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Understanding the Vulnerability of Complex Systems. An Integrated Approach

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The increasing complexity of current system realities (e.g., pandemics, healthcare, energy transition, process industry 4.0 etc.) would require the evaluation of the actual way systems are modified, often referred with “work as done”, rather than “work as imagined”. The safety of a complex system is one of the emergent properties depending upon the interactions between the system's components and subsystems. This paper is focused on the analysis of the nature of the interactions within a complex system when it is subjected to cumulative stresses, crises and accidents. The objective is to identify, test and validate integrated emergency management procedures in the event of accidents, crises or major incidents occurring during the loading and unloading of goods and hazardous substances. To test the applicability of the framework, we developed a prototypal application identifying as a target complex system an Italian port area. An interactive simulation model was ad-hoc designed and developed, which makes it possible to reproduce the evolution of the crisis and its impact on structures, systems, people and goods by considering both the physical aspects and the domino effect in a multiple/sequential accidental scenario simulation. Additionally, it is possible testing the effectiveness of new technological and infrastructural solutions to reduce vulnerability, mitigate damage and prevent possible escalation of the event. Relevant accident scenarios were firstly thoroughly selected and subsequently integrated into a digital twin of the port. The interactivity allows a dynamic simulation of the possible actions of the different elements and active subsystems considered as a complex system, exploring their interactions in the face of crises and disasters, including the determining role of human factor.

1. Introduction

Complex systems are systems that are composed of many interconnected components and are highly sensitive to perturbations. These systems can be vulnerable to various types of failures or disruptions, which can have far-reaching consequences (Chu D. et al, 2003) and are typically characterized by a high degree of interdependence and interconnectedness. This item can make it difficult predicting how a system will behave in response to a particular perturbation as well as to control or mitigate the consequences of a failure (Dobson et al., 2007). One reason of complex systems vulnerability lies in their reliance on a large number of interconnected components that are all working together in a coordinated way. If one of these components fails or is disrupted, it can have a “knock on” effect on other components, leading to a larger failure i.e., "cascading failure". Another reason why complex systems are vulnerable is that they are often subject to external perturbations or shocks, such as natural disasters, political crises, or technological failures, acting as “drivers“, which may affect the normal functioning of the system and lead to disruptions. A notable example in the process sector is provided by the different Covid 19 waves, requiring improved safety management systems to reconcile operation continuity and health requirements (Bragatto et al., 2021). It is of the utmost importance to identify and address potential vulnerabilities, to minimize the risk of failures and disruptions and ensure the stability and reliability of the system (Wu. et al., 2021). Within the context of systems, organizations, and infrastructures, vulnerability

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refers to factors making systems more likely to fail, or to be disrupted. These factors might include the complexity of the system, the reliance on a single point of failure, or the lack of robustness, or resilience. As an overall safety umbrella, resilience allows to support business continuity and requires new ways for process design and shifts in the operation of processes, as well proper rethinking of safety education and training of technicians and engineers, by novel tools (Pasman et al., 2021). Resilience assessment and management of technical systems have been increasingly important and we address the reader to the valuable information reviewed by Chen et al. (2023). Identifying and addressing vulnerabilities can help to minimize the risk of harm or disruption and increase the stability and resilience of systems. Resilience, which is closely related to vulnerability, refers to the ability to withstand, or recover, from adversity, stress, or change. It is often associated with the ability to adapt and bounce back from difficult situations, or to maintain stability and function in the face of stress, or change. This might involve having redundant, or backup systems in place, or having protocols and procedures in place to respond to disruptions (Sigahi et al., 2022). Further improvement of system resilience can be obtained by data-driven modelling, used as integration of "knowledge-driven" models describing the systems physical behaviour (Vairo et al., 2023). As depicted in Fig. 1, a complex system may behave in different ways in dealing with disruptive events. In this regard, "fragility" refers to the susceptibility of a system, such as a material or a system of processes, to break or fail under stress or pressure. A system that is fragile is sensitive to changes in its environment and may not be able to withstand stress or unexpected events. "Robustness" refers to the ability of a system to withstand stress or pressure, for a certain period, without breaking or failing. A robust system is able to prolong its functionality and performance for a time span, under adverse conditions, or when subjected to unexpected events. "Resilience" is the ability of a system to adapt to disruption or change and to continue functioning effectively and even enhance the performance. Robustness and resilience are related concepts that refer to the ability of a system to withstand stress or disruption, but they have some important differences. Robustness is focused on maintaining functionality and performance under stress, but, in this way, the system remains rigid and, sooner or later, fails. Resilience, on the other hand, is concerned with the ability to adapt after a disruption or change. Resilience depends on more subtle factors such as the availability of resources or the ability of a system to monitor, learn, anticipate and respond with adaptation. Ports can be considered complex systems because they often involve the coordination and integration of a broad range of activities, e.g., shipping, cargo handling, transportation and logistics. These activities are typically interconnected and interdependent, and the smooth operation of the port depends on the proper functioning of all of these components. Ports are vulnerable to various types of disruptions, including natural disasters, technological failures and human errors. The evaluation of human factors on safety performance can reveal unsafe attitudes and failures in training, supervision and management (Fabiano et al., 2022), while the quantification of the effect of the enforced safety management system of the facility is a critical issue (Milazzo et al., 2021). To address these vulnerabilities, port authorities and operators typically have contingency plans in place to correctly plan ship routes and mooring (Vairo T. et al., 2017), respond to disruptions of different type and minimize the impact on port operations (Pastorino et al., 2014). These plans include measures such as emergency preparedness drills, backup systems for critical infrastructure, and protocols for coordinating with other stakeholders in the event of a disruption. The design of a virtual environment (VE) outlined in the next section relies on relevant contributing factors: the nature, importance, and context of the risk, availability of the measures, procurement and maintenance costs, the person impact, vulnerability of the environment, determination and weighting of important contributing safety factors (Pasman et al., 2022). The main goal to address vulnerability lies in an effective management and planning, to ensure the system stability and reliability.

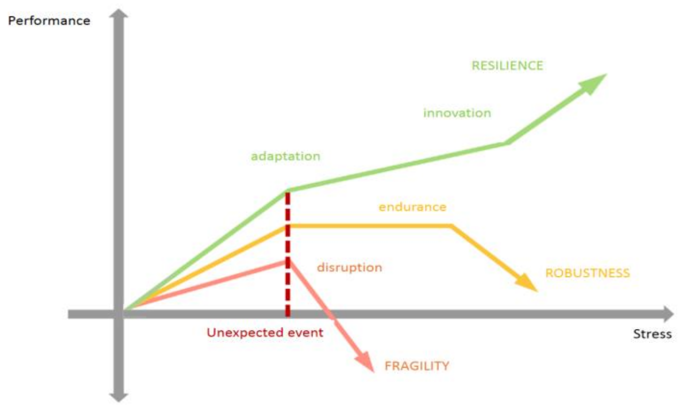

Figure 1: Different behaviour of a complex system when subjected to external or internal stress.

2. Virtual environment design

The ALACRES2 project, developed in the EU Interreg Maritime Program for Regional Development, aims to improve the prevention, warning system and management of risks arising from the transport of hazardous substances in port areas, with specific reference to their movement from land to sea (and vice versa). The project aims to develop and test behavioral protocols, operating standards, emergency monitoring and control procedures and support technologies through the creation of a cross-border virtual laboratory based on different simulators activated in the port systems. The focus is creating a permanent laboratory capable of identifying, testing and validating integrated emergency management procedures in the event of significant accidents, crises or incidents occurring during the loading and unloading of goods and hazardous substances in port areas. The project phases can therefore be traced back to the key concepts of engineered systems resilience:

- Monitoring - development of operational procedures for handling hazardous substances in port areas.
- Learning - development and simulation of appropriate incident scenarios;.
- Anticipating - the development of predictive systems is envisaged in future extension of the VE.
- Response - definition of tests of existing operational and organizational intervention models.

According to the defined Extended Maritime Framework (EMF), the maritime context was divided into different influences domains (i.e., sea surface, underwater, sky, coastline, cyberspace and space), into a co-operative context. The simulation techniques employed are based on the MS2G (Modeling, Interoperable Simulation and Serious Games) concept, which allow the creation of integrated models capable of interoperate and to be used within an immersive and intuitive synthetic environment, as shown in Fig. 2

Figure 2: Examples of the developed virtual environment, mimicking an industrial port area.

The present work was structured to develop the VE and verify the items summarized in the following.
Training games: These games are used to prepare people for real-world situations or tasks. They might be used to train military personnel, emergency responders, or other professionals.
Simulation games: These games are designed to mimic real-world situations or environments and are often used to test or practice decision-making skills. Examples might include simulations of emergency situations, business scenarios, or complex systems.
Emergency response games: These games are designed to help people learn about and practice emergency response procedures. They might include simulations of fires, chemical spills, or other types of accidents, and allow people to practice the steps required to emergency response.
Decision-making games: These games are designed to help people practice problem-solving and decision-making skills. They might involve scenarios where people are required to make alternative choices in responding to an accidental scenario, where the game provides feedback on the actual different consequences.
When properly designed, serious games provide an interactive and immersive learning experience that allows people to practice in a safe and controlled environment. In order assess the potential impacts of multiple accidental scenarios in a port, a logical stepwise process was designed as follows.

- Accident source selection, by identifying the types of activities and operations that are carried out in the port, as well as the potential hazards and risks associated with these activities.
- Accident impact assessment. Once the potential sources of accidents have been identified, it is important to assess the potential impacts of these accidents. This can involve estimating the likelihood of different types of accidents occurring, as well as the potential consequences of these accidents.
- Effectiveness of existing prevention and response measures. This step is focused on the identification of any potential gap or weakness in the current system and designing improvement opportunities.

- Mitigative action planning. Based on the results of the assessment, it may be necessary to identify additional measures that can be taken to mitigate the impacts of accidents. This could include implementing new prevention measures, strengthening response capabilities, or enhancing emergency preparedness plans.

Overall, assessing the potential impacts of multiple accidental scenarios in a port requires a systematic and comprehensive framework that takes into account the various activities and operations performed in the port, as well as the hazards and risks associated with these activities. By identifying and addressing potential vulnerabilities, it is possible to improve the resilience and stability of the port and reduce the risk of accidents and disruptions. The reference accidental scenarios were selected on the basis of major accidents occurring in the port area, as for a detailed historical analysis:

- chlorine release and toxic cloud dispersion;
- release of compressed natural gas and formation of jet fire;
- release from tanker, resulting in:
  crude oil pool fire;
  dispersion of crude oil at sea;
- LNG release from pipeline and subsequent fire;
- BLEVE (Boling Liquid Expansion Vapor Explosion) of LPG tank.

The VE was implemented with explored accidental scenarios properly modelled by tested tools previously verified, or ad hoc developed, namely: EFFECTS v12 (Gexcon), a CFD box-model for determining the consequences of accidental releases of hazardous chemicals and MIKE 3 (DHI), a hydrodynamic model, used for assessing oil spill extent and consequences of oil. The evolution of the oil spill and the related atmospheric dispersion is evaluated with the procedure described in Vairo et al. (2017), which involves the source term evaluation and the dispersion conditions definition. A glance of the modelled scenarios is reported in Fig. 3.

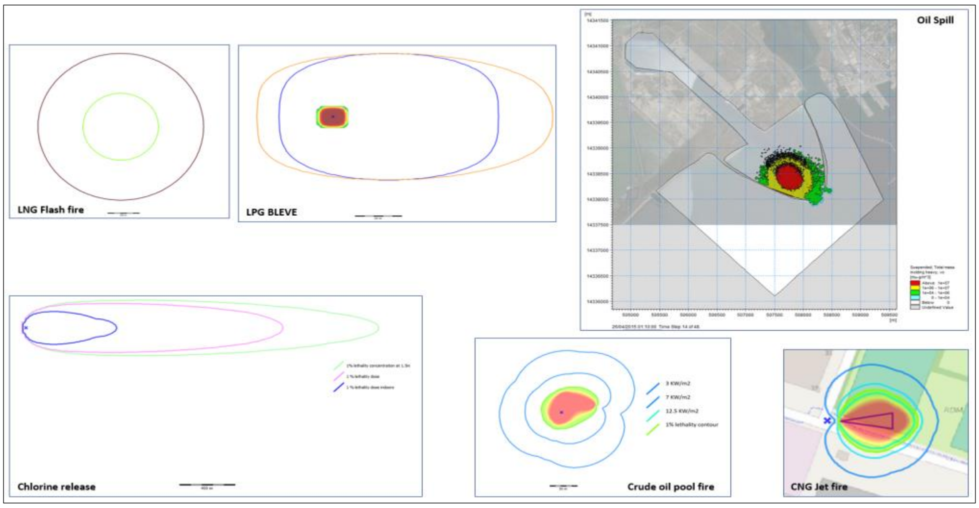

Figure 3: A glance of modelled accidental scenarios.

These models have been integrated into the ALACRES2 Virtual Lab to analyze and develop scenarios in specific port contexts. An illustrative example of jet fire and oil spill form a tanker is provided in Fig. 4.

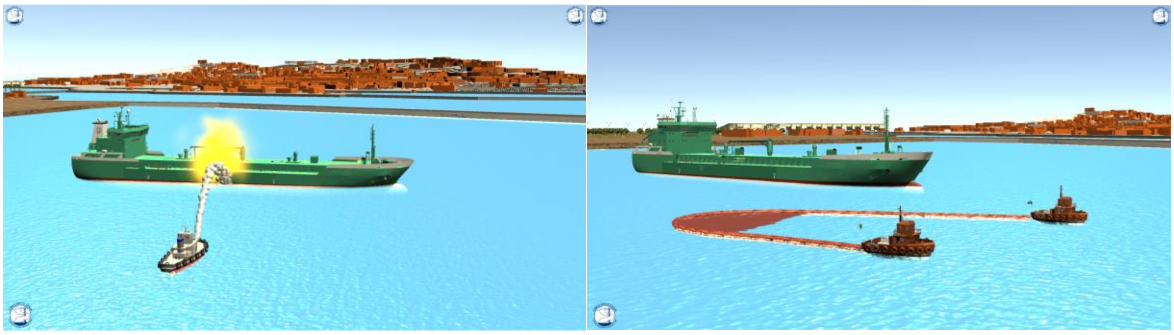

Figure 4: The accidental scenario jet-fire and response emergency plan to an oil release from a tanker.

In this interactive environment, the implemented accident scenarios can also be activated simultaneously in order to assess the impacts and test the effectiveness of emergency procedures and plans.

3. Results

To simulate the occurrence of one or more scenarios within the virtual environment, a Montecarlo (MC) simulation approach was set-up. The MC approach simulates the occurrence of five different scenarios, each with a probability between 0 and 1. The simulation runs for a specified number of times (which in the given case was calculated in 10,000 times) randomly selecting in each run the scenarios based on their probability distribution. The simulation also keeps track of the number of times each scenario occurred, the number of runs where multiple scenarios happened and the number of runs where no accidental scenario occurred.
The MC sampling, which shows the aggregate adversities affecting the system, is represented in Fig. 6, where:

- A is the chlorine release and toxic cloud dispersion;
- B is the release of compressed natural gas and formation of jet fire;
- C is the crude oil release from tanker;
- D is the LNG release from pipeline and subsequent fire;
- E is the BLEVE (Boling Liquid Expansion Vapor Explosion) of LPG tank.

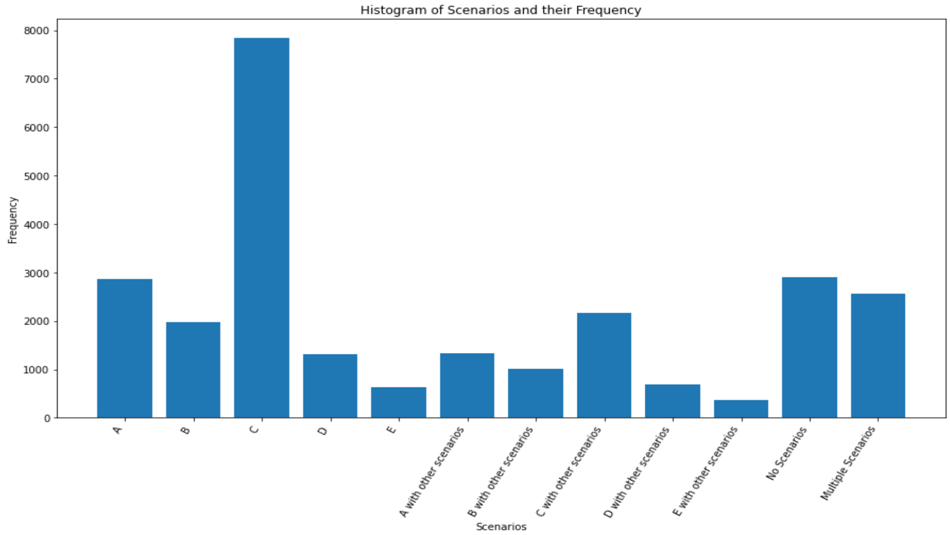

Figure 5: Histogram of the accidental scenarios with their frequency over 10,000 simulations.

Overall, the simulation helps to understand the likelihood of different scenarios occurring and can be useful in decision-making processes. After a statistically significant number of simulation games, which include real time intervention of the operators applying the emergency procedures, it is possible to define, case by case, the consequences of the adversities, weighting contributing safety factors and uncertainties inherent to the available information. The statistics of the accidental scenarios (in several instances with concurrent or overlapping evolution following the initiating event) are summarized in Table 1.

Table 1: MC simulation results

Scenario	Ref.	Observations %
Chlorine release and toxic cloud dispersion	A	28.64%
CNG release and formation of jet fire	B	19.76%
Crude oil release from tanker w. pool fire and dispersion at sea	C	78.36%
LNG release from pipeline and fire	D	13.08%
BLEVE (Boling Liquid Expansion Vapor Explosion) of LPG tank	E	6.30%
Chlorine release with other scenarios	A with other scenarios	13.26%
CNG release with other scenarios	B with other scenarios	10.16%
Crude oil release with other scenarios	C with other scenarios	21.58%
LNG release with other scenarios	D with other scenarios	6.82%
LPG BLEVE with other scenarios	E with other scenarios	3.62%
No events	No scenarios	28.99%
All events	Multiple scenarios	25.65%

A vulnerability index is calculated as the product of the likelihood of an accident occurring and the associated consequences of the accident. Overall, the simulation allows understanding the likelihood of different scenarios and upon refinement may assist in selecting the most appropriate safeguards and decision-making regarding residual risk acceptability. The simple linear AHP approach can also be integrated in alternative comparison (Abrahamsen et al., 2020; Milazzo et al., 2021). After several simulation games, which include real time intervention of the operators applying the emergency procedures and assessing their effectiveness and uncertainties, it is possible to define the consequences of the adversities. At last, a vulnerability index can be easily calculated as the product of the likelihood of an accident occurring and the associated effect severity.

4. Conclusions

The implementation of an interactive, virtual environment, including the time evolution of multiple accidental scenario and emergency intervention simulation can be an effective way to identify and understand complex system vulnerabilities. The tool can help organizations to identify and prioritize risk reduction measures and to support the decision-making process for identifying the most promising courses of action to deal with each threat. Results obtained by testing the virtual laboratory over a one-year time span provided empirical evidence that the most effective aspect for organizations is to adopt a holistic risk management approach accounting for all relevant factors and adopting an optimized range of field-tested tools and techniques. Industrial port resilience can be effectively enhanced through vulnerability mitigation strategies, such as improving infrastructure and systems, developing contingency plans, and providing training and resources to thrive in adversity.

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