Chapter 16

Risk Analysis of Complex Hydrogen Supply Chains

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16.1 INTRODUCTION

This chapter is about methods to assess safety risks of the future hydrogen-based infrastructure in connection with the design, deployment, and operation of a hydrogen supply chain (HSC). The societal goal is to establish an inherently safer hydrogen-based economy embracing new production and storage facilities as well as transportation. It is part of the broader goal to overcome the inherent problems of an unsustainable crude oil-based energy supply.

Hydrogen production can be achieved by several means and may utilize various energy sources. It is therefore rather flexible as it is not dependent on a certain energy source. As the hydrogen economy is assumed to be a part of the goal to overcome an unsustainable energy supply, the known renewable sources for hydrogen production are of great interest, for example, wind and solar energy. Therefore, hydrogen is regarded as one of the future sustainable fuels for mobile and stationary applications. Hereunder, hydrogen technologies are part of scenarios to store electric power produced by unsteady and fluctuating energy sources, as is the case for wind and solar energy. The benefits of hydrogen are that it is a carbon free energy vector and it is not a greenhouse gas. Another benefit is that hydrogen is an excellent fuel for fuel cells. Therefore, hydrogen can both be produced by electrical power and produce electrical power. This makes hydrogen an appropriate storage medium for electrical power with its ever-increasing demand. This also implies the need to develop new large-scale infrastructure with new connecting supply chains.

Nevertheless, hydrogen technologies are new and under development, which provides some uncertainty with regard to the reliability and robustness of the emerging technology. New and developing technical systems need time to mature and hence may provide some unknown aspects with regard to the

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safety risks in the establishment phase. Hydrogen's physical-chemical properties are different from ordinary fuels, such as gasoline, that are common in our daily life. This implies a necessity to rethink the codes for establishing the new infrastructure. It is a learning process for professionals and lay people to handle the new fuel appropriately. Both aspects, the reliability and robustness of the emerging technology and hydrogen's different physical-chemical properties, are important to address in order to develop the best possible future infrastructure and to continue to develop a more inherently safer society relative to the present one. Thus, the overall goal should be to continually reduce the safety risks toward a minimum.

This is not a new thought limited to hydrogen technologies, but is valid for all technologies, and in particular, for energy technologies. It has and always will be a challenge to safely process energy, as it needs appropriate control. Failures in the control may lead to accidents and incidents that may have destructive potential to vulnerable objects, such as people, the environment, and property. This is the essence of the uncontrolled flow of energy (UFOE) model. Energy in this context is to be understood very widely as, for example, kinetic energy, electric energy, heat and radiation, as well as "toxic flow of materials" (Rasmussen and Grønberg, 1997). The UFOE model was originally designed to be used to support accident scenario development in emergency training but is considered to be applicable to also describe HSC-related accidents (Fig. 16.1).

Historically, the application of modern energy using wood, coal, crude oil, natural gas, and LPG has been a long process and throughout the development, many lessons had to be learned as many small, large, and even catastrophic accidents have occurred. For instance, the very beneficial use of furnaces and open fires in our towns has caused substantial and even catastrophic losses. Over the

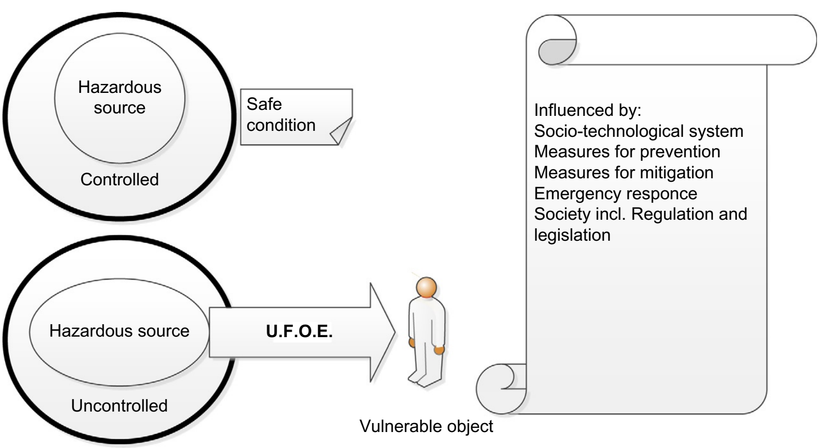

FIG. 16.1 A simple accident model uncontrolled flow of energy.

centuries, disastrous fires occurred in many towns worldwide. They could destroy large parts of towns and cause many fatalities. Well-known examples from historic times are the London fire in 1666 and the Copenhagen fires in 1728 and 1795, to name only a few (Anonymous, 2017b). Triggered by such events, prescriptive fire codes and regulations developed successfully over the centuries to enable the safe use of this type of energy. This was the result of the lessons learned after an accident, as the technical and scientific understanding of central terms, such as "fire" and "fire spread," were only poorly understood. Only recently, a few decades ago, the scientific-based methodologies developed sufficiently to understand and predict the behavior of fires and to have a performance-based approach for the design of new infrastructure. Nowadays, our towns and infrastructure are built with a minimum of fire risks. Unfortunately, some large fire accidents still happen due to design errors, or possibly inappropriate codes and standards, as the 2017 Grenfell-Tower disaster in London (Anonymous, 2017a). The specific choice and installation of the façade's cladding and insulation materials to improve the energy demand of the building, together with other factors, are believed to be the reason behind this accident. Thus, it may be argued that efforts to reduce the building's energy demand were not balanced with an appropriate prescriptive or performance-based fire safety engineering approach. Possibly, an improved and more comprehensive fire risk management, in combination with a sustainability assessment, would have prohibited such a disaster. Any decision support should equally address both the sustainability and the safety risks of technological systems.

The future development of hydrogen technologies and supply chains have the benefit of a much higher understanding of technological systems in general and the availability of science-based methods for consequence modeling (performance-based approach as in fire safety engineering). This higher state-of-the-art knowledge of the systems reliability and the potential consequences as a result of system deviations provides a much better general understanding of causes and effects of accidents involving fire and explosions. It is an excellent basis for risk assessments providing risk-based decision support to establish the HSC. Similar risk assessments have been conducted for large-scale supply chains for LPG and other chemicals (Molag et al., 2004). Parallel to the development of hydrogen applications, prenormative safety risk research for hydrogen technologies is performed within the network activities of NOE HySafe (Thomas et al., 2011) and its successor the International Association HySafe (https://www.hysafe.info). Such research provides important input to the standardization activities. It also provides knowledge support to many different safety-oriented projects concerned with the understanding of the risks of hydrogen and with guidance to establish safer systems (MacIntyre et al., 2007; Luis Aprea, 2008; LaChance et al., 2009; Watanabe et al., 2007; Duijm and Markert, 2009; Marangon et al., 2007), to mention just a few of these activities.

Nevertheless, additional effort is needed, as the HSC grows more and more complex with the developing infrastructure. Therefore, the understanding of the complex system may become insufficient as the possible number of cross-influences increases and the analyst has to face the huge challenge of assessing and evaluating the very large amount of data that a safety risk assessment of complex systems provides. This is discussed by Rasmussen (1997) on the level of risk management comprising a socio-technical system, that is, the technical system together with the legislators, managers, work planners, and system operators. He argues that a system model cannot be built by a bottom-up approach but requires a top-down system-oriented approach based on control theoretic concepts. The reason for this is that *"[…] a system is more than the sum of its elements. Often we found that attempts to improve the safety of a system from models of local features were compensated by people adapting to the change in an unpredicted way."* (Rasmussen, 1997, p. 184). It is similarly argued by Haimes (2018) that common risk assessment of single systems is insufficient at a certain stage of complexity, for instance, for systems of systems. For appropriate risk assessment and management of complex systems, Haimes proposes to extend his 10 guiding principles of risk assessment of single systems to be beneficial for complex systems (Haimes, 2018), as listed in Table 16.1.

This complexity of systems seems to have not been sufficiently addressed in the HSC research field. HSC modeling and analysis provide important decision support for establishing the hydrogen economy. Current research on the HSC only partly focuses on developing a holistic model for supply chain analysis to predict safety risks in the energy sector. There are, though, many different modeling approaches for hydrogen supply chains, as discussed in the reviews by De-León Almaraz et al. (2013, 2014, 2015).

Early research into hydrogen supply chains tended to focus on individual technologies of the supply chain, such as production, storage, and distribution, and also focused on specific areas, for example:

- A Southern California case study to develop a hydrogen vehicle refueling infrastructure (Ogden, 1999; Ogden et al., 1999).
- The feasibility of developing an initial hydrogen infrastructure for refueling hydrogen buses in London, and whether this infrastructure might provide a sufficient and suitable platform for private vehicles (Joffe et al., 2004).

Other authors have used mathematical models to describe and integrate all components of a hydrogen supply chain within a single framework. Examples include:

- The integration of production planning and reactive scheduling for the optimization of a hydrogen supply network (van den Heever and Grossmann, 2003).
- Design of a hydrogen supply chain and creation of a single framework for such a design and analysis of the important tradeoffs in such a supply chain, using OR methods to optimize the supply chain design (Almansoori and Shah, 2006).

TABLE 16.1 Risk Analysis According to Haimes' 10 Guiding Principles and Adoption to Complex Systems of Systems (Haimes, 2018)

Principal		Adaption for Complex Systems
1	Holism is the common denominator that bridges risk analysis and systems engineering	For interdependent and interconnected complex systems of systems the holistic approach must account for the impacts of adverse initiating events on systems with multiple shared states, coping with multiple objectives of the systems and taking account for multiple time horizons associated with each subsystem and the hole system of systems
2	The process of risk modeling, assessment, management, and communication must be methodical, disciplined, systemic, integrated, and commensurate in its comprehensiveness with the criticality of each subsystem and the entire systems of systems	The basic questions central to quantitative risk analysis need updating: (1) What can go wrong? (2) What is the likelihood? (3) What are the consequences? The update need to address the complexity to search for and to understand the nature, configurations, and levels of the interdependent and interconnected complex subsystems
3	Models and state variables are central to quantitative risk analysis	Modeling require the utmost understanding and appreciation of the critical role of shared states by risk practitioners engaged in decision making under risk and uncertainty
4	Multiple models are required to present the essence of the multiple perspectives of complex systems of systems	Central principle: Complex systems of systems cannot adequately be modeled and represented from a single perspective
5	Meta-modeling and subsystems integration must derive from intrinsic states of the system of system	The task is interdisciplinary and the modeler has to learn from other contributors. Thus, he or she has to develop a coherent methodological process that builds on what we know and extend this knowledge forward
6	Multiple conflicting and competing objectives are inherent in risk management	Individuals and organizations often have to deal with multiple, competing, and conflicting objectives, which is a main

Continued

TABLE 16.1 Risk Analysis According to Haimes' 10 Guiding Principles and Adoption to Complex Systems of Systems (Haimes, 2018)—cont'd

Principal		Adaption for Complex Systems
		characteristic of complex systems. Balancing the outcomes of decisions is needed, for example, maximizing the benefits from risky actions, and minimizing the cost resulting from associated risk management
7	Risk analysis must account for epistemic and aleatory uncertainty	This principle is one of the most difficult to identify, to model and address for complex systems of systems
8	Risk analysis must account for risks of low probability with extreme consequences	The common metric of risk: likelihood times consequences. This practice has played a decisive role in dangerously masking the criticality of extreme and catastrophic events. It is important to recognize the averaging of risk (a misuse) when it is used as the sole criterion for risk in decision-making
9	The time frame is central to quantitative risk analysis	The role of the time frame is probably the most important, yet the least recognized, in risk modeling, assessment, management and communication of complex systems of systems, given that each system or subsystem will be commonly driven, or affected by different adverse initiating events
10	Risk analysis must be holistic, adaptive, incremental, and sustainable; and it must be supported with appropriate data collection, metrics with which to measure efficacious progress, and criteria on the basis of which to act	This principle should be the sine qua non for all risk analysts, especially when addressing complex systems of systems

- A case study of a future hydrogen supply chain for Korea to develop a stochastic model to take into account the effect of the uncertainty in the hydrogen activities and examine the total network costs of various configurations of a hydrogen supply chain in an uncertain environment for hydrogen demand (Kim et al., 2008).

Presently, systems safety in the energy sector has been addressed by Caputo et al. (2011). They found a high safety cost for long-range hydrogen transport through densely populated regions. Also Kim and Moon (2008) predicted the safety costs for an optimized Korean infrastructure partly based on renewable energy and Dayhim et al. (2014) implemented risk costs into a multiperiod optimization model with the objective function "minimization of the total daily social cost" of a hydrogen supply chain network. Other discussions focus on topics, such as the potential growth of supply chain networks, optimizing the investment and running costs, and calculating the environmental impacts, by assessing single impacts, for example, the carbon dioxide reduction potentials using energy models (see e.g., Agnolucci, 2007; Andrews and Shabani, 2012).

In the following, a number of methods and emerging ideas for risk assessment of complex systems are presented. They partly relate to Haimes' principals and follow the basic idea of a holistic approach. Hereunder, the methods will show a new approach for establishing meta-models using the concept of "functional modeling" that can support collection and storage of data for systems under development. The concept supports cross-disciplinary assessments needed for a holistic safety and sustainability evaluation. Furthermore, a method is discussed to better handle dynamic and time related events using discrete event simulation. Finally, a case study provides an example of an integrated modeling and simulation of an HSC, including dynamic event simulation.

16.2 LAYOUT OF A MODEL HSC

This section describes a basic hydrogen supply chain taking various modes of production, storage, and transport into account. Hydrogen is produced from various energy sources and is therefore a common platform for many other applications. It is also assumed to be a link between the energy supply sector providing power to industries and households and the transport sector providing fuel and power to fulfill these transport needs. This scenario defines a complex infrastructure as it involves many different processes with many different process plants. It involves complex supply chains to transport and store hydrogen for the retailers and customers. This makes the HSC a complex system of systems.

Part of the infrastructure will be hydrogen production by electrolysis. This may utilize wind power, but hydrogen is not bound to be produced in close proximity to the large wind parks as the electrical power may be cost efficiently transported to other locations and the needed water is available everywhere. Thus, scenarios to distinguish between large-scale remote site production and small-scale on-site (e.g., at hydrogen refueling stations) may be considered (Markert et al., 2007).

Planning such an infrastructure is a challenge and it will need the application of appropriate HSC models to ensure an optimized development. This includes the application of methods to assess the safety risks of such a new and complex supply chain. Such assessment should be part of wider optimization modeling to find a truly optimized sustainable supply chain that comprises the environment, the economy, and the social aspects, which include the potential safety risks. Hereunder, as any complex technology change will not be completed overnight, it is essential to assess the new supply chain with its technologies and applications together with the old one and to ensure a smooth transition from one technology to the other.

In the following, a specific case scenario is drawn to facilitate the discussion of the methods to assess complex safety risks of the new hydrogen economy. This discussion will use a simplified scenario in which the components of a hydrogen supply chain are divided into four categories, including production, storage, transportation, and delivery to the end users. Such an HSC can be seen in Fig. 16.2. As mentioned before, hydrogen may be produced by several means. The most mature technology is steam reforming using hydrocarbons. This technology, though, is not to be considered a sustainable hydrogen production method but enables production of hydrogen in cost-efficient large quantities.

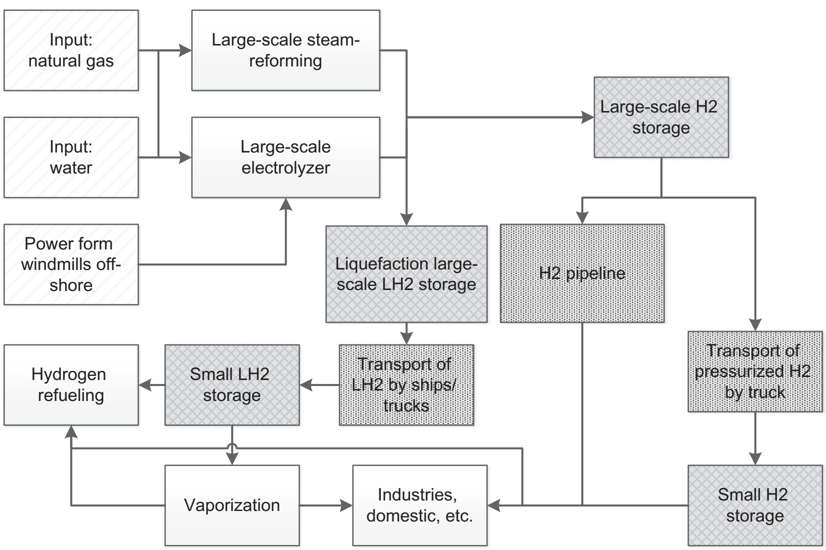

FIG. 16.2 An example of a HSC (Markert et al., 2017).

A sustainable production method is included in the model using wind energy to electrolyze water.

The model assumes that in the introduction phase of the hydrogen economy the demand will be low and therefore hydrogen will preferably be transported in pressurized containers or be produced in decentralized small-scale units placed at the refueling stations. In the long term, the demand for hydrogen is assumed to increase and therefore hydrogen is assumed to be produced in large-scale centralized units and then transported as liquefied hydrogen to the refueling stations by trucks, rail, or pipelines. The last is shown in Fig. 16.2.

Decentralized hydrogen production can take advantage of the existing and widely available grids for electricity and natural gas for hydrogen production. Moreover, delocalized hydrogen production reduces or even eliminates costs linked to hydrogen transportation and delivery. However, small-scale production units require effective process control and high safety standards mainly due to the localization of the production units in inhabited areas (Drennen and Rosthal, 2007). Natural gas reforming and small-scale water electrolysis are the current processes used for small-scale hydrogen production.

Centralized production units allow large-scale production of about 750 ton day^{-1} (U.S. Department of Energy, 2016). Reforming, electrolysis, and recovery of industrial hydrogen byproduct are the most commonly used processes to produce hydrogen in large-scale quantities. The main advantage of centralized large-scale hydrogen production is the lower production cost (economy of scale). However, hydrogen needs to be transported and delivered to the end users resulting in considerable capital investments (Drennen and Rosthal, 2007).

The production of hydrogen leaves many design choices that affect the risks to the supply chain. Some of the main ones include:

- Production in urban areas or not—the closer production is, the less risk of the transportation but the greater risks associated with the production facility;
- Transport by various means (local to regional), including transport by large-scale transporters (ship, H_2 liquid, train, and other means)—transportation means and distance will also affect risks and therefore the security of supply;
- Storage facilities (large to small scale): The larger the storage facility, the less risk associated with the frequency of transportation to the facility, but greater risk will be connected to the facility itself.

Safety and security of supply are central topics in the establishment of a future hydrogen economy, as these address the basic demands of any society.

16.3 FUNCTIONAL MODELING

The future HSC will have to fulfill several objectives, as it will likely supply the fueling system for transport and the system for power production. Such a complex and large infrastructure is a challenge when conducting risk assessment and performing risk management, because of the increasing interactions between the subsystems of the overall socio-technical system (Haimes, 2018; Rasmussen, 1997). The challenge for risk analysts is to treat a number of different threads in a dynamic and emerging system, as described by Markert et al. (2017).

In order to make the necessary and appropriate strategic decisions to establish the new infrastructure, quantitative risk assessment (QRA) may be applied in Europe and worldwide. It is a valuable tool to measure and evaluate the individual and societal risk for new infrastructure, that is, for process plants, storage, and transport routes, including tunnels, for hazardous goods transport (Baesi et al., 2013; Pasman and Reniers, 2014; Vianello and Maschio, 2014). It supports risk informed land-use planning and therefore directly supports the overall goal of moving toward inherently safer systems. This is, of course, only a part of the broader decision support needed to introduce a new technology. For planning, design, and establishment of an HSC, many different aspects have to be considered, which concern energy economy, efficiency, and security of supply. It also concerns technical reliability, safety risks, and security, as well as the general sustainability of an HSC. Usually, different experts at different times conduct these assessments for a wide variety of customers. Implicitly, there is a certain time delay between these assessments. In the meantime, the hydrogen systems being evaluated may have developed in technology and may not be fully comparable. Therefore, it would be beneficial to align these different assessments in one way or another, as a result from one study may influence the assumptions of another.

Conducting a comprehensive QRA in connection with other assessments imply, of course, some serious challenges. An important one is the handling of large amounts of data and the necessary set of assumptions used to conduct the quantitative risk assessment (Markert et al., 2017). Such data also need to reflect the aleatory and epistemic uncertainties of the parameters, the models, and the systems boundaries (Leveson, 2004; Bedford and Cooke, 2001; Aven and Reniers, 2013).

The method of “Functional modeling,” discussed below, shows a potential way to analyze complex systems and to create a meta-model to store data for the different assessment methods.

16.3.1 Functional Modeling of Hydrogen Supply Chains

Functional modeling is a high-level hazard identification method (Rasmussen and Whetton, 1997) that is capable of analyzing large socio-technical systems. The methodology enables identifying hazards already during the planning and design of systems in the future hydrogen infrastructure, as exemplified in Fig. 16.2. It uses a functional breakdown followed by a high-level hazard identification method.

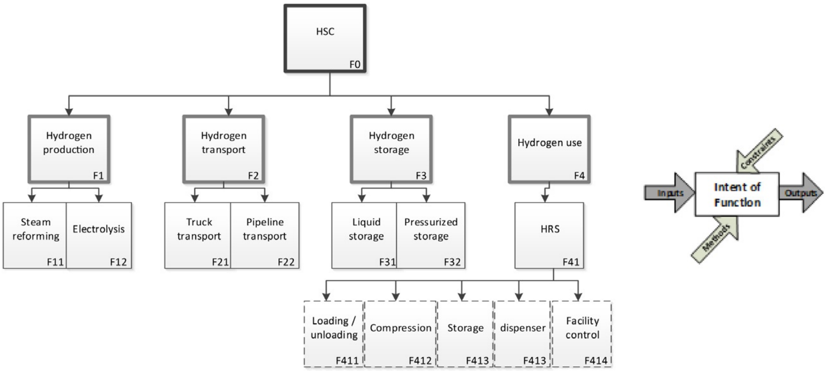

FIG. 16.3 Functional modeling of an HSC. Each function has Inputs, Outputs, Methods, and Constraints.

The idea of a functional breakdown is that a set of functions is needed to establish systems, such as a plant or HSC. The socio-technical system implements hardware, software, operations, work organization, and many other aspects. The principal of the functional modeling assumes that each function "Fx" of a system is an object that has a certain "Intent" or goal to fulfill. The function is associated with "Methods" that are necessary to establish the function and with "Constraints" that need to be regarded for safe operation.

Each method or constraint can itself similarly be regarded as an object and can be further decomposed into a hierarchy of other lower level intents. This is shown in Fig. 16.3 and in Table 16.2.

The starting point for the functional breakdown is the whole HSC, indicated in Fig. 16.3 as F0. It represents the HSC drawn up in Fig. 16.2. The inputs are the natural gas, water, and electricity needed to produce hydrogen. The output would here be the hydrogen that is dispersed at the hydrogen refueling station HRS.

The methods for the HRS are the production plants, storage, and means of transportation. These have constraints, for example, technical limits and potential safety risks. Each function is further detailed, as well as each method and constraint. This procedure should be continued until the system's hazardous areas can be identified with reasonable precision using hazard identification methods. Thus, already during the design stage, a comprehensive assessment of the system can be initiated and the assessment can be continued and extended when new information is available due to, for example, new methods being implemented or new constraints being discovered. Hereunder, the functional modeling comprises detailed technical and organizational solutions of the socio-technical HSC system (Markert et al., 2017).

16.3.2 Hazard Identification

Having established the functional model, the basis for several types of assessments in the framework of decision support can be provided. The first type is the

TABLE 16.2 Outcome Example of the Functional Breakdown

Code	Inputs	Intent	Method	Constraints	Outputs
F12	Electrical power Water Etc.	Hydrogen production	Electrolyzer	Max. pressure Availability of cheap power sources Hydrogen purity Etc.	Hydrogen Oxygen Etc.
F21	Hydrogen gas Engine fuel Etc.	Hydrogen transport	Truck	Max. pressure Route planning ADR regulation Etc.	Hydrogen gas Engine pollutants Etc.
F3	Hydrogen gas Energy Etc.	Hydrogen storage at large amounts	Cryogenic storage Pressurized storage	Max. pressure Temperature control Evaporation control	Hydrogen gas/liquid Engine pollutants Etc.
F4141	Data Power Etc.	(HRS) Remote control signals	Internet/software HRS safety functions Surveillance: Detection and Alarm ➔ Decision ➔ Action Communication Training	On-line uninterrupted power supply Knowledge on specific HRS Intercultural understanding Etc.	Control of HRS

identification of possible safety risks using the methodology of QRA. Hereunder the first step is the hazard identification, which may apply many different methods. Some of these are developed for certain purposes, as HazOp and FMEA, for example. HazOp (hazard and operability study) is developed within chemical industries and is very suitable to analyze process flows, while failure mode and effect analysis (FMEA) is an excellent method for analyzing component failures and their effects on the system (IEC, 2001, 2006). Following these basic procedures, accident scenarios are defined and more detailed analysis performed. The analysis applies methods, such as Fault Tree and Event Tree (ISO, 2010), which may be combined with additional methods, such as the safety barrier diagrams, which focus more on the safety barriers of a system and provide some advantages in terms of readability and communication to non-experts (Duijm, 2009; Duijm and Markert, 2009).

For assessing the high-level functional breakdown, general methods, such as Checklists or What-If questions, are suitable. The method of "Concept Hazard Analysis" (CHA) is applied to identify the main hazards, as suggested by Wells et al. (1993) and applied by Rasmussen and Whetton (1997). The CHA may be used in the early stages of planning and design of supply chains and need only block diagrams or preliminary process flow diagrams as input. The assessment is based on a list with generic keywords agreed upon by the group of analysts of the specific systems (see Table 16.3).

The outcome for the functional breakdown is exemplified in Table 16.2, while the correlation with the Hazard identification method is shown in Table 16.4. These results can be combined with other methods and types of assessments as shown in the following chapters.

16.3.3 Support by Geographic Information Systems

An important issue when analyzing hydrogen supply and distribution networks, is the knowledge about the specific geographical positions of the hazardous areas to evaluate social risk criteria. This is closely related to decisions on additional preventive and mitigating measures to ensure the acceptance criteria of a given installation. It is important to know the population density, the environmental vulnerability, and the location of hospitals and emergency services, among others, along the networks. For this Geographic Information System (GIS) is a very efficient and valuable tool (Verter and Kara, 2001; Rigina, 2002) as it allows for superimposing thematic maps and analyzing the population density for any geographical position, for example. It is straightforward to model the hydrogen supply and distribution networks with a GIS environment using established geographical maps and CAD drawings from the planning state of the networks.

As functional modeling defines objects (the intents), it is possible to attach one or several graphical object(s) from the GIS describing the HSC to a functional model intent to preserve its geographical position. In that way, it enables

TABLE 16.3 CHA- Examples for Generic Keywords

Category	Keyword	Category	Keyword
Flammables	Ignition Fire Explosion/ detonation	Mechanical hazards	Structural hazards Collapse, drop
Chemicals	Toxicity Corrosion Off-specification	Mode of operation	Start-up/shutdown Maintenance Abnormal Emergency
Pollutants	Emissions Effluents Ventilation	Release of material	Release on rupture Release by discharge Fugitive emissions Periodic emissions Handling/Entry
Health hazards	Chemical contact Noise Illumination	Loss of services	Electricity Water Other services
Electrical/radiation hazards	Electrical Radiation Laser	External threats	Accidental impact; drop/fall Extreme weather External interferences Loosening/vibration Sabotage/theft External energetic event External toxic event External contamination Corrosion/erosion
Thermodynamic hazards	Over-/under pressure Over-/under-temperature		

TABLE 16.4 Analysis of the Found Intents (I), Methods (M), and Constraints (C) Using Selected Keywords From CHA

Function			Concept Hazard Analysis				
Ref	**T**	**Description**	**Keyword**	**Main Variance**	**Consequences**	**Mitigation**	**Notes**
F12	M	Water electrolysis	Chemicals: corrosion	Release ➔ Fire	Heat radiation on equipment	ATEX	
F3	I	Hydrogen storage	External: accidental impact due to obstacle collision	Structural damage: ➔ Leakage ➔ Insulation	Release of hydrogen/ overpressure in cryogenic system	Fences authorization to enter	
F4141	C	On-line with data connection	Mode of operation: abnormal	Off-line ➔ Loss of control of HRS	Possible escalation of minor events	High SIL level local operation	HRS shuts automatically down on loss of data connection

the assessment of GIS databases together with the results from the functional modeling, including the results from the hazard identification.

For a quantitative risk assessment, data on the system state (amounts, pressures, temperature, etc.) could be attached as well to the graphical objects supporting consequence assessments, while respective thematic maps could provide necessary weather, population densities, and other data.

16.3.4 Combination With Methods for Sustainability Assessment

In order to establish sustainable hydrogen supply and distribution networks, there are the environmental, economic, and social aspects to be evaluated for a comprehensive decision support. Together with the evaluation of the safety aspects, such an approach provides a more comprehensive decision support for complex systems. It is intended to support decisions and to support further communication in order to discuss and reach social acceptance of emerging technologies, for example.

The decision support within sustainability assessment is commonly provided using the well-established and widely used methods within life cycle assessment (LCA) and life cycle costing (LCC). The LCA method has been standardized by several ISO standards, for example (DS/EN ISO 14001, 2015; DS/EN ISO 14040, 2008; DS/EN ISO 14044, 2008). The steps to perform the assessment according to the ISO standard involve, for example, a goal and scope definition, and the definition of the fuel unit (called functional unit, e.g., the amount of hydrogen to fill a fleet of 1000 vehicles) that is followed through the different stages of the life cycle of the fuel, as shown in Fig. 16.4. Each stage will have an environmental impact due to the respective processes, amount of energy, and materials used at each stage. This is followed by establishing a comprehensive inventory for all the materials going into and out of the stages and the energies used. Having established all that, a high-level environmental impact assessment for potential adverse effects on the ecosystem and humans is performed, resulting in scores for defined categories and an overall score. For each step, an interpretation of the results is done. Similarly, the LCC method as described by Hunkeler et al. (2008) models the costs of the stages. The calculation applies the same model that was used for the LCA (Fig. 16.4).

The functional model (Fig. 16.3) and the LCA/LCC model may be structured in the same way to ensure model compatibility. In that way, the functions F1 to F4 are directly comparable to the stages 1–4 of the LCA/LCC (Table 16.5).

16.4 DYNAMIC RISK ANALYSIS

To ensure proper safety management, qualitative and quantitative risk assessments are powerful and widely accepted decision support methods to predict

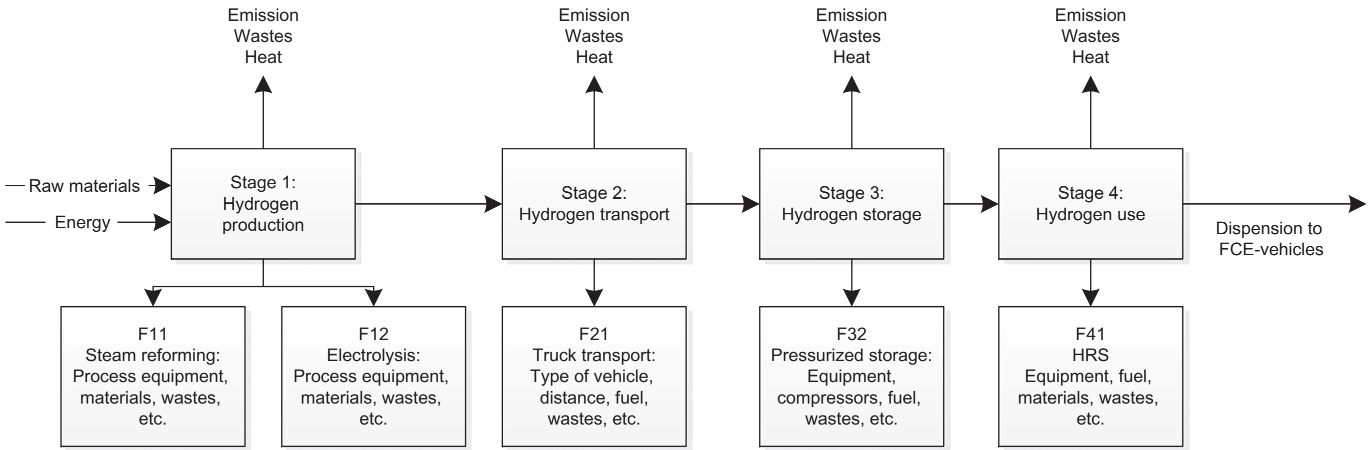

FIG. 16.4 LCA/LCC assessment for a fueling system: Stages and indication of detailed input.

TABLE 16.5 Example of the Combination of Hazard Identification and LCA

Function			Hazard Identification (SA Part)					Inventory (LCA Part)		
Ref	T	Method	k	Keyword	Main Deviation	Consequence	Mitigation	Material	Unit	Quantity
F12	M	Water electrolysis		Chemicals: corrosion	Release ➔ Fire	Heat radiation on equipment	ATEX	Water Wind power	Kg kWh	X Y

the safety level of processes. Hereunder, application of event and fault trees are very common and widely accepted tools. In this way, the risk analyst records and evaluates the events' probability, their consequences, and final impacts.

The overall objective of a quantified risk assessment (QRA) is to evaluate an installation's safety level based on acceptance criteria, for example, the number of people that potentially may be exposed to intolerable risk levels. The risk level is established by identifying the most important, representative events that contribute to safety risk. The risk evaluation is also used to ensure that the overall safety risk is effectively and efficiently reduced to an accepted risk level by implementing preventive, or at least mitigating, measures.

The widely accepted state-of-the-art risk assessment techniques use static methods to analyze the systems, as (static) fault trees and event trees, for example. Time-dependent input parameters are applied as averages over a period, for example, average failure rates over the installation's lifetime, average ignition probabilities, average numbers of workers, and average escape route distances. This includes also weather data and the process conditions, using initial release data, for example.

In conducting a QRA for complex accident scenarios, some simplifications are made in order to regard events as classes of scenarios that can be treated in a homogeneous way. To calculate the total risk, the combined outputs for these representative scenarios (the consequences and likelihood) may be mapped to a single parameter, the risk indicator. An example is the F-N curve describing the multifaceted aspect of "consequence" to a number of fatalities or financial damage in the form of a cumulative probability distribution. Alternative ways of reporting the QRA output can be by using the concept of individual risk, the location based risk, or the fatal accident rate. Thus, a QRA applies a set of linked models describing possible events and their outcomes. The outcome of the QRA is determined through the models and the way they are linked.

Analyzing complex and dynamic systems, in which the occurrences of concurrent events may be mutually dependent, this static approach is challenged. Therefore, it has been suggested to use a dynamic risk assessment approach (Markert et al., 2017). The mentioned simplifications used to simplify static risk assessment methods are not sufficient to avoid very complex event trees as an outcome for such systems. This complexity in the outcome causes difficulties in comprehensively analyzing and using the assessment for improvements. Moreover, the simplifications do not capture the dynamic nature of the system in a fully convenient manner, leading to conservative assumptions to avoid underestimation of the risks.

The term "dynamic risk assessment," though, provides some ambiguity in the definitions used by different authors. Hakobyan et al. (2008) identified three different interpretations in reviewing the literature. These are:

1. Methods for periodic updates of a probabilistic risk analysis (PRA) to address any changes in a plant configuration (Villa et al., 2015);

2. Updates to account for the aging of equipment;
3. Approaches that include explicit deterministic modeling of dynamic processes combined with stochastic modeling to describe a systems evolution.

The third definition introduces time-dependent variables to describe the plants states when establishing an event tree. It is this third understanding that is applied in the following discussion of methods for dynamic risk assessment. An example is given of modeling a complex system simulating the dynamic interactions (see Figs. 16.5–16.7) of concurrent phenomena and procedures following a loss of containment situation. These are:

- The physical processes (outflow, dispersion, ignition, heat radiation, explosion);
- Detection, alarming, and emergency shutdown;
- Escape and evacuation; and
- Impact on persons, escalation, and impairment of safety functions.

The simulation model, as shown in Fig. 16.6, runs a large number of loss-of-containment scenarios to evaluate the associated stochastic events in time with random delays, durations, instances of occurrences, and others. The output datasets are collected for all the simulated scenarios and are stored in a database. Therefore, these data are accessible for further statistical processing of the results. They may be used to predict the important risk indicators, such as the individual fatality risk (IR), the potential loss of life (PLL), the fatal accident rate (FAR, at workplace level), and the group risk (distribution of number of simultaneous fatalities). The approach also provides a new possibility to find

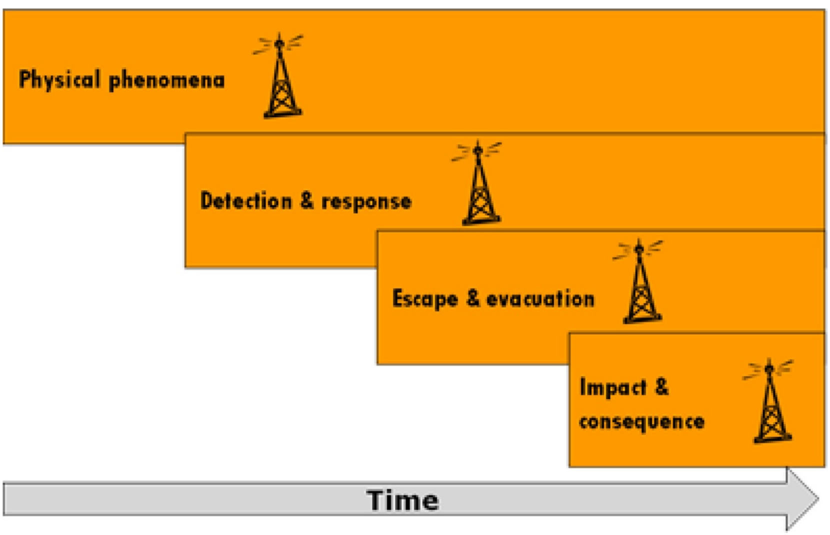

FIG. 16.5 Time dependence of events.

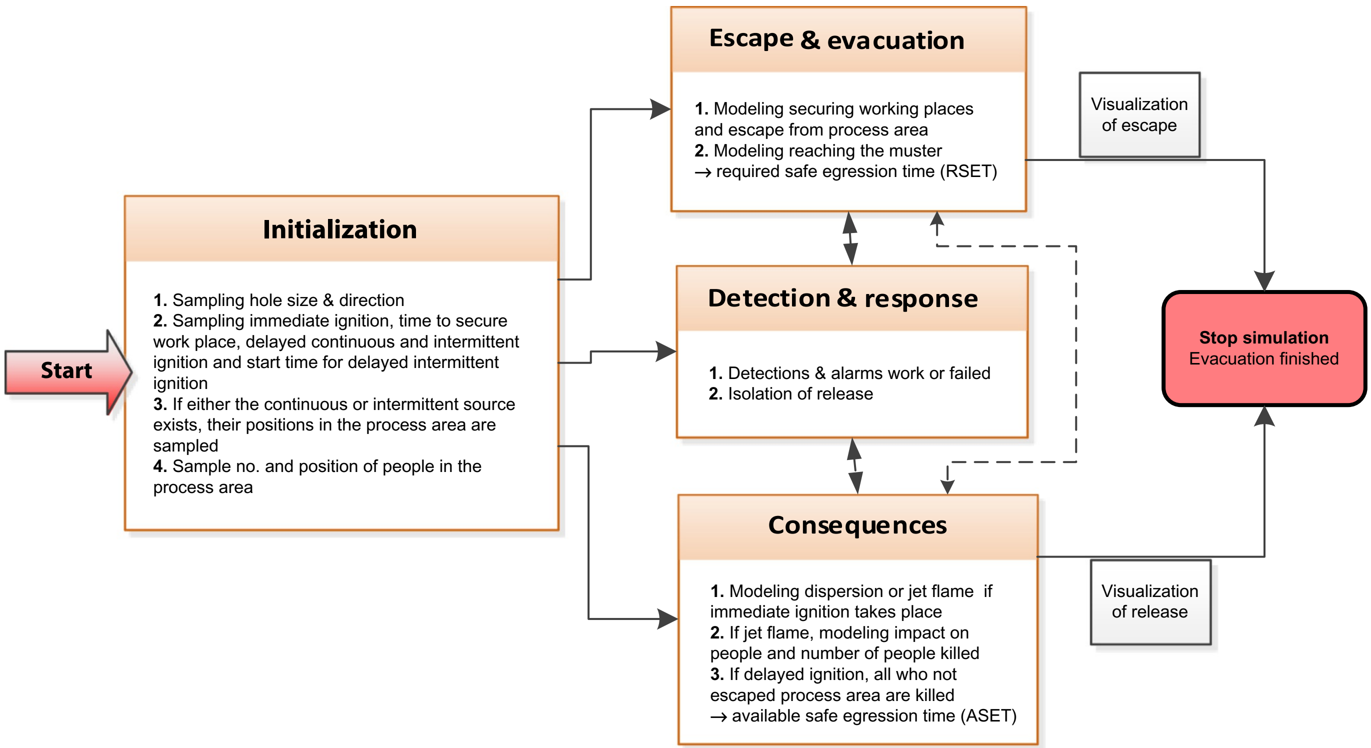

FIG. 16.6 DES model logic.

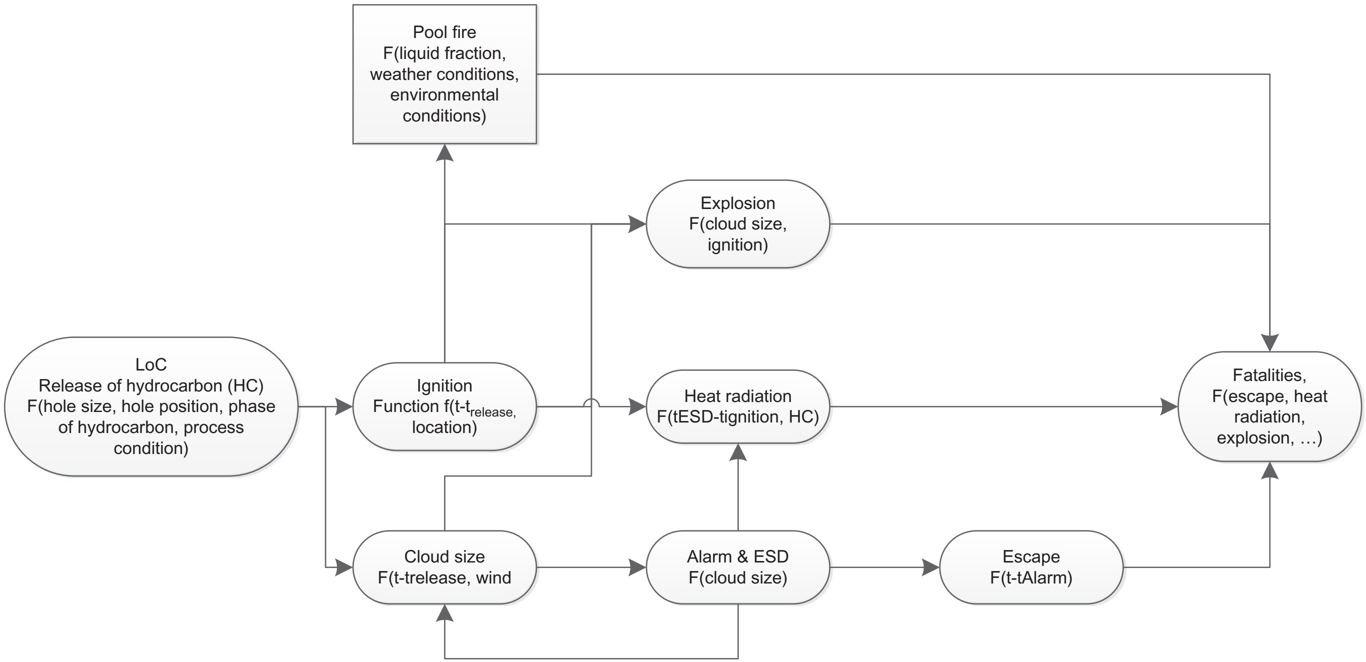

FIG. 16.7 Indication of interdependencies used in the model. The ones in the *squared box* are still optional.

the worst-case scenarios resulting from the very many combinations of parameters and events using the database. The latter is not possible with static risk assessment methods.

This approach allows capturing the specific characteristics of different workplaces, dynamic change of people's responses, and other characteristics. Scenarios with severe consequences can be "played back" to learn from them and can be animated, which, in addition to the learning effect, provides a new method of validation. This also makes the simulation models a good communication tool between system analysts and domain experts.

16.5 HSC MODELING INCLUDING SAFETY RISK

This section describes an example in which HCS and safety risk modeling are combined in order to combine supply chain modeling and dynamic risk assessment simulations. An example is presented with two distinct interconnected models: (1) for the HSC; and (2) for the consequences of a hydrogen release (Belamaric, 2016). The modeling and simulation uses the SimEvents commercial software package for discrete event simulation (DES) provided with the MatLab environment.

This case study assumes a large-scale hydrogen production plant located in a rural area with compressed hydrogen stored onsite in a high-pressure storage tank. On demand, the pressurized hydrogen is transferred to a tube trailer that transports it to a hydrogen refueling station located in a town. At the refueling station, the hydrogen is unloaded and further compressed to be stored in a high-pressure storage tank onsite. On demand, new hydrogen is ordered from the production plant when the amount of stored hydrogen runs low after being dispensed to a number of hydrogen vehicles.

The large-scale production plant produces hydrogen continuously. A part of the production will be delivered to the refueling stations in the HSC. This hydrogen is compressed and stored in high-pressure vessels. Another industry plant buys the major part of the hydrogen production. It is connected through a pipeline system.

A loading gate is located next to a high-pressure vessel that allows hydrogen loading in tube trailers. After arriving at the refueling station's unloading gate, hydrogen is transferred to the high-pressure storage.

The model assumes a varying customer arrival rate at the refueling station dependent on the weekday as well as a varying hydrogen refill amount.

The model structure is made up of four main submodels, namely submodels for: (1) hydrogen storage in the large-scale production plant; (2) hydrogen transportation and storage in the refueling station; (3) hydrogen dispensing to hydrogen cars in the refueling station; and (4) equipment reliability. For submodel 4, it is assumed that all the equipment has a lifetime of 25 years. For securing a realistic outcome, the model parameters for the HSC model are calibrated using data provided by the NREL (2015) that were collected from real observations

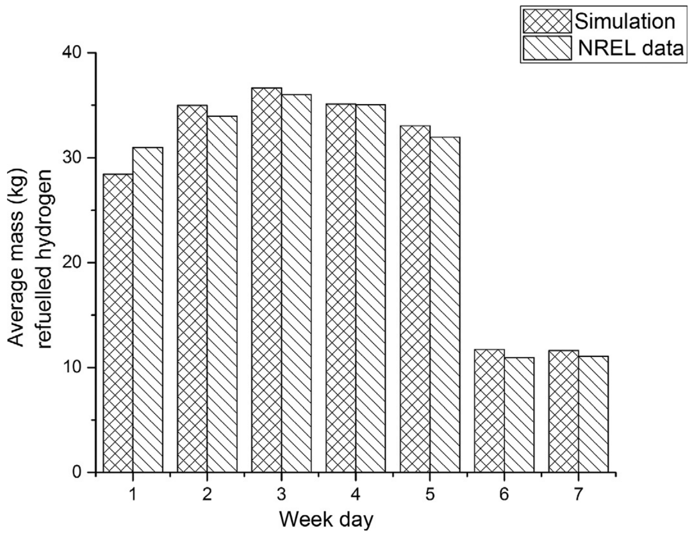

FIG. 16.8 Comparison of simulation results with real-world NREL data.

made on operational hydrogen refueling stations in the United States over the period from 2009 to 2015. Fig. 16.8 shows that the simulation results are in excellent agreement with the real data.

The simulation of a realistic customer demand allows the modeling of the necessary amounts of hydrogen stored and transported within the designed supply chain. Based on the simulation results for the specific scenario with a limited number of hydrogen vehicles, a single dispenser, and storage tanks with a capacity of 350 kg, the hydrogen at the production plant and the refueling stations is enough to meet the customer demand. The mean amount of hydrogen dispensed per day is about 27 kg averaged over a week (see Fig. 16.8).

Jaramillo (2014) describes an algorithm to simulate equipment failure and repair times using SimEvents. The same logic is adapted for this case in submodel 4 and is constituted by seven loops in which each loop simulates the availability of a specific component with their specific mean-time-to failure (MTTF) and mean time to repair (MTTR) parameters, as listed in Table 16.6. One HSC simulation with this model covers a period of 25 years as shown in Fig. 16.9. The simulation starts on a Monday at 00:00 a.m. Looking at the refilling demand of the customers, a uniform refilling rate is observed during the first 5 days. This is due to the uniform intergeneration time of customers between Mondays and Fridays. Then, between day 6 and 7, the rate of vehicles refilled decreases. This corresponds to the weekend, when demand is lower. Then at the start of the second week, the rate of vehicles refilled increases again. This pattern is repeated week by week. It may be seen in Fig. 16.9 that during the days 11 and 23, the rate curve of vehicles refilled is distorted for a

TABLE 16.6 MTBF and MTTR of the Supply Chain's Equipment

Equipment	MTBF (days)	MTTR (h)
Compressor	13	10
Storage	19	2
Loading and unloading gates	25	14
Dispenser	48	6

Adapted from NREL, 2015. Hydrogen fueling infrastructure analysis. Available from: https://www.nrel.gov/hydrogen/hydrogen-infrastructure-analysis.html [Accessed August 8, 2017].

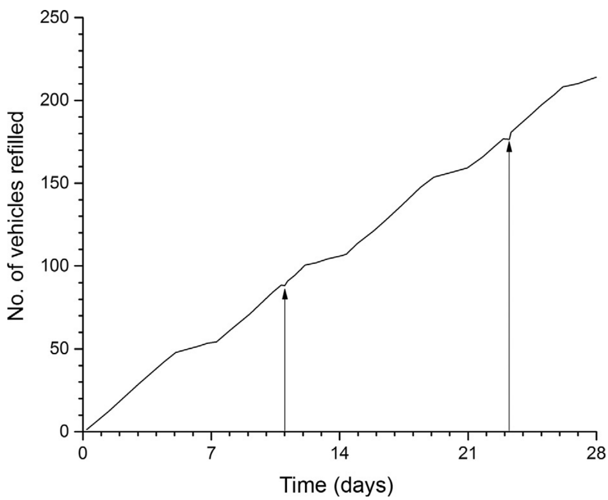

FIG. 16.9 Refuelling of hydrogen cars simulation. The *arrows* indicate reliability issues caused by MTTF and MTTR.

short period. This is due to failures that occurred at the dispenser and at the storage tank of the refueling station, preventing hydrogen dispensing to vehicles.

16.5.1 Risks Analyzed

The initiating event assumed in the case study is a hydrogen release caused by a hole in a high-pressure storage tank, which can be located at different locations within the HSC, for example, at the production plant or at the refueling station. An accident, such as a hydrogen release, may develop into different consequence scenarios as indicated in Fig. 16.10. The release scenarios may result in jet fires, flash fires, or explosion (detonation or deflagration) (Cadwallader

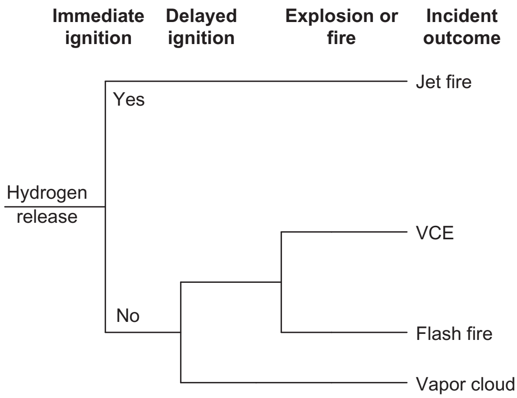

FIG. 16.10 Event tree for gaseous hydrogen release through a hole of a pressurized tank. *(Adapted from Moosemiller, M., 2011. Development of algorithms for predicting ignition probabilities and explosion frequencies. J. Loss Prev. Process Ind. 24(3), 259–265.)*

and Herring, 1999; Moosemiller, 2011). Possible accidents are modeled using the event tree shown in Fig. 16.10. The International Association of Oil and Gas Producers (OGP) (2010) suggests the use of the frequencies presented in Table 16.7 for each range of hole diameters. Estimation of the discharge rate is a crucial step in the evaluation of the consequences analysis.

In order to estimate immediate and delayed ignition in the consequence model according to the event tree as shown in Fig. 16.10, the following probabilities are used: (1) immediate ignition = 0.15; (2) delayed ignition = 0.30; and (3) explosion = 0.40 (Moosemiller, 2011). The general model developed for the case study has four submodels: (1) general parameters; (2) jet fire consequences; (3) VCE consequences; and (4) flash fire (explosion) consequences. One DES entity representing an initiating event is created and receives a number of attributes, as listed below. On demand the attributes can easily be extended if other scenarios are to be calculated.

TABLE 16.7 Pressure Vessel Hole Frequencies (OGP, 2010)

Hole Diameter (mm)	Leak Frequency (Per Vessel Year)
1–3	2.3×10^{-5}
3–10	1.2×10^{-5}
10–50	7.1×10^{-6}
50–150	4.3×10^{-6}
Total	4.6×10^{-5}

- Attribute 1: Hole diameter;
- Attribute 2: Immediate ignition;
- Attribute 3: Delayed ignition;
- Attribute 4: Explosion or fire;
- Attribute 5: Time before ignition;
- Attribute 6: Hole height;
- Attribute 7: People in zone 2;
- Attribute 8: People in zone 3 (rural area); and
- Attribute 9: People in zone 3 (urban area).

In this way, each entity receives a unique set of parameters and will trigger a specific set of consequence models to estimate the outcome of a specific scenario. In order to estimate the fatalities for each accident, the number of people around the facility is generated and assigned to the entity. Three zones around the location of the initiating event are considered, as indicated in Fig. 16.11. The first zone corresponds to the area occupied by the storage vessel with a radius of 2.2 m. This zone is, to a large extent, occupied by the equipment and only a very few persons may conduct maintenance work for a few hours during a year. Zone 2 represents the safety area around the vessel. Main safety distances around a hydrogen storage tank are defined by codes and regulations, such as the National Fire Protection Association (NFPA 50A from 1999) or the California Energy Commission (Venkatesh et al., 2004). These distances vary from 4.6 to 15 m and therefore a mean safety distance of 8 m is assumed in this study. Therefore, Zone 2 corresponds to a circular area with an outer radius of 10.2 m,

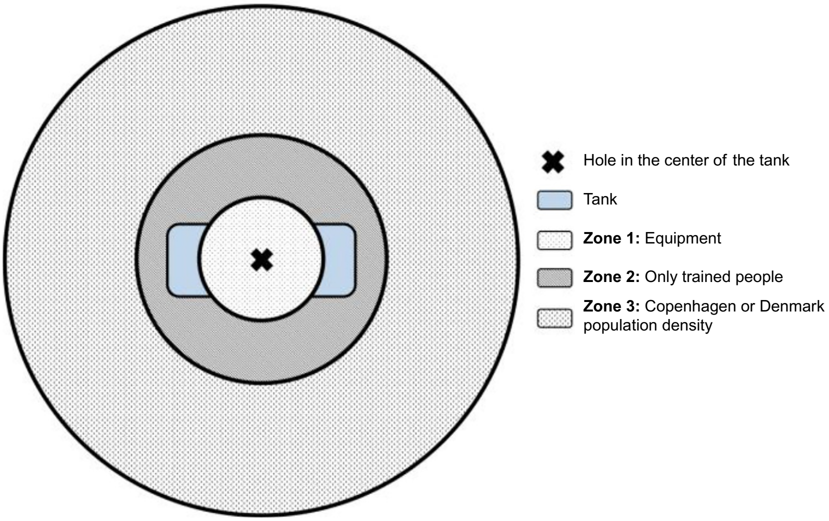

FIG. 16.11 Introduction of zones with different population densities around the LoC (not to scale).

excluding the area of zone 1. The case study assumes between 0 and 4 people may be located in zone 2. Finally, zone 3 assumes a population density typical for the specific wider area for simplicity. The simulation operates here with two scenarios, an urban population and a rural one.

Analyzing the consequences of a continuous hydrogen release through a hole in a high-pressure storage tank, this analysis can now incorporate specific states of the storage or the HSC. Therefore, based on the dynamic inventory data, different risk scenarios may be assessed and the individual and societal risks can be calculated not only for the individual parts of the HCS, but also for the whole chain. In conclusion, the DES models built in this study using SimEvents are powerful tools that allow the analysis of complex systems involving stochastic variables. The main limitation resides in the availability of data. As more data from hydrogen supply chains become available in the future, such models as described in this case study can be improved and provide reasonable prediction of security of supply and safety risk scenarios.

16.6 CONCLUSIONS

This chapter describes the challenges to assess the safety risks of complex hydrogen infrastructure together with possible methodologies to address these challenges. The development of new large-scale infrastructure is a stepwise procedure and it needs different decision support tools, such as cost-benefit assessments, sustainability assessments, optimization of supply chains, the best placements of buildings and process equipment in a growing market, and, last but not least, safety risk assessment and management.

It is argued that complex systems may behave differently, as the overall safety risks are not just the sum of risks from its components. Therefore, a holistic approach is needed, which provides a challenge for any analyst. Some methods are indicated that could help ensure that the different methods for decision support regards the same HSC and that may support comprehensive data collection. For dynamic systems a new modeling approach is suggested that enables the modeling of the time dependence of events. The dynamic approach may also be combined with DES-based supply chain modeling.

The suggestion is to establish basic models based on the functional method, which may store the input data, the set of assumptions, and the system model. The system model may be enlarged in parallel with the growing maturity of the system. Functional modeling can model a supply chain down to small details, depending on the actual state of knowledge. Therefore, it is applicable for developing systems, as applicable already in early design phases. With this as a basis, data important for the system may be stored and updated in a structured way. The data should be stored on a centralized server, and cloud solutions seem to be promising to ensure that each of the assessments uses the correct, updated data, and ensures improved comparability of the assessments, as they will look at the same design stage and the same model.

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