many building blocks like information systems, databases, collaborative networking, expert systems, ontologies, web semantics and organizational culture. KM enables foresight in safety by allowing a wider involvement and consideration of greater operating experience (i.e. from other plants and industries, including less significant events).

Computing and software related technologies do not always depend on high computing power or sophisticated solutions. *Novel approaches* and *advanced algorithms* solutions could result in safety improvement like in the central control of trains to avoid rear-end collisions in [21]. However, the computing power and the software needed to design and test these solutions are still necessary.

Applications of technologies useful for foresight in safety
Technologies applications for foresight in safety: optimised design without safety compromise; enhanced validation and verification; virtual/augmented experience for better design, operation and emergency planning; improved and effective education, training, operation and maintenance.

12.3.1.2 Sensors, internet, communication, "big data" and artificial intelligence

Sensors are (essential) components required for an efficient and safe operation (they are critical e.g. for avoiding dangerous situations and for reducing unwanted consequences). The requirements for sensors (like precision, speed, robustness, connectivity, energy consumption and cost) depend on the domain and application. One example in security checking for explosives, where both speed and sensitivity are required, is the use of thermo-desorption mass spectrometry, [22]. Further examples are the use of hyperspectral imaging technique for automated non-destructive analysis and assessment applied to a wide range of food products (for disease detection and quality control), reviewed in [23]. The values measured by sensors also depend on the software capabilities to interpret signals and diagnose conditions, and to predict developments. In [24] the use of a distributed equation and artificial immunity system is proposed for the online monitoring and prediction in condensate and feed water system of the NPP. Sensors enable foresight in safety by expanding the possibilities of collecting small signals.

Internet, as a network of computers, sensors and people, has a growing potential for technologies and applications in many domains. Information about online search queries is useful for various applications, e.g. early detection of food related epidemics, [25]; perception and prediction of viral and other outbreaks, [26] and [27]. Together with sensor equipped devices like smartphones, this presents an additional potential for the use of technology to improve safety, e.g. monitoring health behaviour, [28]; managing construction, [29]; and for collision warning while driving, [30]. The traceability of (and thus the possibility to prove) the origin of safety parts could be solved with new software technology, like blockchain, by assuring the validity of records, [31]. Other technologies like cloud computing rely on the internet for accessibility and affordability. Internet and *communication* enhance foresight in safety by enabling wide and instant participation.

Geographical information system (GIS) is useful for area integrated risk management like regional risk assessment in [32]. The optical, radar and other satellite data obtained with GIS are useful as a support for emergency response services for natural, technology and social related hazards, [33]. The disaster planning, warnings and response incorporate the use of social networking like tweets, [34]. The combined use of an increasing number of satellites could improve both the resolution and the responsiveness (i.e. to hours). *Global positioning system* (GPS) has many applications from industry to personal use and it is critical for real time use. However commercially available resolution still limits some new applications, like autonomous driving, [35].

Data from *video* and *mobile* sensors are useful for improving safety in many applications, like intersection monitoring for safety analysis, [36]. Wearable personal devices with biosensors (e.g. for hart beat, movement, sleep behaviour) are able to track physiology data that make health diagnostics and decisions about therapies easier, [37]. The accumulation of data from an increased number of sources presents an opportunity for a better understanding of complex systems and for providing new insights to safety science, [38].

The analysis and interpretation of huge volumes of data ("*big data*") requires and enables the use of new techniques like *machine learning* (ML) and *artificial intelligence* (AI). Impressive recent AI results, surpassing humans in GO game and medical diagnostics, show huge promises. However, the limits and timescale for the development of the further potential of AI are not easy to predict. About 50% of the experts believe that high-level machine intelligence will be developed in the next 30 years and that superintelligence might be developed in the subsequent 30 years, [39]. New AI applications like automatizing human work are increasingly available, e.g. restaurants food safety check and simple news writing, [40]. ML and AI enable foresight in safety by analysing all available data and by identifying important patterns that are hardly noticeable for humans. A wider participation in safety assessment is possible with user friendly tools based on ML and AI.

Modern vehicles are increasingly equipped with safety technologies assisting drivers (e.g. automatic emergency braking, blind spot monitoring, road line support system, objects recognition). Fully *autonomous vehicles* could be commercially available in several years. Automated vehicles are result from the implementation of leading edge technology solutions, including advanced sensors, computing power and edge AI, [41].

The number of technologies having the potential to enable foresight in safety is significant. Two more technologies are mentioned here to illustrate this growing and varied potential. *Unmanned aerial vehicles* (UAV, drones) are useful for numerous applications in remote monitoring (e.g. 3D radioactive contamination mapping, [42]). Eye movement recording and analysis allow experts like pathologists to learn and improve their diagnostics, [43]. Advanced 3D printing is used in many domains for the preparation of difficult tasks, for producing custom complex parts, and for education and training, e.g. in medicine [44].

12.3.2 Issues with the use of technology for safety and foresight

Some potentials and promises of new technologies for improving safety and enabling foresight need testing before wide adoption. This is necessary even for simple applications like material condition monitoring ([45]) and especially for complex solutions like digital control rooms (DCR), [46]. An example of DCRs show that the potential might be different for various domains depending on many elements like the implementation and the operators' age. For instance [46] documents potential side effects reducing the operators' reliability in DCRs for NPPs.

The verification and validation (V&V) for digital technologies is an open problem. While by nature digital technologies allow for realistic virtual testing, the existence of an immense number of possible states makes a full testing practically impossible. This is the case for example with the autonomous car [47] and with the nuclear digital instrumentation and control, [48]. Experience proves that hardware and software induced failures are inevitable in complex digital systems and this should always be factored into the design redundancy and the system's recovery function, [49]. Completely new problems arise from the limited capability to provide for adequate reasoning and arguments for the results created by AI. A number of recommendations for the research and development prioritisation in the development of NPPs relates to the adaptation of digital technologies addressing V&V and other issues, [50].

The Internet and related social networks are both useful and cause many bad unintended consequences (e.g. effective dissemination of false information). The reliability of information is important for a better functioning society and especially during an emergency situation when it can have detrimental effects, as it was tragically illustrated during and after the Fukushima Daiichi nuclear accident, [51]. The possibility that online data are imperfect, incomplete and changing should be always considered, [52]. Human and AI based solutions are in development to help with this problem. However, the problem of information reliability is increasing and additionally complicated with other issues like free speech, who is provider, etc.

While smartphones allow for easy communication and access to information, they are also a distraction for important activities like driving, and could be the cause of accidents, [53]. This is regulated in some countries and easy to identify through the availability of recording of activity by the smartphone before any accident.

The cost limits the introduction of some technologies with proven benefits. Usually a wide use would make them affordable. The cost and potentials depend on many factors specific to each application, country or situation. E.g. the difference in perception of the so-called "value of prevented fatality" justifies the installation of commute bus crash avoidance systems in the U.S. but not in Colombia, [54].

Cybersecurity is one of the major issues for many internet and wireless based technologies because a perfect protection is impossible without losing functionality, e.g. for autonomous vehicles [55]. Hacking is an increasing problem on the Internet and it might reduce the trust in some new technologies like various applications of IoT and AI, e.g. for autonomous vehicles and medical assistance devices, [56].

Issues with the use of technologies for safety
Use of technology for safety and foresight in safety has number of issues: cost, complexity; verification & validation; faster change cycles; cyber security; disinformation; distraction; proved benefits; privacy; AI explained.

Solutions for the issues mentioned are not trivial and will require continuous development. For some of these issues the solution is technology itself, either already built in (e.g. communication for UAV collisions, [57]) or complemented with other solutions (e.g. documenting scientific software for nuclear safety applications, [58]). Another part of the solution is learning by doing (e.g. for health information technology, [59]) after accepting a new technology with simple criteria in order to prove that it is at least as good as the technology already in use. Some issues with a new technology will require the development of new methods which will help to prevent unwanted consequences, e.g. for detecting promoted social media campaigns, [60].

12.3.3 Discussion about the role of technology in safety and foresight

The examples of the current and potential benefits from the use of technologies presented in this review demonstrate their usefulness for the whole life cycle of various safety related systems. The potential for the role of technology in improving safety seems is vast. Technology is beneficial for more efficient and safer operation. Advanced technologies enable foresight in safety in all three dimensions: plausibility, scope and inclusiveness. Enhanced analytical capabilities enable the consideration of less probable events and scenarios. Affordable advanced simulations allow for the consideration of long-term developments. The Internet, big data analytics and visualisation make it feasible for more actors to participate and to include the views and assumptions of non-experts' in the considerations.

Use of technologies for foresight in safety, examples:
Foresight in safety use of technology examples: improving the participation, the scope and the realism of safety analysis and related simulations; continuous improvements based on data, simulations and a wider participation; prompt and appropriate accident management based on the improved assessment and a wide participation; designing faster and better emergency response, based on the realistic assessment and a wide participation to minimise consequences and prevent societal disruptions; use of simulations and a wider participation to improve accident prevention and emergency preparedness.

Technology enables and improves foresight in safety with an extended scope of assessment, a long-term consideration and a wider participation. Some examples of how technology improves foresight in safety are the improved analysis and simulations to identify and anticipate safety issues; implementing adaptive maintenance to prevent failures; enabling continuous safety improvements with operating data assessment; assuring accident prevention with timely preparation and appropriate response; helping prompt and appropriate accident management with real time assessment; supporting faster and better emergency response with appropriate organisation and communication, [61]; improving learning from accident investigation; preventing societal disruptions with proper communication.

12.4 Conclusions

A systematic literature review provided many examples of technology used for improving safety and enabling foresight in safety. The numerous examples presented in this chapter demonstrate how various technologies, both individually and combined, could improve the safety and enable foresight in safety.

Many benefits are already in realised while some benefits are still in development.

The role of technology in enabling foresight in safety is to complement the conventional approaches with the consideration of a more extensive scope (including less likely events and considering scenarios for long-term horizons) as well as with means for a wider participation.

There are also issues caused by complexity and too fast introduction of new technology without sufficient regulation. Some of these issues (related to design and testing) can be solved by using advanced technologies, while others (related to safety assessment) require further intrinsic development. These issues will require the solution of specialists, but they also depend on the regulation, on the users' participation and on the change of perception.

The adaptation of new technologies might improve by accepting relative criteria in respect to existing technology, i.e. by keeping the same safety requirements for new technologies as it is applied for current technology, and by adopting a "learning while doing" approach with a demonstrated minimum initial safety level.

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