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Dipartimento di Ingegneria Meccanica, Energetica e Gestionale

Dottorato di Ricerca in
Ingegneria Civile ed Industriale

CICLO
XXXI

EMERGENCY PREPAREDNESS IN INDUSTRIAL PLANTS: AN INDUSTRY 4.0 DRIVEN TRAINING SOLUTION

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Abstract (English)

Major accident hazards industrial sites or high-risk industries lack of a dedicated training methodology and environment to enhance significantly the personnel rate of retention as well as emergency preparedness and response skills (both technical and non-technical, e.g. leadership, decision-making, team-working, stress management). The need for effective industrial emergency preparedness and response training systems is widely acknowledged also from academic communities that have invested a great deal of time and effort to detect methodologies to enhance emergency response staff performance (emergency manager and emergency team members). This study takes a step forward in current practice proposing a multiplayer industrial emergency preparedness and response training system, which leverages on Industry 4.0 enabling technologies – namely Simulation, Virtual Reality & Serious Games – and on a cooperative, experiential and differentiated training strategy. It also pushes for an increased attention on human factors in the Occupational Health and Safety 4.0 and proposes an approach to analyze the effects of human factors with the ultimate aim to include them in the design of industrial safety protocols and regulations and in the assessment of hazards. This way, after an experimental campaign and statistical analysis of the results, the proposed training system has been critically investigated to ascertain:

- how the emergency response staff performance evolves along repeated training sessions;
- to which extent the proposed solution is effective in delivering procedural knowledge to the emergency response staff;
- whether it is realistic enough to think that the training experience produces psychological stress in those people that are trained with it and how they cope with stress over the repeated replications
- whether and to which extent human factors, such as stress and perceived workload, are correlated to the capability of the emergency manager to coordinate and monitor the execution of all the measures and actions intended to deal with an industrial accident and its effects.

Abstract (Italiano)

Gli impianti industriali e, in generale, i settori industriali a rischio di incidente rilevante sono generalmente privi di un sistema per l'addestramento del personale dedicato alla gestione delle emergenze (il manager dell'emergenza e l'intero team) capace di migliorare significativamente le competenze tecniche, procedurali e trasversali (es. capacità di leadership, di decision-making, di lavorare in team e di gestire lo stress) in preparazione alle potenziali situazioni di emergenza. La necessità di sistemi efficaci a supporto dell'addestramento del suddetto staff è riconosciuta ampiamente anche dalla comunità accademica che sta investendo tempo e sforzi per definire delle metodologie efficaci. Il presente lavoro di ricerca propone un sistema multiplayer per addestrare il personale ad essere preparato e gestire un'emergenza in un sito industriale. Il sistema si basa sulle moderne tecnologie a supporto dell'Industria 4.0, come la Simulazione, la Realtà Virtuale e i Serious Games, e su una strategia di addestramento definita esperienziale, cooperativa e differenziata. Una maggiore attenzione ad aspetti legati ai fattori umani è fondamentale nell'ambito della Salute e Sicurezza sul Lavoro 4.0 ed un approccio per l'analisi degli effetti dei fattori umani è stato applicato allo scopo di includerli all'interno della fase di progettazione e definizione dei protocolli e regolamenti di sicurezza industriale o nella valutazione dei rischi. A valle dello sviluppo di tale sistema, è stata condotta una campagna di sessioni di addestramento i cui risultati sono stati analizzati statisticamente al fine di valutare:

- come la performance dello staff sottoposto all'addestramento evolve in seguito a ripetute sessioni di training;
- in che misura e rapidità, la soluzione proposta è capace di incrementare la conoscenza delle procedure e protocolli di emergenza da parte dello staff;
- se un'esperienza di addestramento di questo tipo possa produrre stress psicologico (così come nella realtà) ed in che modo lo staff sottoposto alle sessioni di addestramento affronta tale stress, generato dal disastro industriale in corso, dopo ripetute sessioni;
- se (e quanto) fattori umani come stress e carico di lavoro percepito sono correlati alla capacità del manager dell'emergenza di coordinare e monitorare l'esecuzione di tutte le azioni volte alla gestione del disastro industriale e dei suoi potenziali effetti.

1 Introduction

When dealing with complex industrial systems and organizations, what immediately emerges is that they cannot be described and modeled mathematically and their behavior is unpredictable to some extent (Dekker, 2016) mainly because (among other causes) of the dynamic interactions among a large number of elements (including systems' reliability, human factors, environmental conditions). The industrial and societal world is also experiencing obvious and increasing conditions of risk due to major natural and man-made disasters (Liu et al., 2016) that compel to redesign the way industrial organizations prepare to cope with them. Of paramount importance to emergency response staff (managers and members of the different teams) is the question of how to prepare for as yet unseen disasters and major accidents in industrial sites. Major accident hazard industrial plants or high-risk industries typically lack a dedicated training methodology and environment to enhance significantly the personnel rate of retention and emergency preparedness technical (i.e. procedural) and non-technical (e.g. leadership, decision-making, team-working, stress management) skills during training sessions. With this in mind, the proposed research work recognizes the crucial role of training activities in implementing an effective multi-player industrial emergency preparedness and response training system, which leverages on Industry 4.0 enabling technologies – namely Simulation, Virtual Reality & Serious Games – and on a cooperative, experiential and differentiated training strategy. The system will be eventually used to ascertain (i) whether it is capable to enhance the technical and procedural emergency staff performance along repeated training sessions; (ii) whether it is realistic enough to think that the training experience produces psychological stress in those people that are trained with it and how they cope with stress over the repeated replications, and (iii) whether and to which extent human factors, such as stress and perceived workload, are correlated to the capability of the emergency manager to coordinate and monitor the execution of all the measures and actions intended to deal with an industrial accident and its effects. This study pushes therefore for an increased attention on human factors, such as stress and perceived workload, in the Occupational Health and Safety 4.0 and proposes an approach to train industrial operators and analyze the effects of human factors with the ultimate aim to include them in the design of industrial safety protocols and regulations and in the assessment of hazards.

This research has been conducted in the context of the DIEM-SSP (Disasters and Emergencies Management for Safety and Security in industrial Plants) PRIN research project (CUP: B88C13002040001), sponsored by the Italian Ministry of University and Research, whose aim is to propose new approaches to deal with and analyze the complexity resulting from emergency management in industrial plants and critical infrastructures.

The body of the present thesis is organized as follows:

- Section 2 is entitled 'Background & State of the Art' and provides an analysis of the current safety context in complex 4.0 industrial systems, the major accident hazards in industrial sites based on laws and regulations in force, and the latest advances in the field of education & training in industry;
- Section 3 presents the 'Research rationale and proposal', with details on the problem, the study aims and the roadmap of the study in the light of the analysis of the state of the art;
- Section 4 describes in detail the different methodological and implementation aspects of the proposed industrial emergency preparedness and response training system as well as the underlying mathematical models;

- Section 5 presents the case study and the setup of the experiments (i.e. training sessions) carried out with the system;
- Section 6 shows and discuss the findings related to the performance of the emergency response staff;
- final remarks, including limitations and recommendations for future works, are given in Section 7.

This thesis concludes with a brief description of some related research work carried out in parallel to the main work described in this dissertation, the reference list and the acknowledgments.

2 Background & State of the Art

This chapter provides an overview of the background and of the state of the art related to the subject of this thesis. It is structured in three main sections as follows:

- the first section, entitled 'The current context: the Industry 4.0', identifies the general application context of the thesis and current trends in the industrial domain;
- the second section, entitled 'Major Accident Hazards Industrial Sites', describes the specific application domain, highlights the reason why further research is needed in this topic and provides an overview of the current legislation;
- the third section, entitled 'Advances in Education & Training in Industry: Virtual Reality and Serious Games', provides an introduction and description of the technologies and methodologies that will be applied in the identified application domain.

The review of the state of the art and analysis of the background works has been done by using the following approach. Academic, popular and non-academic sources have been explored. More than 200 relevant papers in the field identified through title, abstracts, and keywords from interdisciplinary search engines such as SCOPUS, ISI and Google Scholar have been analyzed. Major attention has been devoted to conference papers and journal articles published in the last 10 years. Public reports from consulting companies have been also retrieved from the Internet and examined in order to identify current and future research issues as well as trends in Industry. The gaps where this research fits are generally described throughout this chapter.

2.1 The current context: the Industry 4.0

Industries are on the edge of a new revolution. The vision of a ubiquitous factory (Yoon et al., 2012) characterized by a computing technology that 'recedes into the background of our lives' (Weiser, 1991) is unquestionably on the forefront of technological advancements. Powerful, autonomous microcomputers (embedded systems) are increasingly being wirelessly networked with each other and with the Internet. In the industrial realm, this phenomenon can be described as the 4th Industrial Revolution, or *Industrie 4.0*.

2.1.1 From Industry 1.0 to Industry 4.0

The first three industrial revolutions came about as a result of mechanization, electricity and Information Technology (IT) and are spanned almost 200 years (Figure 1). Industrialization began with the introduction of mechanical manufacturing equipment at the end of the 18th century, when machines like the mechanical looms driven by steam engines revolutionized the way goods were made. Fabric production left private homes in favor of central factories followed by an extreme increase in productivity. The second industrial revolution began about 100 years later in the slaughterhouses in Cincinnati, Ohio, and found its climax with the production of the Ford Model T in the United States. The development of continuous production lines based on both division of labor and the introduction of conveyor belts resulted in another productivity explosion. Third, in 1969, Modicon presented the first programmable logic controller that enabled digital programming of automation systems. The programming paradigm still governs today's modern automation system engineering and leads to highly flexible and efficient automation systems.

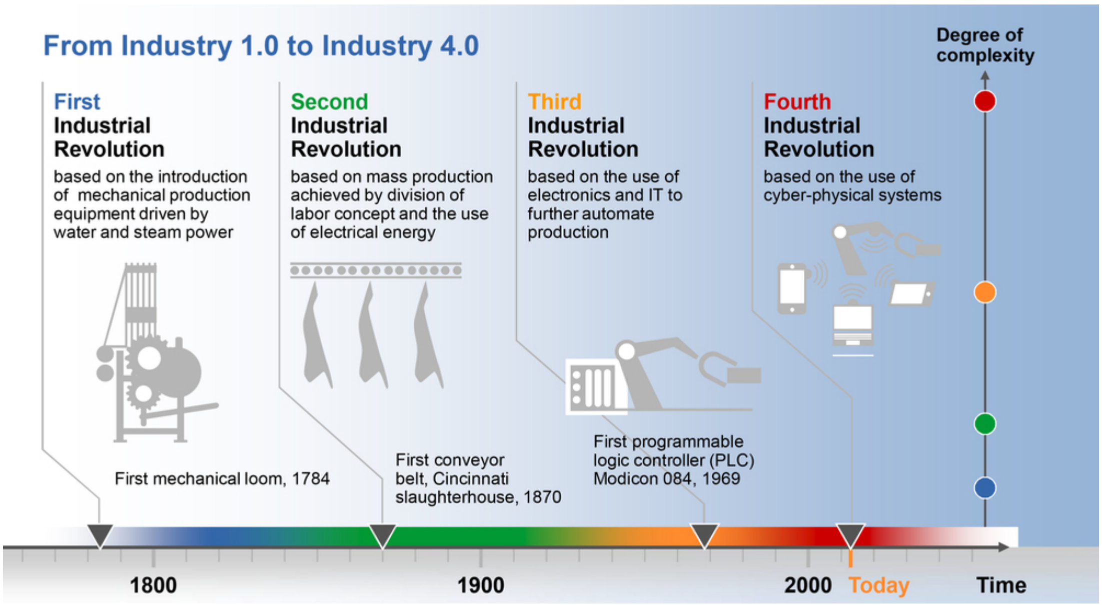

Figure 1: Industrial revolution timeline[1]

Nowadays, industries are on the edge of a new radical change, widely referred to as Industry 4.0. The term Industry 4.0 is today prevalent in every industry-related fair, conference or call for projects. First used under the name of *Industrie 4.0* at the Hanover Fair that was held in Germany in 2011, it refers to a national strategic initiative of the German government that was adopted as part of the High-Tech Strategy 2020 Action Plan in November 2011. Its initial implementation recommendations were formulated by the Industrie 4.0 Working Group between January and October 2012 under the coordination of acatech – National Academy of Science and Engineering. The recommendations were submitted as a report (Acatech Study, 2013) to the German government at the Industry-Science Research Alliance's Implementation Forum on 2 October 2012. The Industrie 4.0 Working Group identified 8 areas for action:

1. Standardization and reference architectures;
2. Managing complex systems;
3. A comprehensive broadband infrastructure for industry;
4. Safety and security;
5. Work organization and design;
6. Training and continuing professional development;
7. Regulatory framework;
8. Resource efficiency.

Going forward, further implementation measures will be progressed under the joint initiative Industrie 4.0 Platform, which was established by the industry's professional associations BITKOM, VDMA and ZVEI. The report delivered by the Industrie 4.0 Platform on January 2016 (Platform Industrie 4.0, 2016) aimed at proposing an implementation plan over 20 years (from 2015 to 2035) for the actions identified by the Industrie 4.0 Working Group. This report highlights that, despite some overeager marketing messages, the 4th Industrial Revolution is still ongoing and the Industry 4.0 is still in the future as also

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[1] Copyright: Siemens AG/Industry Sector

confirmed by Drath & Horch (2014). Most of the technical ingredients are indeed already available but they are not yet used in practice in an Industry 4.0 perspective.

Despite the variety of terms (Thoben et al., 2017), the Industry 4.0 wave identifies the same phenomenon. The current excitement for the 4th Industrial Revolution can be deemed to be the idolization of a manufacturing intelligence embedded into physical systems, machinery, equipment, warehousing systems and production facilities spread out and networked within an industrial environment. Smart products are uniquely identifiable, may be located at all times and are aware of their own history, current status, the environment and alternative routes to achieving their target state. Autonomous machines, equipment, storage systems and production facilities able of autonomously exchanging information, triggering actions and controlling each other independently gave birth to *Cyber-Physical Systems* (CPS), well described in different research works (Lee et al., 2015). The embedded manufacturing systems are vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics. This way, individual customer requirements can be met and even one-off items can be manufactured profitably. The resulting *Smart Factory* (also called *Factory of the Future*) that is already beginning to appear employ this completely new approach to production.

Some clarity in a plethora of terms

Germany is not the only country to have identified the Industry 4.0 trend in manufacturing and industrial processes as strategic challenge. A variety of different terms is used around the world to describe this phenomenon, which has caused confusion rather than increasing transparency:

- **Smart Manufacturing**

  In response to the German government, the United States promoted an initiative known as the Smart Manufacturing Leadership Coalition (SMLC). The SMLC is comprised of 25 large global companies, 8 manufacturing consortia, 6 universities, 1 government lab and 4 high-performance computing centers. It has built on earlier National Science Foundation (NSF) funded work by 20 companies and 20 universities to develop a roadmap for Smart Manufacturing, which identifies three objectives: plant-wide optimization, sustainable production, agile supply chains. Therefore, it can be considered as a synonym of Industry 4.0.

- **Industrial Internet**

  At the end of 2012, US-based company General Electric (GE) publicly launched an initiative focused on the Internet of Things (IoT). GE's Industrial Internet strategy has applications in a huge variety of different areas to realign and embed their information technology capabilities into physical equipment to offer value added services and obtain economic benefits (Agarwal & Brem, 2015). Later, an open membership organization, called Industrial Internet Consortium (IIC), founded by AT&T, Cisco, General Electric, IBM and Intel in 2014, catalyzed all the efforts to establish priorities and roadmaps regarding the development, adoption and widespread use of Industrial Internet technologies. Some argue that the main difference between Industrial Internet, Smart Manufacturing and Industry 4.0 is the fact that the first one has a more focused scope, mainly looking at the machine and maybe the shop-floor level instead of the overall supply network (Rüßmann et al., 2015).

- **Intelligent Manufacturing**

  Intelligent Manufacturing is sometimes used synonymously with Smart Manufacturing. While the close collaboration of the Intelligent Manufacturing Systems organization (https://www.ims.org/) with several smart manufacturing funding agencies and research institutions support this, there is a notion that intelligent manufacturing may focus more on technological aspects and less on organizational ones. Intelligent manufacturing is a broad concept of manufacturing with the purpose of optimizing production and product transactions by making full use of advanced information and manufacturing technologies (Zhong et al., 2017).

- **Smart Factory**

  Smart Factory is a term that is focused more on the individual entity, the plant level, rather than the broader enterprise and supply network scope of Smart Manufacturing and Industry 4.0 (Lucke et al., 2008; Zuehlke, 2008; Wang et al., 2016). In this case, the smart factory paradigm relates strongly to the Industrial Internet of things (IIoT) and Cyber-Physical Systems (CPS). However, other sources refer specifically to the South Korean Smart Factory initiative, sponsored by the Korea's Ministry of Trade, Industry and Energy (MOTIE).

- **Internet of Things/Industrial Internet of Things**

  While Intelligent Manufacturing and Smart Factory paradigms may be argued to be similar to Smart Manufacturing and Industry 4.0, the Internet of Things (IoT) paradigm is more ICT-oriented (Atzori et al., 2010). IoT's vision of ubiquitous computing (Tan & Wang, 2010) is to connect the physical world with the virtual world and facilitate communication between all connected entities (Gubbi et al., 2013). In recent years, a subparadigm, the Industrial Internet of Things (IIoT) emerged, focusing on the interconnectivity of industrial assets, such as manufacturing machines, tools, and logistics operations (Da Xu et al., 2013). Overall, IoT/IIoT can be understood as an Industry 4.0 enabling technology (Mittal et al., 2016).

2.1.2 The Industry 4.0 key enabling technologies

In order to fully accomplish the 4th Industrial Revolution, the mutual integration of different technologies is required (Wan et al., 2015). Kang et al. (2016) started to analyze the major key technologies related to the Industry 4.0 in the policies and technology roadmaps of Germany, United States and Korea. These technologies enabling the Industry 4.0 are being widely investigated by several reviews (Mittal et al., 2016; Oztemel & Gursev, 2018) but most of them agree on nine key enabling technologies (Figure 2):

- **Big data and analytics**: the collection and comprehensive evaluation of huge amount of data from many different sources – production equipment and systems as well as enterprise and customer management systems – will become standard to support real-time decision making and explain uncertainties (Lee et al., 2014);

- **Autonomous robots**: more affordable robots with a greater range of capabilities will interact with one another, work safely side-by-side with humans and learn from them (Robla-Gómez et al., 2017);
- **Simulation**: using simulations based on real-time data and mirroring the physical world in a virtual model (like a digital twin) will allow operators to test and optimize the virtual world before the physical changeover as well as to predict the evolution of complex systems (Uhlemann et al., 2017);
- **Horizontal and vertical system integration**: companies, departments, systems, functions, and capabilities will become much more cohesive as data-integration networks evolve and enable automated value chains (Zhou et al., 2015);
- **Cybersecurity**: the increased connectivity and use of standard communications protocols that come with Industry 4.0 require secure, reliable networks as well as sophisticated identity and access management technologies to protect critical industrial systems and manufacturing lines from cybersecurity threats (Rubio et al., 2017);
- **Cloud**: cloud technologies can be widely used for increased data sharing across company boundaries, improved system performance and reduced costs through bringing systems online (Liu & Xu, 2017);
- **Additive manufacturing**: companies have just begun to adopt additive manufacturing, such as 3D printing, which they use mostly to prototype and produce small batches of customized products that offer construction advantages, such as complex, lightweight designs (Dilberoglu et al., 2017).
- **Augmented reality**: Augmented reality based systems support a variety of services, such as providing spatially registered information on the task directly in the user´s field of view to guide the user through unfamiliar tasks (e.g. assembly of new products), thus improving decision making and work procedures (Paelke, 2014).

The present study will pick up some of these technologies, namely simulation, virtual reality and serious games, that will be used to mirror the real world system and let workers experience a rare scenario, represented by a major industrial accident in an industrial site.

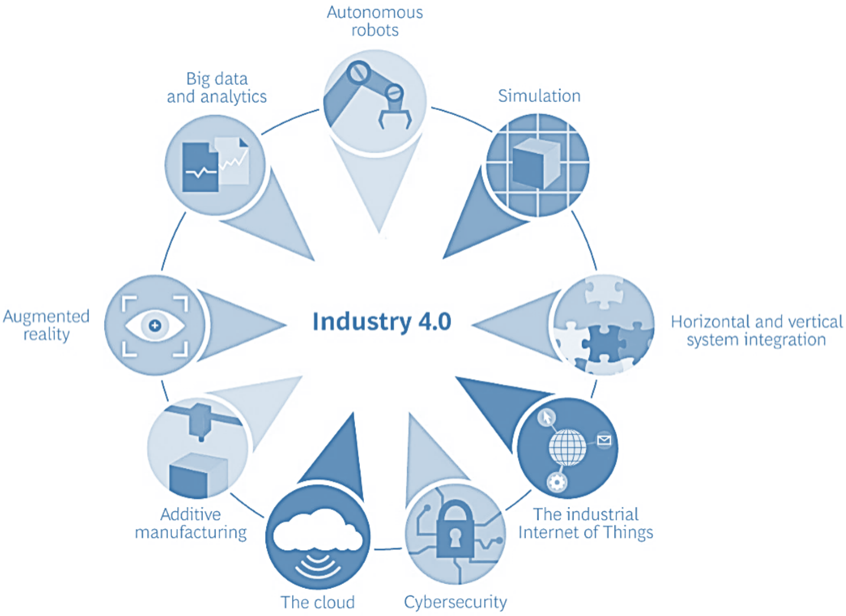

Figure 2: Industry 4.0 key enabling technologies[2]

2.1.3 Safety and training requirements in complex 4.0 industrial systems

The industrial transformation associated with the smart manufacturing revolution creates numerous challenges for organizations, technologies, and employees. Three areas for actions identified by the Industrie 4.0 Working Group will be covered by the present thesis, namely:

- managing complex systems,
- safety and security,
- training and continuing professional development.

As illustrated in Figure 1, the complexity in production and processes has increased with each industrial revolution. Nowadays, Industry 4.0 production systems are increasing even more in complexity (Waschneck et al., 2017; Block et al., 2015). As the fourth industrial revolution or Industry 4.0 becomes the predominant reality, it will bring new paradigm shifts, which will also have an impact on the management of occupational health and safety (as highlighted in a thorough analysis by Badri et al., 2018). In the Italian Industry 4.0 framework, INAIL (Italian Institute for Insurance against Accidents at Work), and in particular DIT Laboratory 2 Machine and Work Equipment, executed research activities on machines and work equipment to analyze new technologies, such as Augmented Reality (AR) and Artificial Intelligence (AI), as well as additive technologies and collaborative robots, from a safety perspective (Di Donato, 2018). Despite safety is widely recognized as a crucial strategic organizational objective (Nenonen et al., 2015) and more restrictive safety regulations and technological innovations have been introduced (e.g. the Seveso III Directive), the nature of Smart Factories pose significant safety assurance challenges (Jaradat et al., 2017). Some of the guarantees provided by the ‘things’ (e.g. machinery, equipment, systems) are deemed as necessary in order to ensure the safety of the manufacturing processes and the resulting products. However, designers or operators of factories do not have much control over the design and evolution of the ‘things’ or cloud-based services that are increasingly being used in

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[2] Source: BCG Analysis. Retrieved at: https://www.bcg.com/it-it/capabilities/operations/embracing-industry-4.0-rediscovering-growth.aspx

manufacturing processes. This potentially weakens confidence in the safety of the factory and can undermine the overall safety case, i.e. due to high degrees of uncertainty about the actual performance, reliability or behavior of these ‘things’. Furthermore, huge concerns can be related to potential cyber threats that can cause failure of the systems. Different management frameworks at international level have been developed to guide occupational health & safety practices as well as emergency preparedness and response in the industrial sector, including:

- the ISO 45001:2018 specifies the requirements for management systems of occupational health and safety, whose goal is to give guidance for its use, to enable organizations to provide safe and healthy workplaces by preventing work-related injury and ill health, as well as by proactively improving its OH&S performance;
- the ISO 14001:2015 specifies the requirements for an environmental management system that an organization can use to enhance its environmental performance. It also includes a section related to the management of the environmental impacts in case of emergencies;
- the ISO 11320:2011 provides criteria for emergency preparedness and response to minimize consequences due to a nuclear criticality accident;
- the ISO 15544:2000 describes objectives, functional requirements and guidelines for emergency response (ER) measures on installations used for the development of offshore hydrocarbon resources;
- the ISO 22315:2014 provides guidelines for mass evacuation planning in terms of establishing, implementing, monitoring, evaluating, reviewing and improving preparedness. It establishes a framework for each activity in mass evacuation planning for all identified hazards. It will help organizations to develop plans that are evidence-based and that can be evaluated for their effectiveness;
- the ISO 15544:2000 describes objectives, functional requirements and guidelines for emergency response (ER) measures on installations used for the development of offshore hydrocarbon resources.

These frameworks propose a general guide for managing accident prevention, training, emergencies and regulatory requirements specific for industrial activities. However, following the changes brought by Industry 4.0, they should be more flexible and hence better suited. For example, industry currently lacks fully standardized platforms for personnel safety training (Reniers, 2017) as well as for enhancing emergency preparedness and response capabilities. An excellent emergency preparedness and response strategies should begin with the mindset that workers are the customers of safety efforts and need to acquire knowledge – in the perspective of a continuing professional development – so that employees are confident in what they are doing.

2.2 Major Accident Hazards Industrial Sites

The industrial and societal world is experiencing obvious and increasing conditions of risk due to major natural and man-made disasters (Liu et al., 2016) that compel to redesign the way industrial organizations and communities respond and recover. In order to reduce risks, several countries have launched a number of laws and regulations for industries dealing with dangerous materials and substances or with hazardous processes. Nevertheless, accident causation analysis revealed that human errors and low preparedness are the main sources of industrial hazards. This section investigates the trend of Major Industrial Accidents (MIAs) over the last years and current European and Italian legislation on the topic for Major Accident Hazards Industrial Sites. The role of the 'human factor' in determining MIAs or influencing the post-disaster response and recovery is finally analyzed.

2.2.1 Trend and examples

A recent article by Blanton & Peksen (2017) states that one of the costs of the economic globalization starting from the World War I was an increased number of MIAs. The 'exponential' growth of the number of reported MIAs is confirmed by an extensive cross-analysis carried out as a preliminary step to this doctoral thesis from different accident databases (e.g. eMARS[3] and FACTS[4]) and media reports, reported in Table 1.

Table 1: Accident databases

Database	Period	Number of Incidents	Geographical Area
MARS	Dal 1980 ad oggi	450	EU-OECD
FACTS	Dalla fine del 1970	24000	Worldwide
MHIDAS	Dal 1964 ad oggi	11000	Worldwide
ERNS	Dal 1987 ad oggi	275000	USA
RISCAD	1949–2006	4796	Giappone
RMP*Info	Dal 1990 ad oggi	15430	USA
IRIS	Dal 1990 ad oggi	605400	USA

Figure 1.a shows a heatmap where the opacity of the filling red color represents the percentage of reported MIAs occurred in the last century (1916-2016) in a given country. Figure 1.b shows instead the trend worldwide in the number of reported MIAs in the period of interest. Starting from the '60s, the growth of the number of reported MIAs involved mainly countries with a traditionally high industrial activity (United States, United Kingdom, China, Germany and Japan) and emerging industrial powers (e.g. India, Bangladesh). Notwithstanding, significant improvements have been made in hazard assessment and disaster prevention – even resulting from natural disasters or terrorist attacks (Lovreglio et al., 2016) – which explains the latest decreasing trend in the number of reported MIAs depicted in Figure 1.b. The number of near miss and major industrial accidents per year is however still very high in different sectors, such as in chemical plants, as confirmed by Pariyani et al. (2010).

A survey of some examples of MIAs occurred worldwide in industrial plants and facilities was useful to understand the most important commonalities and critical issues in disasters management. For a complex

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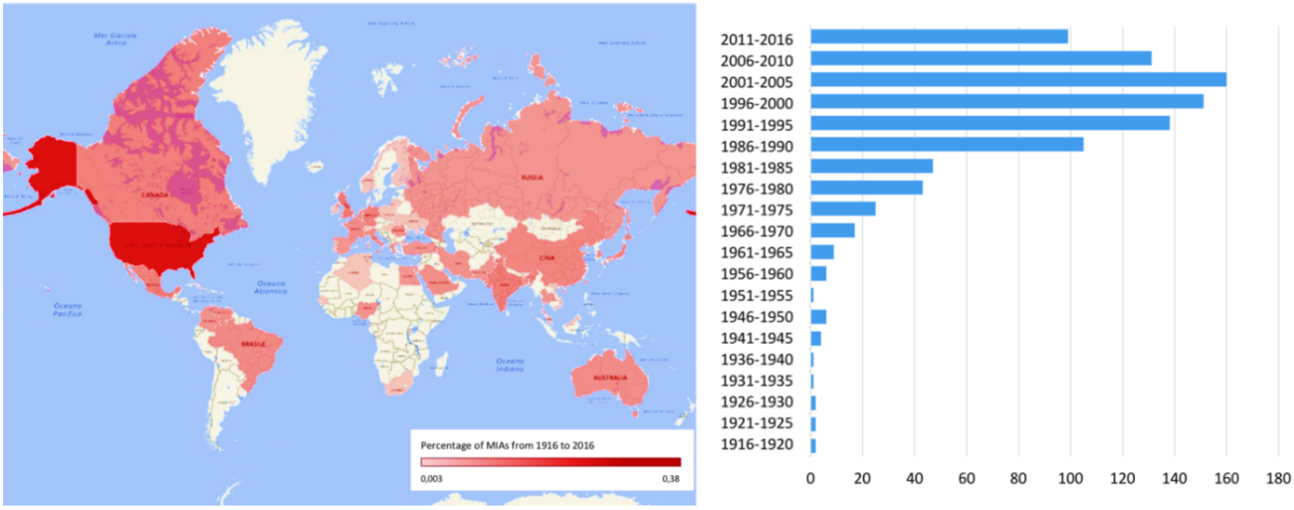
[3] eMARS, Major Accident Reporting System, https://emars.jrc.ec.europa.eu/en/emars/content

[4] FACTS, Failure and ACcidents Technical information System, http://www.factsonline.nl/

industrial system, the incident frequency is low but consequences are serious (Venkatasubramanian, 2011). Figure 4 reports the locations of a group of MIAs occurred along the last years. It is possible to observe that disasters have occurred in almost all the five continents showing that disasters management has to be regarded as a common problem worldwide.



(a) (b)

Figure 3: Heatmap (a) and number (b) of MIAs in the century 1916-2016

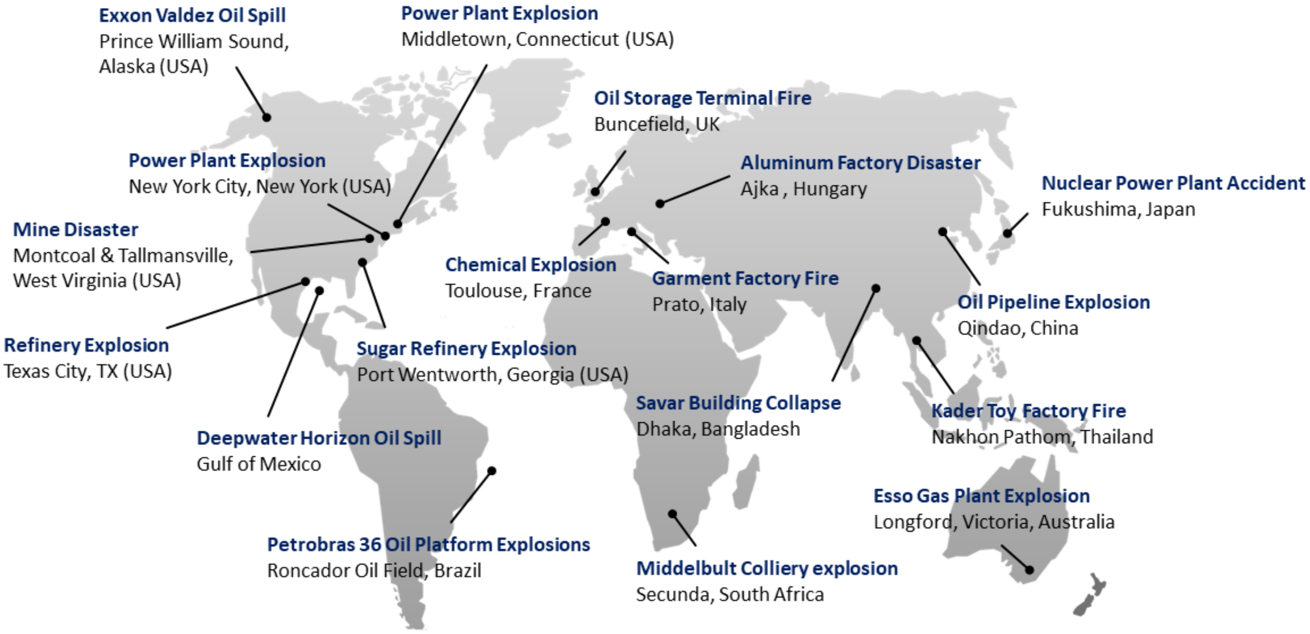


Figure 4: Examples of Major Industrial Accidents worldwide

Causes, consequences and characteristics of some of these MIAs are hereunder described:

- **Oil Storage Terminal Fire, Buncefield, England – December 11, 2005**

  The Buncefiled disaster is a major conflagration caused by a series of explosions at the Hertfordshire Oil Storage Terminal, an oil storage facility located in Hertfordshire, England. The terminal was the fifth largest oil-products storage depot in the United Kingdom, with a capacity of about 60 million imperial gallons (270 Ml) of fuel and was owned by TOTAL UK Limited and Chevron. The disaster caused 43 injuries and 2 serious injuries. As far as the main rescue units are concerned, the Fire department of Hertfordshire was fully involved in rescue and firefighting operation with more than 150 people. Additionally, also the United Kingdom Fire Service Search and Rescue Teams (UKFSSART) as well as the Urban Search and Rescue Teams (USAR) provided a strong help for rescue and emergency management operations. The major hospitals (Hemel Hempstead Hospital and Watford General Hospital) were involved to host the injured people coming from the disaster zone. Moreover, hundreds of homes in the Hemel Hempstead area were evacuated and about 2.000 people had to find alternative accommodation due to the large fire developed from the disaster area as showed in Figure 5.

Figure 5: Buncefield fire: aerial view of the disaster zone during the ongoing emergency procedures

- **Aluminum Factory Disaster, Ajka, Hungary – October 4, 2010**

  The Ajka alumina sludge spill was an industrial accident at a caustic waste reservoir chain of the Ajkai Timföldgyár alumina plant in Ajka, Veszprém County, in western Hungary. The plant suddenly released a huge mass of water and red mud, which stepped in the surrounding countryside as it is showed in Figure 6. It was not initially clear how the containment at the reservoir had been breached. The red mud was dangerous because of its high pH: it caused an alkaline reaction in contact with the skin, which resulted in 90 people that have been taken to the hospital with chemical burns and 4 people deceased. During the operations, the Mal (Magyar Aluminum) S.A, the National Directorate General for Disaster Management (NDGDM), Hungarian Civil Protection and Hungarian army were involved. The main involved hospitals were the Magyar Imre Hospital and the Tapolcai Hospital.

Figure 6: Ajka disaster: aerial view of the disaster zone during the ongoing emergency procedures

- **Savar Building Collapse, Dhaka, Bangladesh – April 24, 2013**

  The 2013 Savar building collapse or Rana Plaza collapse was a structural failure that occurred in the Savar Upazila of Dhaka District, Bangladesh, where an eight-story commercial building named Rana Plaza collapsed (as showed in Figure 7). The structure housed several textile factories in Bangladesh, who built clothes for Western companies. Multiple causes were identified: the building have been built on a filled in pond, which compromised structural integrity; it was converted from commercial use to industrial use; 3 floors above the original permit were added; substandard construction materials were used. The Bangladesh Garment Manufacturers and Exporters Association confirmed that 3122 workers were in the building at the time of the collapse. The disaster caused 233 victims and 700 serious injured. Rescuers immediately have saved about 2,500 people, but there were many missing. Many hours were needed to extinguish the flames and despite the fatigue and the sickening odor of decomposing bodies, rescuers continued to work for days. The hospitals involved include the Enam Medical College & Hospital, the Monorom Hospital and the Prime Hospital.

Figure 7: Rana Plaza disaster: an aerial view of the disaster zone after the building collapse

- **Oil pipeline explosion, Qingdao, China – November 23, 2013**

  The 2013 Qingdao oil pipeline explosion occurred when several workers were trying to repair a leak in the pipes owned by Sinopec, the largest Chinese oil company, in the city of Qingdao, Shandong Province, China. The serious damage in this incident has highlighted major problems, including the location of the pipelines and the sewerage grid, and the negligent maintenance of the oil pipeline that caused the oil leak. The blast killed at least 62 people but more than 150 were injured. The emergency management was led by Firefighters Huangdao oil hub of Sinopec with an additional aid from the Chinese Army as showed in Figure 8. About 18.000 people were evacuated from Qingdao. The following hospitals were involved to help people from disaster area: Qingdao west coast Medical Center, International Clinic of Qingdao Municipal Hospital (ICQD), ChengYang People's Hospital.

Figure 8: Qingdao disaster: Chinese Army during the rescue operations

- **Garment Factory Fire, Prato, Italy – December 2, 2013**

  A fire in December 2013 in a Chinese-owned clothing factory in the Italian town of Prato broke out in a loft of an industrial facility that was used as a dormitory. The estimated victims were 17, 7 dead and 10 seriously injured. The disaster underlined the unsafe conditions in which the workers are employed although the causes of the fire are unclear. The entities involved in the disaster management were the National Firefighters, the Health Emergency departments, the Civil Protection and Prato Gold Cross and Red Cross. The firefighters and ambulances arrived almost immediately and the rescue operations (see Figure 9) began.

Figure 9: Prato garment factory disaster: building collapse and rescue operations

The survey of the MIAs occurred in the last years was relevant to highlight the common aspects (e.g. causes, consequences, entities involved) among different accidents in different industrial areas and sectors. In general, MIAs pose a significant threat to humans and the environment, cause huge economic losses and disrupt sustainable growth. Accident causation analysis has proved to be a good way to trace industrial accident causes and, ultimately, to prevent similar accidents from happening again (Li et al, 2017). The increasing complexity of engineered social-technical systems driven by the Industry 4.0 paradigm brings greater risks that can potentially contribute to an accident. To minimize the associated risks, measures and regulations are necessary to prevent major accidents and to ensure appropriate preparedness and response.

2.2.2 An overview of the current legislation and reach in the European Union and Italy

In Europe, the catastrophic accident in the Italian town of Seveso in 1976 prompted the adoption of legislation on the prevention and control of major accidents. The Seveso disaster was an industrial accident that occurred on July 10, 1976, in a small chemical manufacturing plant approximately 20 kilometers north of Milan in the Lombardy region of Italy. It resulted in the highest known exposure to 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), a persistent environmental contaminant and carcinogen substance, in residential populations. Although several thousand people were exposed to the released chemicals, there were no human fatalities. The aftermath included the culling of animals to prevent the toxins from entering the food chain, removal and incineration of topsoil and the prohibition of farming over a wide area, which represented a significant economic impact.

The so-called Seveso Directive was adopted in 1982 as European Union Directive 82/501/EC, which aimed to harmonize the Member States' legislation on serious chemical accidents. Its primary objectives were to prevent major accidents involving dangerous substances and limit the possible consequences of such accidents for human health and the environment.

Subsequent incidents (e.g. Bhopal disaster in India and Sandoz warehouse fire in Switzerland) led to amendments to the original Seveso Directive, which was replaced in 1996 by the Seveso II Directive 96/82/EC. Whilst Seveso I targeted specific activities and included a list of dangerous substances, Seveso II introduced a classification system for dangerous substances (toxic, flammable/explosive, and dangerous for the environment) and specified threshold quantities for certain types, categories and group of categories of such substances. Based on whether the upper or lower threshold is exceeded, Seveso establishments are classified as lower tier or upper tier, with corresponding obligations.

The Seveso II Directive was adopted in Italy following
the Legislative Decree No. 334 issued on August 17th, 1999.

On December 2003, following lessons learned in the adoption of the Seveso I/II Directive by the Member States and further industrial accidents (e.g. fertilizer plant explosion at Toulouse, France), the scope of the Seveso II Directive was itself extended by the new Directive 2003/105/CE (c.d. Seveso II bis).

The Seveso II-bis Directive was adopted in Italy following
the Legislative Decree No. 238 issued on September 21st, 2005,
which modified, without major differences, the Legislative Decree No. 334/99.

In Italy, the Italian Institute for Environmental Protection and Research, ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) has issued a report on July 2013, which analyzes the types of industrial sites that are included in the Legislative Decree 238/2005 (Table 2). A total amount of 1142 high-risk industrial sites have been identified, 576 of them overcoming the upper safety threshold for harmful substances. Based on this list, a map representing the distribution over the Italian territory of Major Accident Hazards Industrial Sites has been created (Figure 10), which shows a roughly uniform distribution.

Table 2: Type of Major Accident Hazards Industrial Sites in Italy (D.lgs.238/05)

Sector	**Lower tier**	**Upper tier**	**Total**	**%**
Chemical and Petrochemical Sites	107	175	282	24,69
Liquefied Gas Storage Sites	161	114	275	24,08
Refineries	0	17	17	1,49
Mineral Oil Storage Sites	43	67	110	9,63
Pesticides Storage Sites	9	23	32	2,80
Toxic Materials Storage Sites	12	23	35	3,06
Distillation Plants	17	0	17	1,49
Explosives Production and/or Storage Sites	54	25	79	6,92
Thermoelectric Power plant	4	26	30	2,63
Electroplating Plants	76	53	129	11,30
Technical Gases Production and/or Storage Sites	33	8	41	3,59
Steel Mills and Metallurgical Plants	8	21	29	2,54
Treatment Plants	7	12	19	1,66
Underground Natural Gas Storage Sites	12	0	12	1,05
Other	23	12	35	3,07
Total	**566**	**576**	**1142**	**100,00**

The data analysis from the UE's e-MARS accident database revealed a significant turnaround of the number of MIAs (although at a slower pace than expected). In addition, a new European Regulation 1272/2008 for the Globally Harmonised System for the classification, labelling and packaging of chemical substances and mixtures (CLP) has been issued on June 2015. The Seveso II Directive was based on a previous classification (the Dangerous Substances Directive 67/548/EEC), hence the requirement for change.

The Seveso III Directive 2012/18/EU aims to align Seveso legislation with the new classification scheme for chemical substances provided for by the CLP Regulation. Seveso III must be implemented by the Member States by 31 May 2015, in order to coincide with the entry into force of the CLP on June 2015.

The Seveso III Directive was adopted in Italy following
the Legislative Decree No. 105 issued on June 26th, 2015,
which fully repealed the previous Legislative Decrees No. 334/1999 and 238/2005.

According to the Seveso Directives, an industrial site is subjected to major accident hazards because of the presence of a certain amount (over a given threshold) of harmful substances (toxic substances, combustible materials, explosive materials, oxidizing substances, environmentally hazardous materials).

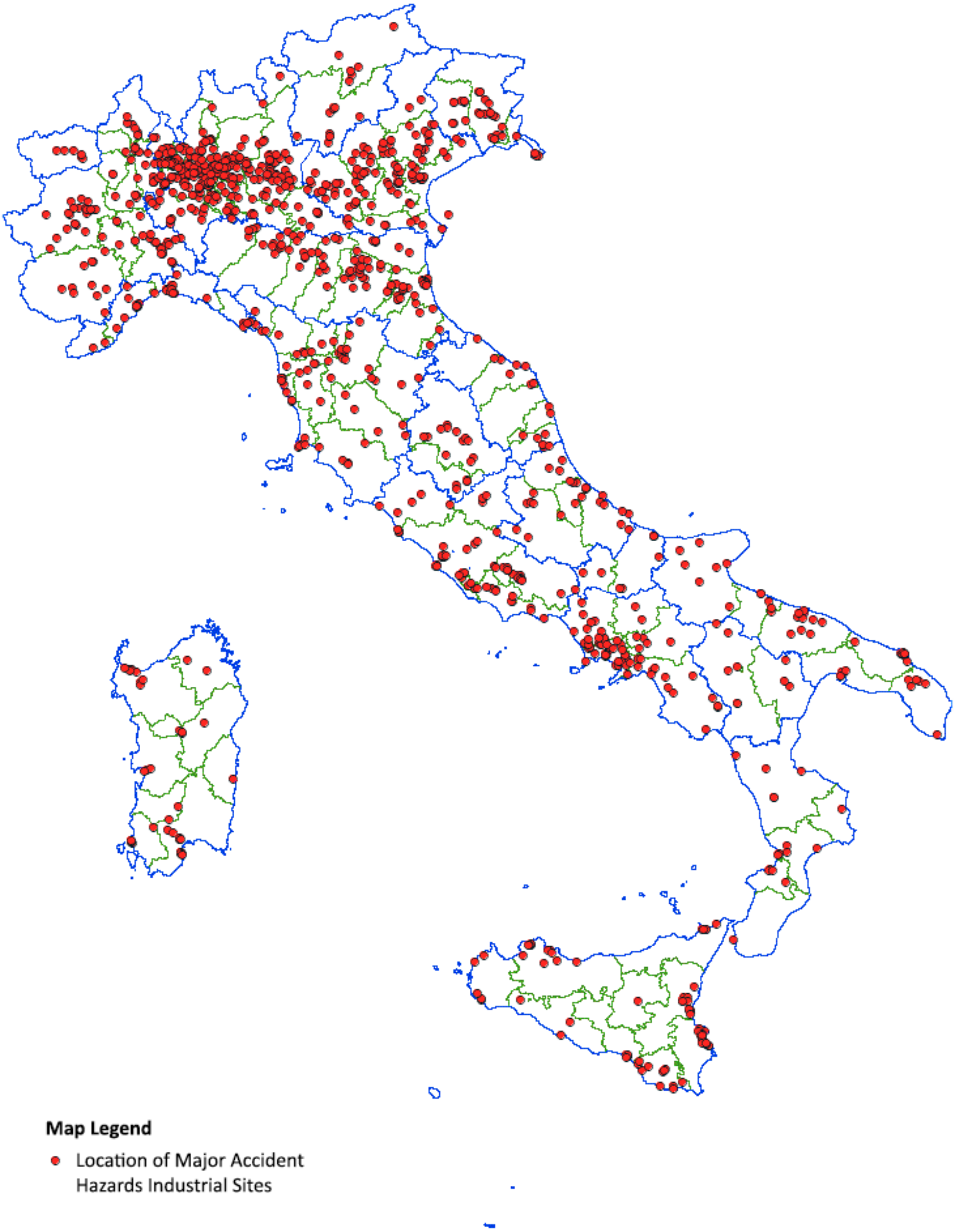


Figure 10: Map of Major Accident Hazards Industrial Sites on July 2013 (based on Decree 238/05)

A Major Industrial Accident (MIA) has been then defined as an unexpected, usually sudden occurrence including, in particular, a major emission, fire or explosion, resulting from abnormal developments in the course of an industrial activity, leading to a serious danger to workers, the public or the environment, whether immediate or delayed, inside or outside the installation and involving one or more hazardous substances (Occupational Safety and Health Service, 1994). Major accidents involve the release –

instantaneous or over a relatively short period – of significant amounts of energy or of one or more hazardous materials. These accidents can affect people, property, and the environment. Human consequences can be physical (fatalities or injuries) or psychological and can affect both the employees of the establishment in which the accident occurs and the external population. The consequences on property are usually the destruction of equipment or buildings. Environmental consequences can be immediate or delayed and include the release of a hazardous material into the atmosphere, into the soil or into water. In addition, major accidents usually cause indirect losses such as loss of profits by the company involved or interruption of the business continuity (Casal, 2017). Conversely, a near miss is defined as an unplanned event that did not result in injury, illness, or damage – but had the potential to do so.

In order to prove the importance and potential reach of this thesis, the number of Major Accident Hazards industrial sites in Italy (in Italian 'RIR – Rischio di Incidente Rilevante') are reported. For the purpose of this analysis, the Seveso National Database[5] updated at June 30th, 2018 has been used. Table 4 reports the number of plants affected by the Legislative Decree 238/2005 (updated at July 2013) and by the Legislative Decree 105/2015 (updated at June 2018), the Seveso II and Seveso III respectively.

It can be noticed that the number of Major Accident Hazards Industrial Sites decreased from 1142 to 1000 but it is still relevant. Lombardia is the region with the highest percentage of interested sites (26,0%), while Valle d'Aosta, Molise and Basilicata are the regions with the lowest percentages (0,6%, 0,8% and 1,0% respectively). A complete map of the regional distribution of the Major Accident Hazards Industrial Sites according to the Legislative Decree 105/2015 is illustrated in Figure 11. According to the INAIL open data[6], reported occupational accidents in the Italian industrial context are slightly increasing as shown in Table 3.

Table 3: Italian reported occupational accidents (source: INAIL open data)

Period	**2013**	**2014**	**2015**	**2016**	**2017**	**Gen-Nov '17**	**Gen-Nov '18**
All	137.107	129.320	125.608	126.989	130.566	116.176	128.457
		-5,68%	-2,87%	1,10%	2,82%		10,57%
Fatal	369	313	408	329	369	302	325
		-15,18%	30,35%	-19,36%	12,16%		7,62%

The Directive is widely considered as a benchmark for industrial accident policy and has been a role model for legislation in many countries worldwide. The European Union in general counts more than 12.000 industrial establishments where dangerous substances are used or stored in large quantities, mainly in the chemical and petrochemical industry, as well as in fuel wholesale and storage (including LPG and LNG) sectors. Germany being very densely populated has, at the same time, the highest number of Seveso establishments in the EU (3,264 in 2015) followed by France, Italy and the UK.

Despite the analysis has been done only for Member States of the European Union, this paragraph gives an idea of the potential reach that this study may have also in non-European Countries (e.g. United States, South America, Japan, China) where the number of Major Accident Hazards Industrial Sites is similarly high or even higher.

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[5] http://www.minambiente.it/pagina/inventario-nazionale-degli-stabilimenti-rischio-di-incidente-rilevante-0

[6] https://www.inail.it/cs/internet/attivita/dati-e-statistiche/open-data.html

Table 4: Italian regional distribution of Major Accident Hazards Industrial Sites (D.lgs.238/05)

	D.lgs.238/2005			**D.lgs.105/2015**		
	Updated: July 2013			**Updated: June 2018**		
Region/Province	**Lower tier**	**Upper tier**	**Total**	**Lower tier**	**Upper tier**	**Total**
Abruzzo	16	10	26	12	10	22
Basilicata	4	5	9	3	7	10
Calabria	10	7	17	10	7	17
Campania	52	18	70	53	21	74
Emilia Romagna	36	63	99	32	52	84
Friuli Venezia Giulia	14	20	34	11	15	26
Lazio	33	36	69	28	31	59
Liguria	10	24	34	10	21	31
Lombardia	131	156	287	122	138	260
Marche	9	7	16	7	7	14
Molise	3	5	8	2	6	8
Piemonte	50	53	103	36	43	79
Puglia	23	20	43	16	16	32
Sardegna	14	28	42	10	28	38
Sicilia	37	34	71	31	33	64
Toscana	32	30	62	29	26	55
Trentino Alto Adige - Bolzano	5	2	7	5	1	6
Trentino Alto Adige - Trento	6	4	10	5	3	8
Umbria	12	5	17	11	5	16
Valle d’Aosta	5	1	6	5	1	6
Veneto	52	60	112	42	49	91
ITALIA	**554**	**588**	**1142**	**480**	**520**	**1000**

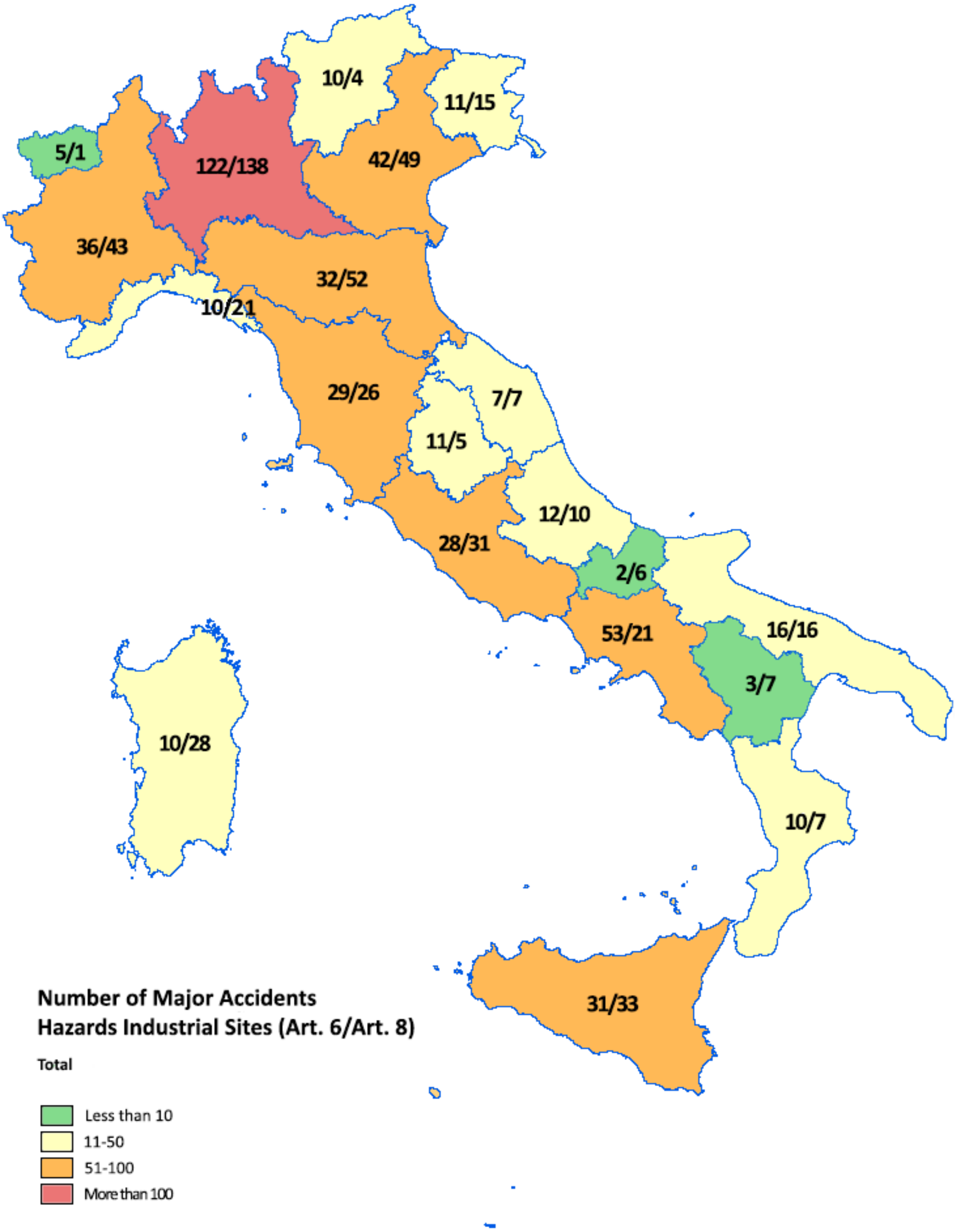


Figure 11: Regional heatmap of Major Accident Hazards Industrial Sites (D.lgs.105/2015)

2.2.3 The 'human factor' as a source of major accident hazards

Living with the risk in industry is as of today unavoidable (Ale, 2005). Despite the quickening pace of technological advances and the greater emphasis on the design of safe systems have drastically reduced the risks (Woods et al., 2010), the corporate quest for zero accidents in highly automated industrial sites is still plainly utopian (Twaalfhoven & Kortleven, 2016). In recent years, considerable effort has been devoted to tackle the technological aspects of intervention strategies and plans for preventing and/or handling high-risk emergencies in complex industrial systems, such as nuclear and petrochemical industries. Besides the systems failure in itself, recent literature on accident causation analysis also recognizes the 'human factor' as one of the main sources (or even the most important) of industrial hazards (Li et al., 2017). Despite some authors think that 'human error' is only a factor eclipsing real causes (Alonso & Broadribb, 2018), the uncertainty and unpredictability of the scenario evolution mainly affect emotivity/stress and perceived workload, which are among the major human factors influencing performance (Di Domenico & Nussbaum, 2011) and safety behaviour (Wang et al., 2018). It is undeniable that accidents such as the Macondo Well Blowout are due to complete human errors, such as poor leadership abilities (Pranesh et al., 2017). In their observation of MIAs, Moura et al. (2017) also show that seemingly unforeseen scenarios involving complex interactions between human factors, technologies and organizations, are capable of triggering major catastrophes. Vinnem (2011) provides instead an overview of human and organizational errors and technical faults in some well-known offshore major accidents. Since the concepts of man-machine-media (environment) model was first proposed by Wright, the human factor has had a profound effect on accident analysis and prevention (Miller, 1991). Some researchers proposed variations of this model, such as the "5M' (i.e. Man, Machine, Method, Material, and Money) model, to evaluate the impact of human, process and technology factors on system failure (Irani et al., 2001). Other authors have noticed that the human factor, rather than existing plans, the management of resources, or the uncertainty of the situation, is often a major source of vulnerability in the decision-making process (Pearson et al., 1997; Smith & Dowell, 2000, Weisæth et al., 2002). Nevertheless, little attention has been generally devoted to the development of decision support aids and training programs to enable the human operator to perform effectively.

Hazard assessments in industry generally neglect the impact of human behavior (Lovreglio et al., 2016). Human factors can no longer be disregarded in the light of the rise of Industry 4.0 paradigm, which is turning technology-driven plants into human-centered industrial systems. The role of ergonomics and human factors research is gaining more and more relevance in the field of Occupational Health & Safety for the Industry 4.0 (Siemieniuch et al., 2015). This is especially true in critical and challenging operations, such as an industrial emergency due to a major accident. Engineers and designers of advanced manufacturing systems often overlook human factors, which conversely may help to reduce risks of major accidents (Ciavarelli, 2016). Some industries, such as aviation, have started to use crew resource management (CRM) tools to reduce human error and, consequently, major accident hazards. They focus on non-technical skills, which deal with psychological and organizational conditions rather than technical knowledge. The interactions among major assets in modern industry 4.0 (real-time communication, Big Data, human–machine cooperation, remote sensing, monitoring and process control, autonomous equipment and interconnectivity) underlie several types of workplace hazards, in particular those in the psychosocial category (Leka & Jain, 2010). This more central role of the human worker requires a deeper understanding of which are the cognitive, physical and psychological aspects, mostly neglected in the literature, that affect the staff behavior and performance in case of an industrial emergency.

Despite awareness and concern about the human factor in industrial disasters had grown considerably over the past years (Granot, 1998), attention has been mainly focused on the human factor in causing such industrial disasters rather than analyzing which outcomes of an MIA are affected by human factors and people's behavior during a disaster. Depending on the role and capability of every individual to cope with a stressful and complex emergency scenario, the consequences and outcomes of an industrial accident can change.

Although human factors assessment methodologies are largely debated because of their subjectivity, they are generally required if someone wishes to determine whether you have sufficient staff, if capacity exists for additional tasks, or whether personnel can cope with emergencies or incidents. A workload assessment study is commonly used to demonstrate whether or not workers are able to perform tasks without unacceptable performance degradation: excess workload usually results in reduced task performance and more errors, while conversely underload leads to boredom and reduced situation awareness and alertness (Jung & Jung, 2001). Workload issues may be even more relevant in the aftermath of a major industrial accident because the demands imposed by a safety-critical emergency situation for human resources vary according to the operators' experience, training level, skills, psychological state when the task is performed and to the cooperation patterns with the other team members (Coelho et al., 2015). Due to a task's multidimensionality (Mehta & Agnew, 2011), people tend to define (and thus experience) workload in different ways – the amount of work that is loaded on them, the time pressure under which a task is performed, the level of physical effort exerted, the success in meeting task requirements, or the psychological and physiological consequences of the task. Given this subjective nature, there is much disagreement not only on its definition but also on the workload assessment methodologies. One of the most frequently cited workload measures in literature is the NASA Task Load Index (Hart and Staveland, 1988), which has received multiple extensions in more recent years, especially in the type and number of factors affecting the perceived workload.

As a matter of facts, workload contributing factors also produce anxiety and stress in industrial operators. Such factors, known as stressors, can occur in many forms: dynamic events, time pressure, high risk and inadequate information have a severely detrimental effect on the performance of those operators involved in the emergency management. Stress is broadly considered a relevant cause for potential loss of human performance. Indeed, the emergency response team (or crisis cell) operating in an industrial site usually shows individual cognitive biases and teamwork errors during an emergency due to everyone's own personality, to dynamic events, time pressure, high risk and emotional involvement (Petrillo et al., 2017). Individual cognitive biases (e.g. weak leadership, erroneous decision-making, blind adherence to procedures, lack of concentration and poor assessment of the situation) are usually shown during emergency situations together with teamwork errors, including role ambiguity resulting in tasks 'falling through the cracks', lack of explicit coordination and communication problems (Svenson & Maule, 1993). Industrial accident response implies physically demanding work to be performed concurrently with cognitive tasks, which may affect mental workload or decrease performance, as demonstrated by Di Domenico & Nussbaum (2011). Crisis management involves quick decision-making in critical conditions, with the obligation of issuing, in some cases, a public report to the media (Sniezek et al., 2001). Crises and major accidents lead decision-makers into an urgent decision-making situation, with the obligation to minimize the potential consequences for a wide range of high-stake elements (Tena-Chollet et al., 2013). Human interaction and collaboration is also crucial (Pan & Bolton, 2016): working conditions, adequacy of training, crew collaboration, availability of procedures and plan within hazardous industrial plants have been under investigation over the last years with the aim to understand the causes of human errors (Monferini et al., 2013), especially in the case of people acting on the basis of incomplete information (Reiman and Rollenhagen, 2011). Emotional involvement may also create instinctive reaction producing even more problems (Sayegh et al., 2004). Moreover, high turnover and tight staffing create an environment with a reduced emphasis on safety culture. Experienced workers are stretched thin and have little time to train and mentor new hires. Inexperienced workers are at high-risk and are rarely prepared to cope with the complexity of an industrial emergency.

Workload measures and stress correlation analyses are frequent in hospitals' emergency departments (Bradley Morrison and Rudolph, 2011), but are becoming of great interest also in major hazard industrial sites, such as nuclear power plants (Gao et al., 2013). For example, the results reported in the study conducted by González-Muñoz and Gutiérrez-Martínez (2007) show that some of the workload factors assessed by the NASA-TLX (mental demand, temporal demand, and frustration) may be considered relevant risk factors for job stress. Most stress assessment methods primarily focus on an individual's subjective perception of stress (Cohen et al., 1983). Since stress is also associated with physiological changes, such as higher heart rate and lowered heart rate variability, they have been proposed to be good indicators for investigating the physiological effects of stress (Van Amelsvoort et al., 2000). The heart rate measures the number of times per minute that the heart contracts or beats. Fohr et al. (2015) suggest that self-reported stress is associated with objective physiological stress, but the latter provides much more information than self-assessment. Stress also affects cognitive function and therefore decision making. As Mather and Lighthall (2012) pointed out, most research on stress and cognitive function has been limited to memory, whereas other cognitions, such as decision making, have received less attention. Previous studies have highlighted that when stressed, individuals tend to make more habitual responses than goal-directed choices (Yu, 2016) therefore the consequences of their actions and decisions on the outcomes of an emergency response may consistently vary. Decision making capabilities are crucial under stressful conditions, such as when circumstances demand a quick course of action. Indeed, the process of decision making in itself can be also stressful, such as when a decision involves high risk and its outcome is uncertain. Thus, the relationship between stress and decision making/human performance is bidirectional. Preston et al. (2007) found that the relationship between stress and human performance followed an inverted U-shaped curve indicating that performance under stress was enhanced up to a point and then began to deteriorate, consistently with the Yerkes-Dodson Law (Yerkes & Dodson, 1908). Similar results have been obtained in Wemm & Wulfert (2017) where they examined the effects of a social stressor on the performance in a decision-making task. Kowalski-Trakofler et al. (2003) provide a thorough discussion on human judgment and decision making under stress within the context of the management of emergencies. They also suggest the development of simulation-based decision support systems to replicate stress conditions in the field and investigate the behavior of the emergency manager.

Hence, it emerges from the background analysis the need to answer the question whether and to which extent human factors, such as stress and perceived workload, are correlated to the capability of the emergency response staff to coordinate and monitor the execution of all the measures intended to deal with the industrial accident and its effects. A renovated perspective on human factors can provide powerful insights and guidelines to industrial plants' hazard assessments, to the research of safety competences and skills, the assignment of tasks to the workforce and the design of emergency protocols and regulations. Emergencies and major hazard situations are therefore an interesting application field where to explore what factors influence a person's ability to make good and rapid decisions.

Decision-making, communication, mental model sharing, leadership and coordination are critical skills to be used by the emergency response staff (Salas and Cannon-Bowers, 2000). Several authors postulate that decision-making in a crisis requires previous learning, and training exercises are therefore a classic way to help crisis management stakeholders to implement strategies with hindsight. The type of exercises carried out to train workers and enhance staff emergency preparedness are depicted in Figure 12. Periodical discussion sessions, tabletop exercises and functional or evacuation drills in which the employees discuss about or practice with the emergency protocols and actions use to affect positively the staff perception of safety inside the buildings and facilities (Vinodkumar & Bhasi, 2010). However, such methodologies provide just a theoretical knowledge of the emergency and evacuation procedures that are unlikely applied by the emergency team in the real emergency scenario. Live full-scale exercises would be the more preferable and trustworthy methodology but are unfeasible mainly because of the following shortcomings:

- Big preparation efforts are required to organize a one shot 'simulated' emergency scenario;
- All the potential courses of action of the training session must be predefined. This means that there is only a fixed storyboard that does not evolve dynamically and/or unpredictably;
- Disrupting events – e.g. fires, explosions – cannot be physically recreated in a real plant, therefore trainees are not face-to-face with the disaster;
- Few exercises can be carried out regularly because business continuity must be ensured. Live exercises require a lot of time and it is unlikely that employees have room for training days;
- Cooperative live and full-scale exercises require the concurrent mobilization of a large number of people (in time and space), which is rarely possible;
- Setting up the emergency scenario may be a quite expensive activity.

Pros and cons of the different types of exercise are clearly summarized in Tena-Chollet et al. (2017), which confirms that traditional exercises have a low effectiveness. They identify a roadmap and a set of recommendations is proposed in three domains: the teaching strategy, the simulation system, the training environment. It can be therefore concluded that safety competency research is highly necessary nowadays in major accident hazards industries (Lin-Hui et al., 2017). Current and future research should spend time in optimizing industrial plants' staff training (Schuermann & Marquardt, 2016) in the light of a renovated perspective on the crucial role of human factors.


(a) (b) (c)

(d) (e)

Figure 12: Emergency preparedness: (a) discussion sessions, (b) functional drills, (c) evacuation drills, (d) tabletop exercises, (e) full-scale exercises

2.3 Advances in Education & Training in Industry: Virtual Reality and Serious Games

Training methodologies and approaches to transfer knowledge are constantly reviewed and updated. Indeed, people learn, acquire information and communicate in different ways. A comprehensive taxonomy of the most used training methodologies is hereunder provided in Figure 13. In the current practice, training activities mostly avail from 'passive' approaches such as classroom or instructor-led training. Protocols, best practices, and rules are introduced and explained to the training audience by means of slides, manuals and frontal lessons. Interactive methods are also very popular but, unlike the first approach, they allow some degree of interaction between the audience and the trainer. In some cases, such classes are also delivered online, via the Internet, thus allowing the trainers and the trainees to be in different places during the class. These teaching approaches are well known by workers and traditionally accepted by many companies and organizations because of their economic affordability. However, it is unanimous that old style lectures are not effective and a lot of effort is needed to engage the trainees, to optimize the chance of keeping their attention, thus increasing learning. Indeed, the span of attention for the learning style 'just sit there and listen' lasts less than half an hour (Svinicki et al., 2014).

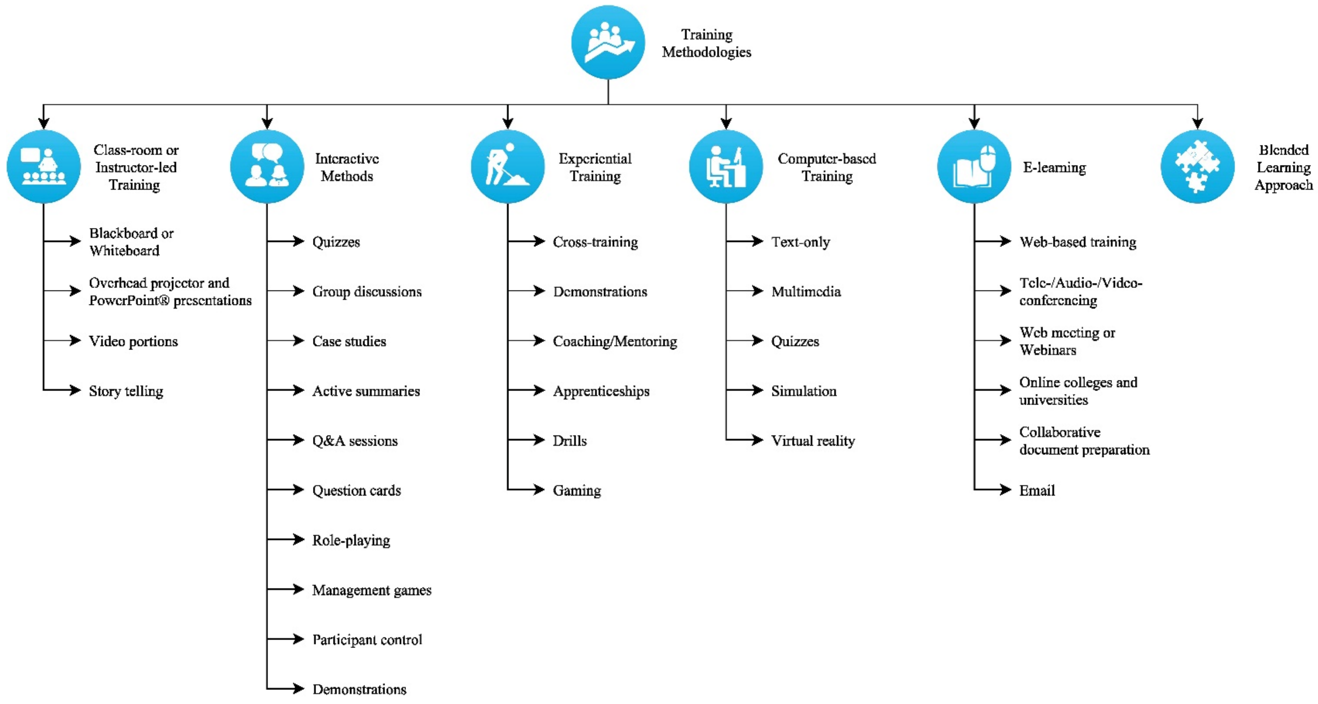


Figure 13: Training Methodologies Taxonomy

Learning is not just the result of cognition but involves the integrated functioning of the total person – thinking, feeling, perceiving and behaving. People have a 'preferred' sense among the five senses – in most cases visual, auditory or kinaesthetic (feeling via the body) – the one that they also engage in learning. The trainer should accommodate all categories by including in a training session not only auditory and word elements (i.e. the traditional lecture), but also visuals (e.g. whiteboard, flipcharts, videos) and kinaesthetic elements (learning by doing, feeling, trying it out). Any good training should be a mix of these four as suggested in the VARK model (Fleming and Mills, 1992). In addition, the trainees should be then engaged in a process that includes feedback on the effectiveness of their learning efforts.

On this wake, David A. Kolb pioneered the concept of Experiential Learning in 1984, even though, as early as 1938, Dewey referred to this relatively modern concept in terms of 'theory of experience'. He stated that it is not sufficient for the trainer or teacher to merely transmit information to the student or for the student to participate in active tasks. Education and training need to be grounded in experience, and experience needs to be accompanied by the student's active reflection on his or her experience. The Experiential Learning theory, which has been inspired by the work of Kolb, Dewey, Piaget, Lewin and many others, is in contrast with the 'transmission model of knowledge', which most training methodologies are based on, wherein pre-existing fixed concepts are transmitted to the trainee or student. The Experiential Learning theory instead posits learning as the process whereby knowledge is created through the combination of grasping and transforming experience and the assimilation of social knowledge as new personal knowledge. This approach includes different training methodologies, such as live demonstrations, coaching/mentoring, drills, gaming, etc. As suggested by Groenewald (2004), there is a variety of terms used to refer to the experiential learning, including field-based learning, on-the-job-learning/training, practice-orientated education, professional practice just to name a few.

In an emergency scenario that involves critical stakes, significant effects and limited reaction times, the decision-making process is mainly naturalistic (Shanteau, 1987, Means et al., 1993). This raises the following paradox: although an industrial accident is exceptional, decisions during its management strongly depend on previous experienced situations. The result is that live exercises test procedures, not people. Decision-making can only improve via some active process of engagement with the command and control task and by building a repertoire of patterns to increase individual 'experience' banks (Kolb, 1984; Klein and Wolf, 1995). Therefore, experiential learning appears to be the most suitable training technique in the case of industrial emergencies and accidents. While the faithful recreation of a major industrial accident to let people experience an emergency scenario is unrealistic, Modeling & Simulation and Computer-based Training have been reconsidering as powerful tools to mirror the real world.

2.3.1 Computer-based training: Modeling & Simulation

Representing the real systems via formal specifications (e.g. mathematical models) of a conceptualization and underlying assumptions and constraints that allow reproducing the dynamics of a complex system would allow exploring the system behavior in a way which is often either not possible, or too risky in the real world. Two phases are identified: while Modeling targets the conceptualization, Simulation challenges mainly focus on implementation; in other words, modeling resides on the abstraction level, whereas simulation resides on the implementation level.

The discipline of Modeling & Simulation (M&S), with application to Decision-making Support or to Education & Training, has emerged in the military industry, always considered as the pioneer of several civilian and business technologies. On the military front, Computer Assisted eXercises (CAX) propose to the participants synthetic crisis scenarios based on Modeling & Simulation paradigms where both civil units (ranging from firefighters, and medical teams to search & rescue teams) and military units (troops, helicopter units, littoral combat ships, etc.) are deployed. Here, the course of actions and events evolves according to artificial intelligence driven forces and to the commands from the exercise participants. CAX are deemed to be the only cost-effective, practical and safe way for testing well-established procedures, validating plans and develop civil-military-cooperation (CIMIC) competences, such as leadership, situational assessment, communication and coordination skills in special and hazardous environments. The notion of 'Train as you fight' is well established within the protocol-driven system of the military tactics and arts of warfare. Military CAX exercises can be considered as the most efficient platform for delivering educational content because it meets the core of the experiential learning theory. The analogy between the military context and the industrial emergency and accident management domain is therefore self-evident.

The effectiveness of M&S-based training has been widely investigated (Anon, 1994). Simulation-based experiential learning gives the trainees the opportunity to apply what they are learning as they are learning it (Bruzzone et al, 2007). Some M&S programs are indeed interactive, requiring trainees to answer questions, make choices, and receive real-time visual feedback about the consequences of their actions. The trainee's performance can be assessed in a synthetic environment created ad-hoc, which can reproduce a number of different scenarios. Unlike the real-world scenario, the synthetic environment is safe, and there is no danger for people acting there, for the property or for the equipment used so that the trainees can explore many possibilities and test the effects of different actions with no risk. The generation and evolution of disrupting events – e.g. fires, explosions – could be therefore physically and realistically recreated. As such, M&S based training would require very long training sessions that undermine the business continuity as concurrent mobilization of a large number of people (in time and space) is needed. Another advantage of M&S is the possibility to compress and expand time to allow the user to speed up or slow down simulated behavior or phenomena depending on specific needs:

- some training sessions can be set up to give trainees the possibility to make decisions and, later, receive the consequences and feedbacks of their decisions in the simulated environment. In this case, fast-time simulation can be used to shrink the training time.
- other training sessions may require the participants to interact with the simulated scenario in real-time as if it was in the real world. In this case, real-time simulation is the only suitable approach and configuring models to run in real time enables using hardware-in-the-loop solutions (Leitner, 1996).

Although these two approaches provide interesting benefits, they have never been coupled for developing applications in industry or other domains. Hardware-in-the-loop solutions are therefore still limited to the real-time simulation and cannot be integrated with fast-time simulation based applications.

In the latest few years, the digital revolution has started giving new impetus to industries worldwide and is revolutionizing the way people train and learn to cooperate. The application of M&S to support training in complex system has increased during the last years above all thanks to continuous simulation software and hardware development (Kim, 2005), which made available high-computing power machines also to the large public and not only to military forces. Indeed, M&S has revealed itself a powerful problem solving methodology (Banks, 1998) with successful applications in many application domains especially industry, logistics and supply chains (Piera et al., 2004). Moreover, the ideology of experiential learning provides then a fruitful basis for integration of M&S with other Industry 4.0 enabling technologies, such as Virtual Reality, to deliver an even more meaningful environment for personnel training.

2.3.2 Virtual Reality and Serious Games

The relevance of M&S coupled with Virtual Reality for Emergency Management has been recognized since 1995, when both the research community and practitioners have begun to appreciate the potential of this approach (Beroggi et al., 1995). However, it is only recently that research works demonstrated the capability of such measures to improve disaster risk preparedness more effectively than ex-post measures (de Hoop & Ruben, 2010). A virtual environment is intended to replace the real world environment with the digital one where the human senses are immersed, thus fully implementing the concept of experiential learning. Immersion is an experience of losing oneself in the virtual environment and shutting out all cues from the physical world. Thanks to user-friendly devices and advanced immersive technologies, simulation-based training programs are more and more easy-to-use even for not very computer-literate trainees and students. Several Virtual Reality technologies and hardware (e.g. the Oculus's headset, Rift, the HTC Vive, the PlayStation VR) are growing immensely and moving toward the mainstream. But the only immersive visualization technologies are not enough to instill in the end-user the feeling of living in the simulated environment. More and more senses have to be involved in the training: that is why high quality surrounding sound equipment, hand- and arm-tracking technologies and motion systems and platforms create more involvement in the virtual world and consequently shut down the cues of real world so that one feels a part of this virtual world (Hu et al., 2017).

In this sense, Serious Games well embody the experiential learning approach (Cohen et al., 2013) and increase drastically the slope of the learning curve (Sawyer & Rejeski, 2002). Serious Games offer an 'edutaining' experience, where educational content is delivered in an entertaining way and concepts and information are absorbed swiftly as consequence of a deeper and spontaneous participation and involvement of users (Osberg, 1995). Serious Games integrate models, scenarios, unexpected events, timed processes, roles, procedures, decisions, consequences, indicators, appropriate hardware (Crichton, 2009) and whatever it takes to permit a safe and full-immersive exploration of various accident scenarios with the rare but possible ripple effects. Trainees are required to 'play' a serious game where they use their skills (and improve them) in order to learn how to perform specific operations and procedures and manage correctly available resources, equipment and tools under stress condition. These considerations inform the conclusion that a Serious Game is particularly suitable when it is dangerous, as well as expensive, to carry out a Live Simulation or to let unexperienced people using real equipment and execute real operations in delicate situations. People are required to dynamically adjust their competencies to changing circumstances, thus providing them a meaningful context in which trainees can be proactive participants. Hence, an increased confidence in competencies and procedures effectiveness can be achieved (Davis et al., 2017). For example, Serious Games based training methods have been proposed successfully in many research works, to enhance fire safety skills while performing evacuation and rescue scenarios (Backlund et al., 2007; Cha et al., 2012), to train healthcare teams of mass-casualty incidents (Heinrichs et al., 2010), to provide a self-learning method to search for and rescue victims (Chittaro et al., 2009), or to teach the principles of disaster triage (Foronda et al., 2016; Dubovsky et al., 2017). As stated by Davis et al. (2016), the design and development of emergency response training systems based on cutting-edge methodologies (e.g. virtual reality, augmented reality, etc.) is still in its infancy. To this end, the recommendations by Tena-Chollet et al. (2017) draw a roadmap for future research in this field.

2.3.3 Distributed Simulation

The military concepts of intercorrectedness and interoperability among forces can be translated into organizational language as coordination and teamwork (for a definition, see Wilson et al., 2007) within an emergency team or crisis cell operating in case of a major industrial accident. Hence, individual or stand-alone simulation-based training is not enough: joint cooperative or collaborative training where participants actively interact with each other are needed. Interoperable and distributed simulation is the natural evolution of the current traditional training methodologies.

The defense sector is currently one of the largest users of distributed simulation technology. On the other hand, the current adoption of distributed simulation in the industry is still limited. It has been predicted that in the coming years, the sectors that will drive future advancement in distributed simulation are not only the defense sector, but also the high-tech industry (e.g. automotive, manufacturing), emergency and security management (Strassburger et al., 2008). Distributed simulations are typically composed of a number of sequential simulations where each is responsible for a part of the entire model. In distributed simulations, the execution of a system is subdivided in smaller, simpler parts that run on different processors or nodes. Each of these subparts is a sequential simulation, which is usually referred to as a logical processor. These logical processors interact with each other using message passing to notify each other of a simulation event. In other words, logical processors use messages to coordinate the entire simulation. This way, the distributed simulation produces the same results as if the simulation was performed sequentially in a single processor (Sokolowski & Banks, 2010). Distributed simulation has the huge advantage that large simulation programs, whose computation time would be prohibitive for a single machine, can be run on multiple processors, each working on a different portion of the simulation computation. Furthermore, the needs of the military establishment to have more effective and economical means to train personnel has driven a large body of work in developing virtual environments where geographically distributed participants can interact with each other as if they were in actual combat situations (Banks, 1998).

From a technological point of view, there are some issues to be addressed. The first one is related to let different heterogeneous simulation components interoperate with each other. To this purpose, several standards and protocols have been developed that support the interoperability and reuse of simulation modules. The Simulation Interoperability Standards Organization (SISO) provides an overview of a broad range of standards. By the 1980s, the need of performing cost-effective distributed simulation started to be used at the U.S. Department of Defense (DoD) to simulate war games (Lenoir & Lowood, 2005). In the mid 1980s, SIMNET became the first successful implementation of a large-scale, real-time, man-in-the-loop simulator networking for team training and mission rehearsal in military operations. The earliest successes that came through the SIMNET program was the demonstration that geographically dispersed simulation systems could support distributed training by interacting with each other across network connections. The Aggregate Level Simulation Protocol (ALSP) extended the benefits of distributed simulation to the force-level training community so that different aggregate-level simulations could cooperate to provide theater-level experiences for battle-staff training. The ALSP has supported an evolving ‘confederation of models’ since 1992, consisting of a collection of infrastructure software and protocols for both inter-model communication and time advance. At about the same time, the SIMNET protocol evolved and matured into the Distributed Interactive Simulation (DIS) Standard. DIS allowed an increased number of simulation types to interact in distributed events, but was primarily focused on the platform-level training community. DIS provided an open network protocol standard for linking real-time platform-level war-gaming simulations. In the mid 1990s, the Defense Modeling and Simulation Office (DMSO) sponsored the IEEE 1516 High Level Architecture (HLA) standard. Designed to support and supplant both DIS and ALSP, investigation efforts were started to prototype an infrastructure capable of supporting these two disparate applications. The intent was to combine the best features of DIS and ALSP into a single architecture that could also support uses in the analysis and acquisition communities while continuing to support training applications. The DoD test community started development of alternate architectures based on their perception that HLA yielded unacceptable performance and included reliability limitations. The real-time test range community started development of the Test and Training Enabling Architecture (TENA) to provide low-latency, high-performance service in the hard-real-time application of integrating live assets in the test-range setting. TENA, through its common infrastructure, including the TENA Middleware and other complementary architecture components, such as the TENA Repository, Logical Range Archive, and other TENA utilities and tools, provides the architecture and software implementation and capabilities necessary to quickly and economically enable interoperability among range systems, facilities, and simulations. Similarly, the U.S. Army started the development of the Common Training Instrumentation Architecture (CTIA) to link a large number of live assets requiring a relatively narrowly bounded set of data for purposes of providing After Action Reviews (AARs) on Army training ranges in the support of large-scale exercises. As of 2010 all of the DoD architectures remain in service with the exception of SIMNET. Of the remaining architectures: CTIA, DIS, HLA, ALSP and TENA, some are in early and growing use (e.g., CTIA, TENA) while others have seen a user-base reduction (e.g., ALSP). Each of the architectures is providing an acceptable level of capability within the areas where they have been adopted.

Another important technological issue to underline is the latency associated with communications between processors and the degree of heterogeneity among the processors in the system. LAN-based machines typically have communication latencies on the order of a millisecond, whereas WAN-based machines have latencies of tens or hundreds of milliseconds or more. Communication latency is important because it can have large impacts on performance; if latencies are large, the computers may spend much of their time waiting for messages to be delivered and synchronization would fail.

Depending on the specific needs of a project sponsor, distributed simulation system architectures and different interoperability standards have started to be applied in a limited manner in Industry. For example, distributed and interoperable systems have been developed to face the problem of operative and procedural cooperative training in marine ports with particular attention to harbor pilots and port traffic controller (Longo et al., 2015) or to support training of air traffic controllers by using interoperable systems reproducing traffic simulation, flight simulation and real time voice communications (Bagassi et al., 2008). The literature analysis has revealed very limited (sometimes only prospective analyses) application studies in the industrial domain (Hintze et al, 1999) and no application at all in a critical and challenging domain such as personnel training for industrial accident preparedness and emergency response.

3 Research rationale and proposal

Although considerable effort has been put into the design of hardware-oriented strategies and technological systems for preventing or mitigating a priori industrial emergencies, the need for effective industrial emergency preparedness and response training system is widely acknowledged from industry and academy. A great deal of time and effort is being invested to detect methodologies and approaches to enhance the effectiveness of training courses and enhance significantly, after repeated training sessions, the capability of personnel to cope effectively with major industrial accidents and emergencies. However, the complexity and unpredictability underpinning a major industrial accident scenario cannot be analyzed with traditional analytical methodologies. In this sense, the human factors play a crucial role. Human performance usually undertakes a strong decline under stress or overload conditions, which makes inapplicable the theoretical knowledge that has been learned during classroom-based training sessions. Today, despite the huge technological advancements and current potential of the integration of different Industry 4.0 enabling technologies, a comprehensive industrial emergency preparedness and response training system, which incorporates an effective training strategy, a flexible system architecture and a realistic training environment, is still missing.

Therefore, the motivation of this study is synthetized in the problem statement below and stems from the following question: 'how can major accident hazards industrial plants or high-risk industries guarantee the maximum effectiveness of their emergency management strategies and protocols as well as enhance their personnel preparedness in case of accidents?'

Problem statement

Major accident hazards industrial plants or high-risk industries lack of a dedicated training methodology and environment to enhance significantly the personnel rate of retention and emergency preparedness technical (i.e. procedural) and non-technical (e.g. leadership, decision-making, team-working, stress management) skills during training sessions.

Given the problem statement above, the study aims have been defined as follows.

Study aims

Study Aim #1: To propose a prototype of an innovative Industry 4.0 driven industrial emergency preparedness and response training system.

> **Study Aim #1.1**: To design an effective training strategy that complies with the characteristics of a major industrial accident and emergency scenario.
>
> **Study Aim #1.2**: To design and develop a system architecture based on the latest Industry 4.0 technologies that implements coherently the training strategy.
>
> **Study Aim #1.3**: To analyze and model the complexity of a major industrial accident scenario, including the disaster itself, the potential course of actions/events, the entities involved (e.g. personnel, external aids).
>
> **Study Aim #1.4**: To implement a system prototype that integrates the training strategy and a realistic training environment into a flexible architecture for repeated and configurable multi-player training sessions.

Study Aim #2: To demonstrate whether the developed industrial emergency response training system is capable of enhancing significantly the personnel rate of retention and emergency preparedness technical (i.e. procedural) and non-technical (e.g. leadership, decision-making, team-working, stress management) skills.

Study Aim #2.1: To design an experimental campaign that could potentially highlight the personnel improvement rate of technical and non-technical skills and capture (if any) the effects on performance and psychological pressure of replacing the partner.

Study Aim #2.2: To carry out structured experimentations and analyze the training results to assess after repeated training sessions.

- how the performance of the emergency manager and of the emergency team member evolve along the replications (see the Mission Fulfillment KPIs);
- to which extent the proposed training approach is effective in delivering procedural knowledge to emergency managers and emergency team members (see the Procedural Compliance KPIs);
- whether it is realistic enough to think that the training experience produces psychological stress in those people that are trained with it (the emergency managers and emergency team members) and how they cope with stress over the repeated replications (see the Psychological Stress KPIs);
- whether and to which extent human factors, such as stress and perceived workload, are correlated to the capability of the emergency manager to coordinate and monitor the execution of all the measures and actions intended to deal with an industrial accident and its effects.

With this in mind, the proposed research work recognizes the crucial role of training activities in implementing high performing response systems in industrial sites and takes a step forward proposing an Industry 4.0-driven solution for emergency response staff training. In order to achieve the aims of this study, the following has been hypothesized.

Hypothesis

A multiplayer industrial emergency preparedness and response training system, which leverages on Industry 4.0 enabling technologies – namely Simulation, Virtual Reality & Serious Games – and on a cooperative, experiential and differentiated training strategy, is capable to enhance in a statistically significant way technical (i.e. procedural) and non-technical (e.g. leadership, decision-making, team-working, stress management) skills of emergency personnel, with benefits on the rate of retention and the hands-on applicability of theoretical concepts related to the correct emergency protocols.

The thesis roadmap that guides through the different phases of the study (analysis, design, development, implementation, experimentation and analysis of the results) is illustrated in Figure 14.

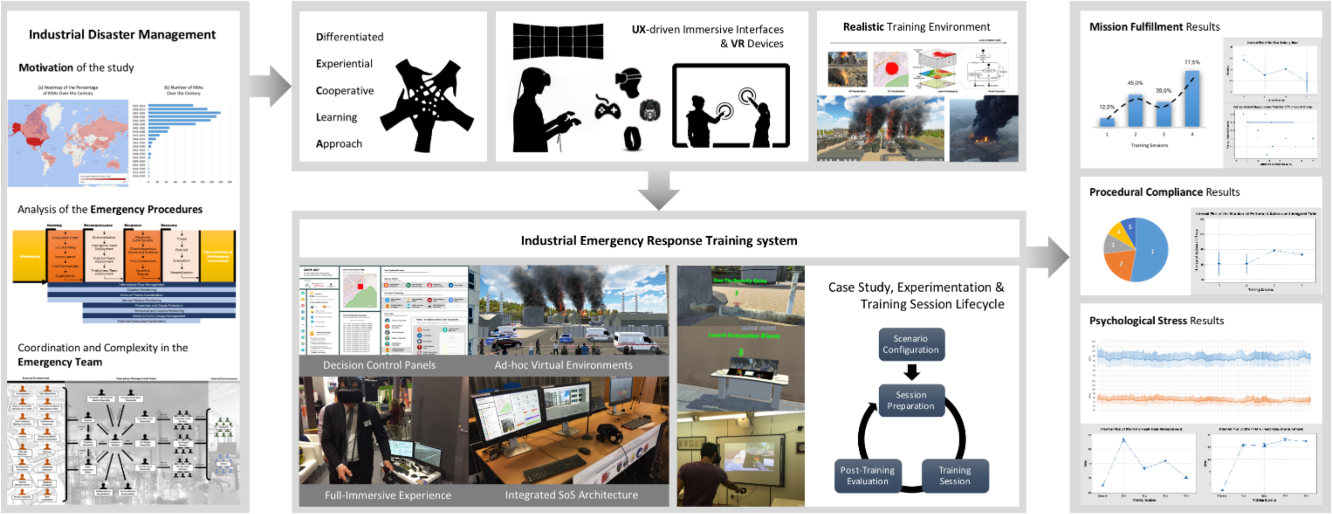


Figure 14: Research study roadmap

In accordance to this development roadmap, an industrial emergency preparedness and response training system has been designed and developed to serve as touchstone. It integrates a training strategy defined as cooperative, experiential and differentiated along with industry 4.0 enabling technologies and approaches such as Simulation, Virtual Reality, Serious Games, Immersive and Interactive technologies. It will be defined to extend the benefits of the experiential learning theory in the case of training for emergency preparedness and response in a way that a ‘personalized user experience’ together with the seamless cooperation among the players promote motivation, a learning attitude and heighten the rate of retention. Such training strategy has been embedded into the design of a system-of-systems architecture, which guarantees computational power (necessary in case of large-scale simulation) and distributed (even geographically dispersed) interoperability. The systems run a specific portion of the simulation and are connected and synchronized thanks to the IEEE 1516 HLA protocol for distributed simulation, which has been opportunely extended. The content is offered to trainees via user-friendly graphic interfaces and immersive devices (such as head mounted displays) while interaction data and performance are continuously recorded by motion trackers and heart rate variability monitoring devices. Realism is ensured, among others, by a realistic three dimensional graphics, a game logic based on standard emergency procedures, the disaster dynamics and the human behavior models. In order to provide evidence of the benefits of the usage of this system, a set of training sessions has been conducted. Data on the response of the trainees (the emergency manager and the emergency response team members) will be collected and statistically analyzed to answer to the research questions stated above based on scientific evidence. As stress has a psychological origin, it affects several physiological processes in the human body, including the heart rate that is used in this study as indicator of the stress levels of the trainees.

This study is the first in-depth investigation of the comprehensive learning outcome (intended as a combination of technical/procedural performance as well as of the magnitude of the psychological pressure evoked by the ‘collaborative’, ‘stress-generating’ and ‘decision-centered’ aspects of an industrial emergency response), thus confirming the real and value-adding potential of the proposed system.

4 Materials and Methods

Although a full-sensorial synthetic training experience is still chimeric, the latest technological and methodological advances can provide a fertile soil where new training strategies can sprout up. This chapter provides a full description of the methodologies, of the conceptual and mathematical models, of the system implementation and of the stress and workload assessment methodologies. As the case study has been provided by a well-known Italian company and because of a confidentiality agreement, a detailed description of the context in terms of operational processes, past accidents and past performances of the emergency response team cannot be fully disclosed.

4.1 A training strategy for industrial emergency preparedness and response training

Starting from the benefits of experiential learning, an innovative strategy has been defined to best fit the characteristics of an industrial emergency preparedness and response training. The proposed training strategy is based on Cooperative, Experiential and Differentiated Learning:

- Cooperative, because many actors are called to act simultaneously, cooperating and coordinating themselves;
- Experiential, because it entails user-centered learning processes where people act and interact in a simulated environment gaining situational awareness and experiencing the outcomes related to individual as well as collective actions/inactions;
- Differentiated, because a ‘differentiated’ approach is needed for strategic operators (emergency managers) and field operators (emergency team members) that are simultaneously trained.

A personalized training experience that responds to the role played by the trainee together with the seamless cooperation among the trainees are required to promote motivation, a learning attitude and to heighten the rate of retention. In accordance to the principles of the experiential learning theory, trainees should be able to play the role of one of the emergency team members, be capable of practicing all the possible tasks in a synthetic environment in a spontaneous manner, to make choices in terms of timing and order of execution, and receive a real-time feedback in order to enable them to proactively adjust their behavior (and performance) according to the scenario evolution. The experiential training experience will be carried out by using virtual reality equipment and head mounted displays (e.g. Oculus Rift or the HTC Vive) that transmit the user the sense of being there. In order to understand whether the trainee playing the role of the emergency manager or emergency team member is truly immersed in the training environment and feels some kind of stress, heart rate measurements (expressed as beats per minute, bpm) will be collected.

The players will be then asked to perform the emergency protocols, intended as a sequence of actions, timely and correctly, depending on the evolution of the course of actions in the serious game. Only if the players will execute the actions described above correctly, the serious game will move towards a resolution. Actions that differ from the general sequencing described above will slow down the operations and jeopardize the whole scenario. The trainees playing the role of the emergency team members are required to execute (effectively and efficiently) the tasks the emergency manager requested them to do. What is more, tasks should be assigned to the right people. The emergency manager should be able to command the emergency response team members to execute even an unsuitable task, thus compromising the efficient and quick management of the situation. To give an example, emergency team members that are part of the medical team have usually little or no skills in making a reconnaissance tour in the plant as well as the internal fire brigade is not suitable for first aid activities. During the emergency response, low-efficiency actions (that depends on the match between the competencies required for executing the action and the actual emergency response team member's skills) must be then reduced as much as possible. The serious game logic is also very flexible in terms of stochasticity: it may happen (in the virtual environment as in reality) that, for example, some members of the emergency response team will remain injured in the accident during the game or that the external aids are slow in coming. The emergency manager and the members of the emergency response team are asked to cope with unexpected difficulties that may come up.

Most of these aspects are affected by the cooperation attitude among the operators who have to share opinions and information, practice the best action strategy and work together to achieve effectively and timely a common goal. In general, to work the emergency out successfully, an emergency manager is asked to foster a 'cooperation' attitude with and among a number of emergency response team members forming his staff. Some emergency response team members may also have their own team of people and can also interact with the external resources, such as firefighters, medical operators, police department. The training strategy should not merely be a multi-player training system, but should foster a cooperative aptitude among the trainees who have to share opinions and information, practice the emergency protocol and work together to achieve effectively and timely a common goal. Therefore, the training strategy requires a differentiated and personalized approach because strategic operators, such as an emergency manager, need to look at the whole picture, whereas field operators, such as the emergency response team members, need a closer analysis of the key performance indicators related to each specific task they perform. For this reason, the impact evaluation stage of the proposed framework leverages on a comprehensive set of Key Performance Indicators (KPIs) has been then defined to analyze the trainees' performances in a differentiated manner according to the training system goals. This must be regarded as one of the most important research effort; no other system includes a large and comprehensive set of performance indicators contemporarily used during the experimentations. They include:

- Mission Fulfillment KPIs (that show how the performances of the EM and of the ETMs improve significantly by the use of the system);
- Procedural Compliance KPIs (that show how fast the EMs acquire enough procedural knowledge to manage successfully an industrial emergency);
- Psychological Stress KPIs (that show whether the training environment effectively produces psychological stress and how EMs and ETMs cope with stress).

The KPIs for the emergency manager will be identified with an ordinal number following the acronym KPI-EM and are here below listed:

- Mission Fulfillment KPIs
    - KPI-EM1: Total real training time (minutes)
    - KPI-EM2: Total virtual (simulated) training time (minutes)
    - KPI-EM3: Final burning area (m^2)
    - KPI-EM4: Time to extinguish the fire (minutes)
    - KPI-EM5: Number of people left in the plant
    - KPI-EM6: Number of rescued people from the plant
    - KPI-EM7: Rescue operations duration (minutes)
    - KPI-EM8: Number of people found during a reconnaissance tour
    - KPI-EM9: Number of blocked and/or injured people
    - KPI-EM10: Number of people who received triage

  - KPI-EM11: Average time to check/unblock emergency exits (minutes)
  - KPI-EM12: Number of unblocked exits
  - KPI-EM13: Number of systems still up and running
  - KPI-EM14: Number of compromised systems
  - KPI-EM15: Number of disconnected systems
  - KPI-EM16: Number of systems disconnected manually
  - KPI-EM17: Number of systems disconnected automatically
  - KPI-EM18: Average time to disconnect the system (minutes)

- Procedural Compliance KPIs
  - KPI-EM19: Number of performed actions and assigned tasks
  - KPI-EM20: Delay in giving the general alarm (minutes)
  - KPI-EM21: Delay in giving the evacuation order (minutes)
  - KPI-EM22: Delay in calling police authorities (minutes)
  - KPI-EM23: Delay in receiving the police authorities (minutes)
  - KPI-EM24: Delay in calling the firefighters (minutes)
  - KPI-EM25: Delay in receiving the firefighters (minutes)
  - KPI-EM26: Delay in calling the medical aids (minutes)
  - KPI-EM27: Delay in receiving the medical aids (minutes)
  - KPI-EM28: Number of checked prioritized exits
  - KPI-EM29: Number of checked prioritized systems
  - KPI-EM30: Delay in performing triage (minutes)

- Psychological Stress KPIs
  - KPI-EM31: Heart rate measurement (bpm)

The KPIs for the emergency response team members will be identified with an ordinal number following the acronym KPI-ETM and include:

- Mission Fulfillment KPIs
  - KPI-ETM0: Total Time for executing all the assigned tasks (minutes)
  - KPI-ETM1: Time for issuing the evacuation alarm - 'Task #1' (minutes)
  - KPI-ETM2: Time for delimiting the danger area - 'Task #2' (minutes)
  - KPI-ETM3: Time for counting/checking the people in the safe zone - 'Task #3' (minutes)
  - KPI-ETM4: Time for calling the firefighters - 'Task #4' (minutes)
  - KPI-ETM5: Time for calling the medical aids - 'Task #5' (minutes)
  - KPI-ETM6: Time for calling the police authorities - 'Task #6' (minutes)
  - KPI-ETM7: Time for disconnecting the electrical system remotely - 'Task #7' (minutes)
  - KPI-ETM8: Time for disconnecting the pumping system manually - 'Task #8' (minutes)
  - KPI-ETM9: Time for preparing a quick report of the EM - 'Task #9' (minutes)

- Psychological Stress KPIs
  - KPI-ETM10: Heart rate measurement (bpm)

The overall training performance is defined as the percentage of success evaluated taking into account mission fulfillment and procedural compliance KPIs for the entire emergency response team (the emergency manager and of the emergency team member). Each KPI can be evaluated against target values collected by the company under consideration in the training session. If the KPI value is equal to the target it means a 100% achievement otherwise the percentage of achievement is calculated based on the ratio existing between the gap that has been identified and the target value. Hence the overall success rate in one training session for one group is evaluated as the mean value of the percentages of achievement for each KPI. For instance, considering the $\mathrm{EM}_{\mathrm{KPI}_1}$, the percentage of achievement $p\left(\mathrm{EM}_{\mathrm{KPI}_1}\right)$ can be evaluated as follows:

$$p\left(EM_{KPI_1}\right) = \begin{cases} 1, & EM_{KPI_1} \leq Target \\ 1 - \dfrac{\left|EM_{KPI_1} - Target\right|}{Target}, & EM_{KPI_1} > Target \end{cases} \tag{1}$$

Similar reasoning applies to the others KPIs. However, in general, the overall evaluation of a training session depends on whether the emergency manager was able to drive the disaster towards a fast resolution (meaning that the fire has quickly extinguished) and whether all the people have been evacuated and are safe (and no one is injured or died because of the team's negligence).

Serious games can be wearing for the users when the game presents an imbalance of challenge relative to the skill level of the players. To maximize their capability to absorb information, players must remain engaged over prolonged periods of time and need to feel part of the game. The game difficulty should match the skill level of the player, therefore, when the player is logging into the game for the first time, he/she is also asked to select a default difficulty level ('Easy', 'Normal', 'Difficult'). Slower propagation of harmful events (in probability terms), optimal support of the resources and extensive knowledge about the scenario will characterize the training scenario in case of default 'Easy' settings, whereas quick propagation of harmful events, mediocre support from the resources and scarce knowledge about the scenario will characterize the default 'Difficult' settings. If the player has played the game before, the last difficulty level of the game play will be loaded from a 'Training Session' database, where all the data for each player are stored.

Based on these features, the training strategy is defined as a general reference framework intended for all industrial sites that are willing to improve the performance of their emergency response staff or that are going to (re)design and implement a new response system. Thus, in the perspective of fostering a continuous improvement, the proposed framework takes on the shape of a Deming's cycle: Plan-Do-Check-Act as illustrated in Figure 15 .

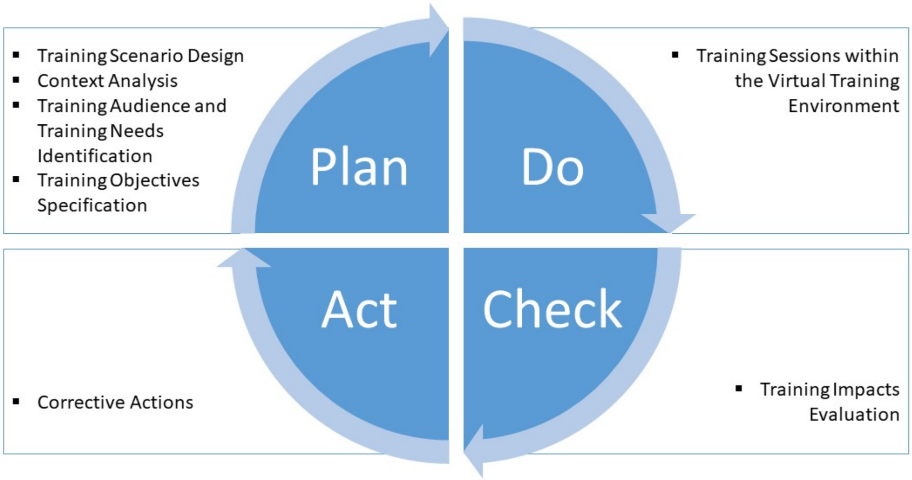


Figure 15: Training strategy based on a Deming's cycle

At the planning stage, the main building blocks of the training strategy include:

- Context analysis focused on roles, responsibilities, procedures, resources as well as historical records about past accidents;
- Identification of the training audience and related training needs;
- Specification of training objectives differentiated for different training groups;
- Design of a purpose-built training scenario that takes as inputs the context specifications detected along the context analysis, the specifications about targeted training groups and related training needs, and the training objectives for each training group.

The phase called 'Do' within the Deming Cycle, entails that the training environment (described in the next section) is set up in accordance with the specifications detected at the planning stage and is used to run the training scenario during training sessions. The 'Check' phase is focused on impacts evaluation and therefore is aimed at evaluating to which extent training goals are attained as well as training outcomes in terms of trainees reaction capabilities, learning, performances and behaviors. Further to this stage, corrective actions or areas of improvement may be detected to prompt a new revised training plan in terms of target groups, needs and training scenarios beginning the cycle again.

The ultimate goals of this strategy are the following:

- to recreate the complex conditions under which decision-making process usually takes place;
- to test and validate the emergency protocols;
- to monitor the evolution of the individual performance under stress conditions;
- to foster cooperation and teamwork in the event of a major industrial accident.

4.2 Contextual analysis: the industrial accident response protocol

Both practical experience and research have shown that emergency protocols should serve as a base upon which the training scenarios are constructed (Salas and Cannon-Bowers, 2001). In this case, we will focus the attention on the 'Response' phase of an industrial accident management lifecycle, depicted in Figure 16.

Figure 16: Industrial accident management lifecycle

The case of an industrial fire accident is considered but similar procedures (with certain differences) can be followed in case of other sources and causes of the accident. In order to respond effectively and efficiently to a major industrial accident, an emergency team (in the form of a task force) usually comes into play. This group of people, selected among the personnel of the plant, can change in size and roles depending on the plant dimensions, on the available resources and assets and on the local, national and international regulations and legislations. High communication, coordination and role specialization are demanded to the team members in order to cope successfully with the accident as illustrated in Figure 17. This is anything but simple because if we look into the roles in an industrial emergency team, it is apparent the heterogeneity of the team members. Emblematic is the role of the Emergency Manager or Incident Commander, 'the one who always has to look at the worst-case scenario or to say 'what if?". Although specific duties can vary significantly from company to company, the Emergency Manager is generally expected to direct the whole team – and more broadly, everyone inside the company premises with good, little or no knowledge about the emergency procedures – and make decisions quickly even on very inadequate information. The process of collecting further information might indeed be time-consuming and acting like a deer blinded by headlights might jeopardize the situation and imply severe material damage, injury to human beings and irreversible environmental impacts. Hence, the role of the Emergency Manager, struggled between subjective choices and observance of the emergency procedures, is characterized by the following tasks:

- coordination of the rescue operations;
- assignment of tasks to the emergency response team members and to act as a catalyst to get them together;
- prevents unauthorized people or vehicles to access the accident area;
- meets the external emergency response teams (firefighters, medical units, police etc.) once they get to the disaster area;
- counts and monitor the people who got to the safe zone.

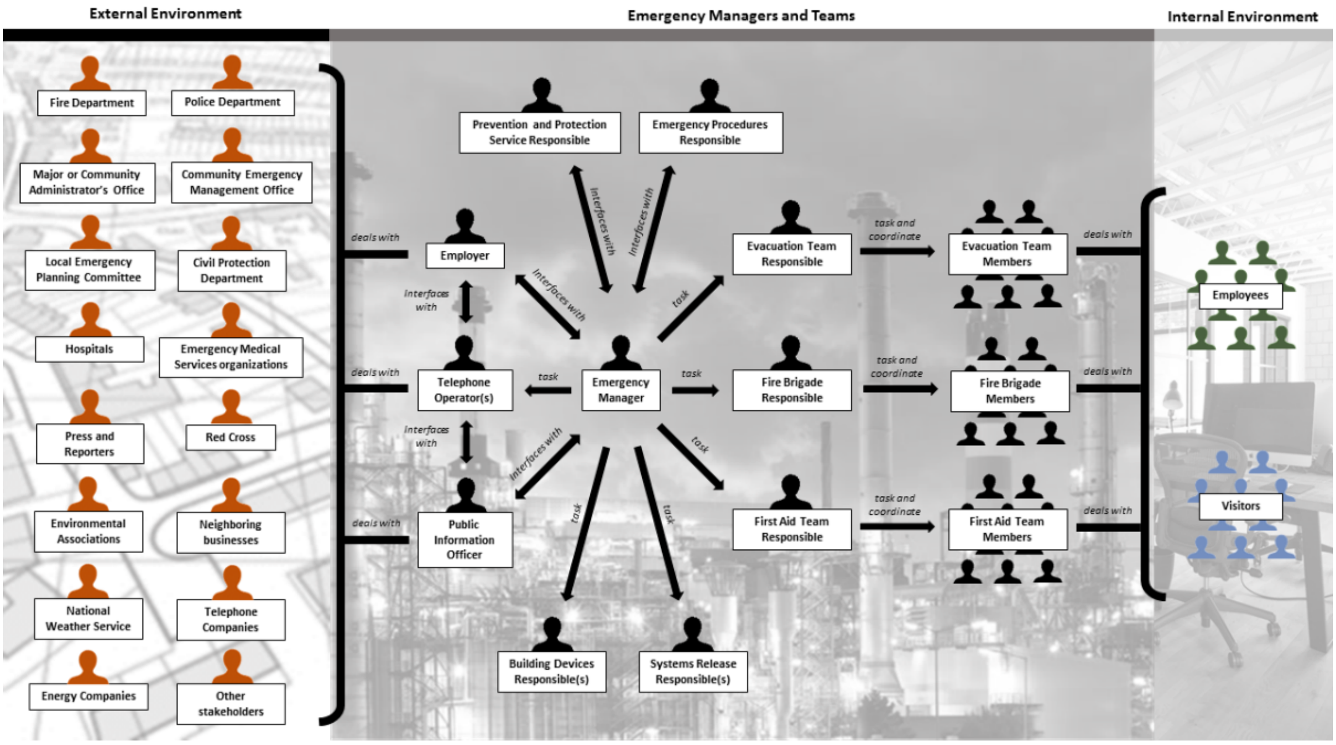


Figure 17: The emergency team and the cooperation patterns

Besides the Emergency Manager, the emergency team vary considerably from case to case (especially in size) but usually consists of the employer, field operators and control room operators whose roles and responsibilities are summarized in a synoptic manner in Table 5.

Table 5: Main roles and responsibilities of emergency response team members

Role	Main responsibilities and tasks
Employer	▪ makes inquiries about the accident evolution without hindering the rescue operations ▪ cooperates with the internal and external emergency response teams and provides them with useful information about the accident
First Aid Team	▪ provides first aid on the spot to the injured according to the training received ▪ ascertain the health condition of the injured people in order to provide as much information as possible to the external medical units ▪ takes care of the injured people until the external medical units arrive
Internal Fire Brigade	▪ intervenes on the spot with the fire extinguishers or other fire containment devices according to the training received ▪ issues the evacuation order and call the external aids in case the employer is missing ▪ helps the employees and operators in difficulty along the escape routes ▪ contains the fire as much as possible until the external fire brigade arrives
Telephone Operator	▪ calls the external aids according to the emergency protocols ▪ controls the entrance/exit of people in the dangerous area ▪ controls steadily the company's phone ▪ silences and filters all the communications not inherent to the accident

Emergency protocol responsible	▪ issues the evacuation order ▪ identifies the type of emergency ongoing ▪ tells the personnel the type of emergency ongoing by means of verbal communication or gestures
Systems Security Officer	▪ shuts off and disconnect all the systems in case of an emergency (e.g. electrical systems, pressurized valves etc.) ▪ tells the emergency manager when the systems have been secured ▪ gets to the safe zone when the systems have been secured
Media Relations Manager	▪ manages the communications with the stakeholders, public opinion, surrounding community and the mass media (e.g. journalists) who are on site to know about the accident

The emergency protocol (that will be later implemented in the system) to be activated in case of an emergency of major accident is below described and depicted in Figure 18. First is the 'Alarming' phase, when the emergency manager has to muster the emergency response team members and issue the evacuation order. The alarm is then collected by an operating center and forwarded to authorities and external aids. After an initial impasse situation (improvisation) usually pervaded by disorganization and panic, the emergency team need to design a possible action strategy. The 'Reconnaissance' phase then starts: the disaster is sectorialized, the resources are rationalized and damaged areas are delimited. Thereafter, the emergency team is expected to check shelters and emergency exits and to start initial safe reconnaissance of the facilities, to carry out fire containment activities where possible (made by the internal firefighters part of the emergency team) and the first aid internal team to prepare the medical post and execute triage on arriving people. The actual 'Response' starts when the external aids (e.g. firefighters, ambulances, resources from the civil protection, police authorities, etc.) arrive on site and, in cooperation with the Emergency Team, starts evaluating the main threats, estimating the number of people being involved in the accident and preparing mitigation operations. While the emergency team shuts down systems and try to secure hazardous materials, the external squads should start containing (and extinguishing) the fire and carry out search & rescue operations. Wounded people will be grouped in a secure area close to the plant called 'Collection Area', where they can be triaged. The final phase, called 'Recovery', considers the set of operations aiming to move the injured people from the 'Rescue Noria' to the 'Advanced Medical Post', from triage and first aid, to the medical post in situ and to an advanced medical post. As the objective of the health emergency is to create different circuits according to the triage code, rescue teams should use victims' selection criteria during the evacuation and mobilization to the nearest hospitals, thus allowing a timely hospitalization of critical cases. It should be also noted that an optimal emergency response requires additional transversal tasks to be executed by the emergency manager and the emergency response team members. It includes (i) the continuous monitoring and reporting of the disaster, (ii) the information sharing among different entities, (iii) the seamless coordination of all the available resources, and (iv) the management of human instinctive behavior and unpredictable reactions that may compromise or slow down the rescue operations. Starting from the Reconnaissance phase, the emergency team has also to secure properties, systems and goods, monitor the people clinical situation, to interact with the external aids and manage the relations with the external environment (media).

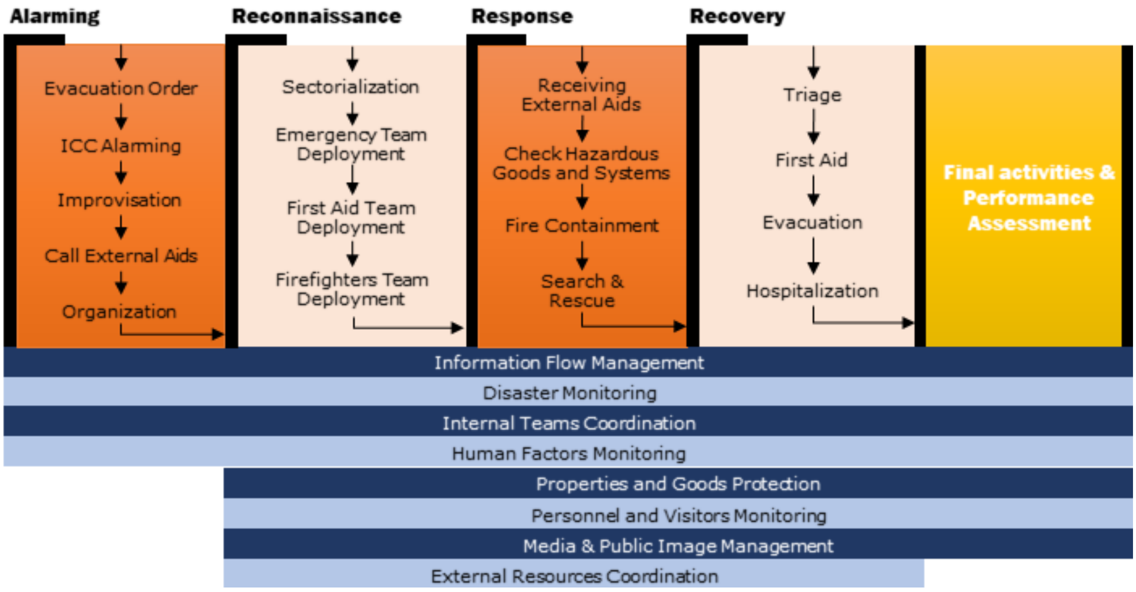


Figure 18: Industrial fire accident response protocol

According to the Deming Cycle, the training needs and objectives have been identified for the main roles within the emergency staff (the emergency manager, the internal fire brigade, the first aid team responsible, the emergency protocol officer). An analysis is provided in Table 6.

Table 6: Emergency response team's training needs and objectives

Roles	**Training needs**	**Training sphere**	**Training Objectives**
Emergency Manager	▪ Reaction capabilities ▪ Context awareness and analysis capabilities ▪ Information processing from multiple sources ▪ Coordination capabilities ▪ Contingency plan execution	▪ Procedural Skills ▪ Communication Skills ▪ Attitude Learning ▪ Performance Training ▪ Physiological Stress	▪ Understand the key factors of preparing for, responding to, and maintaining control throughout the development or escalation of an emergency ▪ Review, manage and assess the information available in an emergency in a timely manner ▪ Establish priorities and take effective action ▪ Implement predetermined emergency plans and procedures in the context of the current emergency ▪ Efficiently communicate information and instructions ▪ Communicate effectively with all appropriate external agencies ▪ Monitor and control resources ▪ Evaluate progress and communicate changes in plans and priorities ▪ Recognize and deal with stress in themselves and others

First Aid Team	▪ How to prioritize interventions ▪ How to execute First Aid procedures ▪ How to find and use First Aid equipment ▪ Incident reporting and communication	▪ Procedural Skills ▪ Communication Skills ▪ Attitude Learning ▪ Performance Training ▪ Physiological Stresses	▪ Know how to apply first aid in the workplace ▪ Manage medical emergencies ▪ responding promptly and appropriately to first aid situations and other emergencies ▪ be effective in reporting incidents, injuries and illnesses
Internal Fire Brigade	▪ Recognize the impact of fire ▪ Fire prevention measures ▪ Use extinguishing media, fire warning systems ▪ Checks on fire alarms and fire extinguishers ▪ Incident reporting	▪ Procedural Skills ▪ Communication Skills ▪ Attitude Learning ▪ Performance Training ▪ Physiological Stresses	▪ Know reporting procedures ▪ Know fire firefighting procedures ▪ Seize fire dimension and deploy available resources
Emergency protocol responsible	▪ Fire safety ▪ Electrical safety ▪ Chemical safety ▪ Equipment handling for security ▪ Accident and near miss reporting ▪ In-service inspection and equipment testing	▪ Procedural Skills ▪ Communication Skills ▪ Attitude Learning ▪ Performance Training ▪ Physiological Stresses	▪ Know safety procedures to be activated in case of emergency

4.3 Development of a training environment

The training environment is the place where the relevant knowledge is intuitively acquired (thanks to the possibility to make realistic concrete and active experiences) and the emergency-response capabilities are quickly developed. To reach this goal, the training environment is, at first sight, based on realistic 3D virtual environments and user experience driven graphic interfaces. However, this is only a minor part of the training environment and research effort behind it (that will be described later). Realism and experiential learning (as required by the teaching strategy) are first ensured by the capability to include a 'serious game' logic able to take into account emergency procedures and protocols (usually executed in case of disasters in an industrial plant). However, even this is not enough; the serious game logic only helps the operators involved in the training in understanding the main steps and scope of the training session. The feeling to experience a real-world emergency and to act (and react) as the operators usually do during a real emergency is mainly provided by:

- the dynamic evolution of the fire affecting the industrial facilities according to several configuration parameters (e.g. disaster's gravity, level of detail, weather conditions, etc);
- how the 'external' factors (e.g. police, ambulances, firefighters, etc.) may influence the evolution of the accident due to their behavior and mutual interaction;
- how the 'internal' factors (e.g. emergency manager, emergency response team members, employees, visitors) may influence the evolution of the accident due to their behavior and mutual interaction;

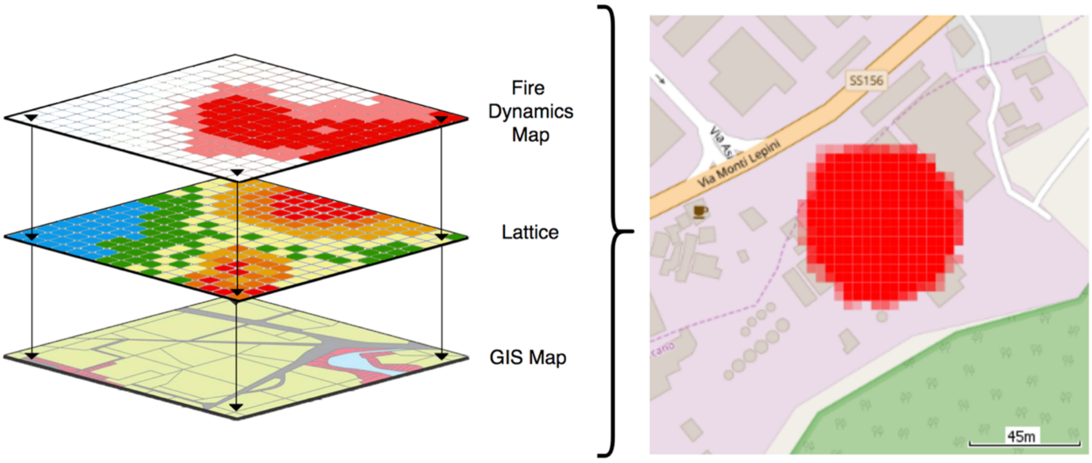
To reach this goal, a number of mathematical models have been developed to model and recreate correctly the complexity of the real-world events. The next sub-sections provide details on each single point.

4.3.1 A fire dynamics model based on stochastic cellular automata and particle systems

As the proposed disaster scenario is a fire in an industrial plant, the authors have worked extensively on the development of a fire dynamics model, which can ensure initial configurability, accuracy in the global dynamics and realism in the visualization.

The first issue to deal with when coping with the reproduction of a fire accident in industrial sites is the use of a reliable fire dynamics model. From a physical perspective, computational fluid dynamics is routinely used to analyze fire- and combustion-related phenomena (Yeoh & Yuen, 2009) but it is not applicable in fast-time experimental studies because it is too demanding in terms of time and computational power. Instead, despite of their simplicity, Cellular automata models provide a fictitious and discrete microscopic world reproducing the correct fire spread at a coarse-grained scale (Couce & Knorr, 2010; Almeida & Macau, 2011). A cellular automata model consists of a lattice, i.e. a uniform grid of cells, which represents the space, where each cell's state is updated synchronously according to a state transition rule in function of the state at the previous time step of a number of cells in its neighborhood (Chopard, 2009). To take into account the natural randomness in physical systems, stochastic cellular automata models have been introduced (Bušić et al., 2013) whose characteristics and computational power have been widely investigated (Schüle et al., 2009; Agapie et al., 2014).

The model is based on a squared two-dimensional lattice of dimensions $L_x \times L_y$, which covers the industrial plant area retrieved by using GIS data. The GIS data will serve as the first layer upon which the lattice is constructed as shown in Figure 19.



Lattice Structure **2D Visualization**

Figure 19. The layered structure of the stochastic cellular automata model

This geo-referenced voxel structure allows the instructor to set up in an easy way the fire seed, that is the exact geographical point where the fire is ignited (e.g. a tank in the plant). In this case, the temperature of all the voxels with the specified geographical coordinates increases until it exceeds the auto-ignition temperature of the related material. This does not mean that the game starts. Indeed, a warmup period for the training session is needed to allow the scenario evolving in a stochastic way. The instructor only sets up the 'warmup area', that is the area affected by the fire when the emergency team starts to intervene and the players will be allowed to start coping with the disaster when the following condition is met:

$$burning\ area\ \geq warmup\ area \tag{2}$$

In the case of the proposed study, a cell of the lattice represents a 2x2 m^2 area. Each cell (i,j) is defined by:

- its discrete position in the lattice, where $i = 1, \dots, L_x$ is the row and $j = 1, \dots, L_y$ is the column;
- its set of neighborhood cells $N(i,j)$, which comprises the eight cells (i^*, j^*) surrounding (i,j) according with the Moore neighbourhood $N(i,j) = \{(i^*, j^*) : |i - i^*| \leq 1, |j - j^*| \leq 1\}$;
- its state at time t, which is defined by:
  - its current temperature, $t_{(i,j)}^t$ (K);
  - the amount of flammable or combustible material, $q_{(i,j)}^t$ (kg), in the cell (e.g. wood, plastic, paper, fabrics, fuels). An example of distribution of combustible material is given in Figure 20. In this application, a cell is not supposed to include more than one kind of material but the lattice can include $P \geq 1$ materials.

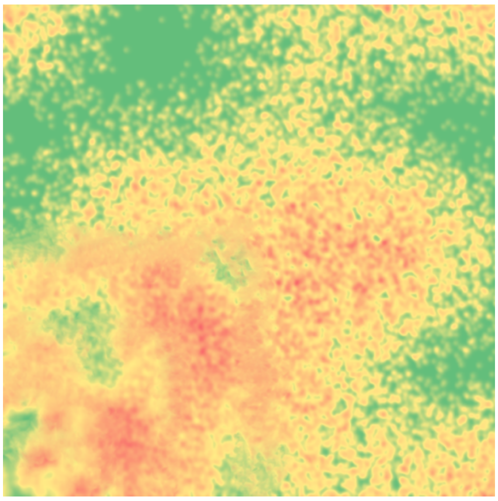


Figure 20: Example of the combustible map

The stochastic cellular automata model requires pre-calculating some parameters for each flammable and combustible material p, $\forall p = 1, \ldots, P$ present in the industrial plant area, including:

- the energy content, e_p (kJ/kg), which is the amount of energy stored in 1 kg of the material p;
- the rate of energy transfer, h_p (kW/kg), which is the amount of energy (kJ) released in 1 second during the combustion of 1 kg of the material p;
- the specific heat capacity, c_p (kJ/kg·K), which is the amount of heat (kJ) required to raise the temperature of 1 kg of the material p by 1 K;
- the expected ignition temperature T_p (K) at which the material is likely to ignite.

As a cell can contain only one material p, we can observe that the previous parameters can be easily referred directly to a cell. For example, if the cell (i,j) contain the material p, then $T_p = T_{(i,j)}$, i.e. the expected ignition temperature of the cell (i,j) is equal to the ignition temperature of the material p itself.

Moreover, the configuration of the model also requires the definition of the following data:

- the disaster's severity, modelled as $g \in [0,1]$, where 0 denotes a low severity whereas 1 denotes a high severity;
- the fire seed, which identifies the cell (or the cells) in the lattice where the fire starts;
- some relevant meteorological conditions (in the case the fire spreads even outside the buildings):
  - the rain intensity $r \in \{1,2,3,4,5\}$, where 1 denotes no rain and 5 denotes a heavy rain;
  - the wind intensity (knots) and direction (N, NE, E, SE, S, SW, W, NW).

The fire spread is here modelled as an energy diffusion process among neighboring cells made up of a series of sweeps. A sweep is a visit to all the cells of the lattice to update their state at time $t+1$ according to a state transition rule based on the state at time t of the cell itself and of the neighborhood cells.

The amount of energy (heat) released by a burning cell (i,j) per unit time containing the combustible material p is:

$$W_{(i,j)} = q_{(i,j)}^{t} * h_{(i,j)} \qquad (kW) \tag{3}$$

As time goes by, the amount of combustible decreases. If the cell ignited at the time t_i, the cell will cease to release energy (meaning that the cell has run out of p) at the time t_o to the neighbouring cells if the condition (4) is verified:

$$W_{(i,j)} * (t_o - t_i) = e_{(i,j)} \qquad (kJ) \tag{4}$$

$W_{(i,j)}$ is not the actual amount of energy released by (i,j) and transferred to the neighbouring cells per unit time, because a percentage of it will be dissipated due to ventilation as well as affected by meteorological conditions when the fire spreads outside of a building. The total amount of energy that is actually released and transferred successfully to the neighboring cells per unit time can be calculated as in (5):

$$W'_{(i,j)} = \omega_{(x,y)} * (1 - \delta - \rho) * W_{(i,j)} \qquad \forall (x,y) \in N(i,j) \tag{5}$$

In particular, δ represents the percentage of energy loss due to ventilation and is proportional to the wind intensity, whereas ρ represents the percentage of energy loss due to the rain intensity.

Generally, this energy is not homogeneously distributed to the eight neighboring cells (x,y), $\forall (x,y) \in N(i,j)$, because of the wind intensity and direction. Indeed, the fire would be more likely to spread in the direction of the wind rather than in the opposite direction. Therefore, we introduced in the model the parameter $\omega_{(x,y)}$, $\forall (x,y) \in N(i,j)$, as the percentage of $W'_{(i,j)}$ trasferred to (x,y) based on an arbitrary percentage factor dependent from the angle between the wind direction vector and the distance unit vector between (i,j) and (x,y). An example is provided in Figure 2, where the wind is headed SW (see the green arrow) and the different distance unit vectors are black-colored. When the angle between the wind direction and the distance unit vector is:

- 0 - see the cell $(i+1, j-1)$ - then the 20% of $W'_{(i,j)}$ is transferred to those cells;
- $\pi/4$ - see the cells $(i, j-1)$ or $(i+1, j)$ - then the 17,5% of $W'_{(i,j)}$ is transferred to those cells;
- $\pi/2$ - see the cells $(i-1, j-1)$ or $(i+1, j+1)$ - then the 12,5% of $W'_{(i,j)}$ is transferred to those cells;
- $3\pi/2$ - see the cells $(i-1, j)$ or $(i, j+1)$ - then the 7,5% of $W'_{(i,j)}$ is transferred to those cells;
- 2π - see the cell $(i-1, j+1)$ - then no energy is trasferred because it is in the opposite direction the 5% of $W'_{(i,j)}$ is transferred to those cells.

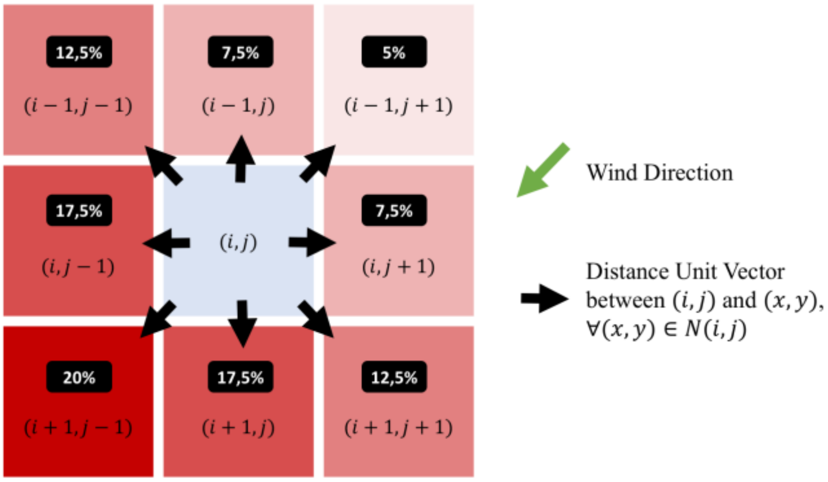


Figure 21. Example of energy distribution percentages due to the wind direction

While the energy is 'absorbed' by (x,y), the amount of energy needed to raise the temperature of this cell from T_1 to T_2 (Δk) can be calculated as:

$$U_{(x,y)} = q^t_{(x,y)} \cdot c_{(x,y)} \cdot \Delta k \qquad (kJ) \tag{6}$$

Based on (3) and (4), we can assert that the time Δt the cell (i,j) needs to raise the temperature of the cell (x,y) from T_1 to T_2 is given by:

$$W'_{(i,j)} = \frac{U_{(x,y)}}{\Delta t} \qquad \Rightarrow \qquad \Delta t = \frac{U_{(i,j+1)}}{W'_{(i,j)}} \tag{7}$$

Obviously, the temperature of the cell (x,y) is influenced by the amount of energy (heat) released by all the neighboring cells - not only (i,j), therefore:

$$\Delta t = \frac{U_{(x,y)}}{\sum_{(a,b)\in N(x,y)} W'_{(a,b)}} \tag{8}$$

Notwithstanding, in the present stochastic cellular automata model, the cell's ignition process is not deterministic, i.e. the cell (x,y) catches on fire as soon as its temperature is equal to or rises above $T_{(x,y)}$. The ignition process is stochastic because the probability to catch on fire varies based on the cell's current temperature and on the disaster's severity g. Logistic functions are widely used in logistic regression to model how the probability p of an event may be affected by one or more explanatory variables (Sperandei, 2014). This basically means that, when the temperature of a cell (i,j) is equal to $t^t_{(i,j)}$, it is likely to catch on fire with a probability $P_i\left(t^t_{(i,j)}\right)$ according to the following S-shaped logistic function:

$$P\left(t^t_{(i,j)}\right) = \frac{U}{1 + Ae^{-Bt^t_{(i,j)}}} \tag{9}$$

where:

- U is the curve's upper asymptote that can be shifted upward and downward on the basis of the disaster's severity, g. For the purpose of this application:

$$U = 0.5 + \frac{g}{2} \tag{10}$$

so that, for a given cell (i, j) and at a specific time t:

  - when $g = 0 \Longrightarrow U = 0.5$;
  - when $g = 1 \Longrightarrow U = 1$.

- A is determined from (7), where we suppose that $U = 1$ and that at $t_{(i,j)}^{t} = 0\ K$ the probability to catch on fire is close to zero (0,01%):

$$P(0) = \frac{U}{1 + A} = 0{,}0001 \tag{11}$$

- B represents the steepness of the curve and can be determined if we suppose that the cell has the probability of 50% to catch on fire in correspondence of the expected ignition temperature $T_{(x,y)}$. As the coordinates of the inflection point are $(lnA/B\,, U/2)$, then:

$$B = \frac{lnA}{T_{(x,y)}} \tag{12}$$

Some resulting ignition probability functions for 3 different materials - with expected ignition temperature equal to 600 K, 800 K and 1000 K respectively - and for a disaster's severity equal to 0, 0.5 and 1 are provided in Figure 22.

Some assumptions have been done to keep the model simple, such as the fact that a cell transfers heat only to the Moore neighboring cells and not to the other ones nearby. However, the potential of this model is the reduced computational power required to run it fast-time.

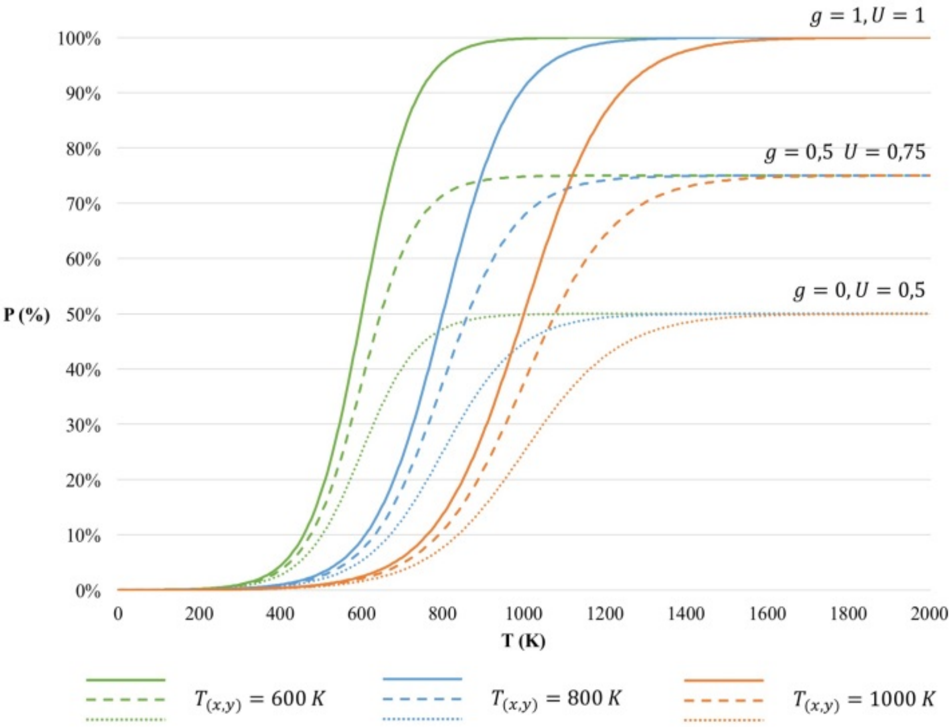


Figure 22. Ignition probability for materials with different temperatures and with different disaster's severity

This mathematical model has been translated into a computer-readable format. The statechart illustrated in Figure 23 summarizes the event- and time-ordering of states describing how the state of a cell of the lattice evolves over time by certain conditions (timeouts, messages received or Boolean conditions). A brief description is provided. A cell catches on fire once it receives a message 'ignition'. As soon as it starts combusting, the cell enters the composite state 'Burning'. An internal transition, called 'spreadFire', has been used to model the spreading of the fire over the neighboring cells. Since it has both start and end points in the same composite state, it is defined as a recursive method executed with a predefined low rate (1 per second) until the cell is burning. If the condition on the fire spreading probability is met, the 'ignition' message is sent to the considered neighboring cell. The inner states, namely 'FireLevel' and 'MaximumLevel', have been used instead to model the amount of energy released by a burning cell and the temperature evolution of the cell itself. If the temperature goes down to zero it means that the fire in the cell has been extinguished and the cell enters the 'savedOut' state. If the cell reaches the maximum temperature and keep that temperature for a given time (depending on the material in that cell), it will burn out completely.

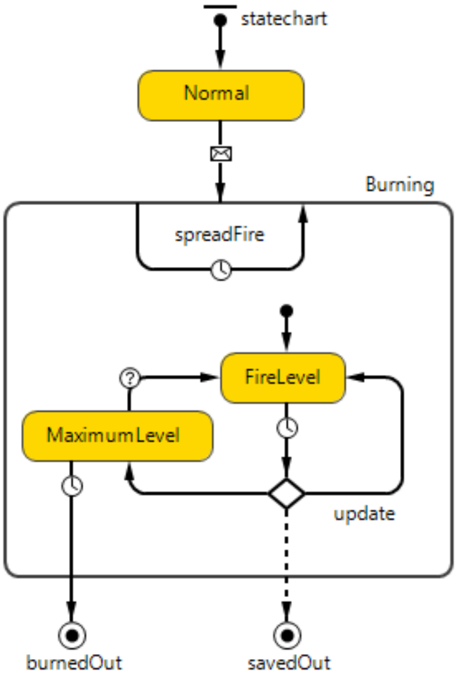


Figure 23: Modeling the cell dynamics as a statechart

Particle system technology has been used to visualize the flames and smoke in the 3D virtual environment (as showed in Figure 24) and the fire-extinguishing fluid (as depicted in Figure 25). This modeling approach allows us to set up external forces (which represent the meteorological phenomena, e.g. wind intensity and direction, rain intensity, the fire-extinguishing fluid etc.) that tend to push down the particles of the fire. Concerning the number of particles, the flames and smoke particle systems dynamically adjust to the number of burning cells. If a certain ratio of the lattice is burning, the size of the particle system in that specific area grows and the emission rate rises. If the cell is hit by particles of the rain particle system or of the fire-extinguisher fluid, the emission rate and the amount of burning cells decreases.

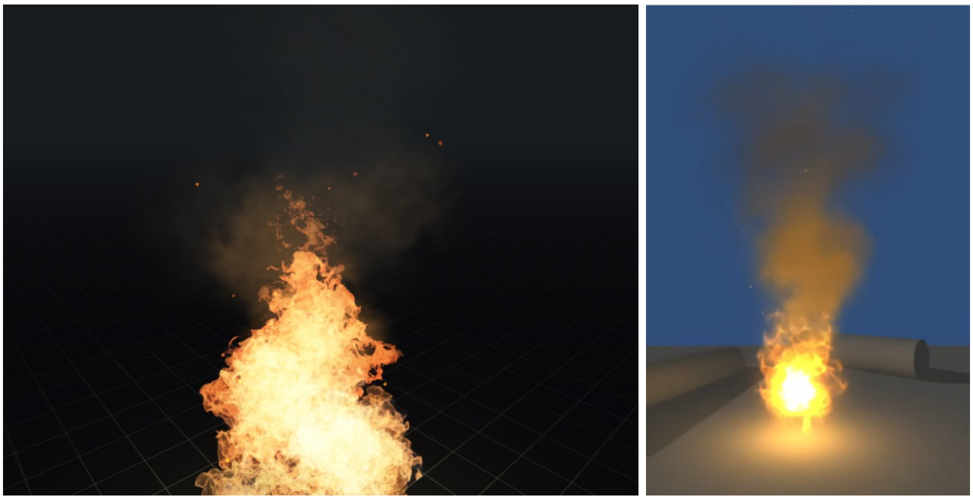


Figure 24: Example of flame particle system in Unity 3D

Figure 25: Using particle system technology for the fire extinguishing fluid

Figure 26 shows two triggering events of a major accident in an industrial facility of the training environment developed in the context of this study. Particle system technology appeared to be a very realistic approach to visualize flames, smoke, flares and easy to configure based on the input data of the stochastic cellular automata.

Figure 26: Example of flame particle system in an industrial environment

4.3.2 External agents: integrating a multi-agent and discrete-event based serious game logic

The training environment has to include also all the resources, external to the industrial plant, that come into play when a major industrial accident occurs (see Figure 27). The training system should allow the training session facilitator to configure multiple (from 1 to n) fire stations, hospitals, Civil Protection headquarters, Carabinieri stations and local police stations. Each of these 'resource pools' contains multiple (from 1 to n) resources of different type that can be deployed on the emergency site in the virtual environment.

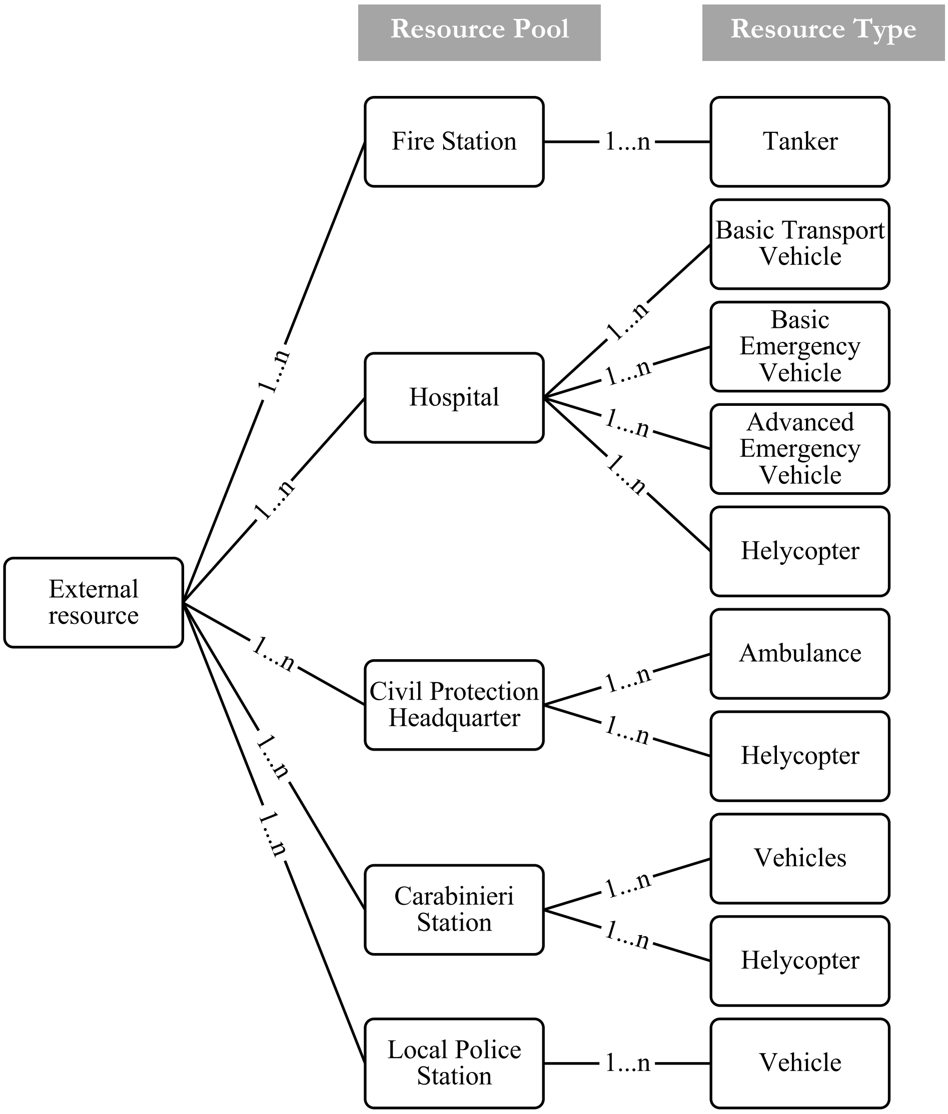


Figure 27: External resource pools and types in the training environment

The behavior of these resources, their mutual interaction and their interaction with the environment has been defined based on a multi-paradigm model that combines the multi-agent based approach and the discrete-event based approach. The choice of these two paradigms depended on how time and behavior have been modeled. Time is represented in simulations in two common ways: discrete-event and continuous. In discrete-event simulation, time jumps from event to event in discrete steps, and there is a sudden change in at least one of the system state variables. In continuous simulation, models are defined by differential equations that allow both the state and the simulation time to change smoothly and continuously. Instead, behavior in a simulation needs to capture how the system being modeled will change in the future, given its present state. Agent-based simulation and system dynamics are commonly used approaches for modeling behavior. Agent-based simulation is used to represent the actions and interactions of autonomous agents (e.g., individuals or organizations) with a focus on assessing the effect that the agents' behavior might have on the system as a whole (e.g., how do individual drivers' behavior affect traffic). System dynamics is an approach to understanding the behavior of complex systems over time. It deals with feedback loops (when information about the past influences the system's behavior in the future) and time delays that affect the behavior of the entire system (e.g., cause-and-effect relationships of traffic congestion and air pollution). Agent-based simulation and system dynamics are paradigms more focused on how to model behavior, which means that they are not bound to a specific approach for managing time. In other words, they can use either discrete-event or continuous time approaches. In the case of this study, agent-based simulation has been combined with discrete-event simulation paradigm. On one side, agent-based models give the possibility to build complex social structures from the bottom-up: an agent type has been created for every external resource with a dedicated and unique 'behavior'. Conceptual models have been developed by means of statecharts and flowcharts representing their behavior according to the evolution of the events. On the other side, the discrete-event modeling paradigm allows to translate in programming code the emergency protocols previously described and to provide the basis for the time-stepped and event-stepped evolution of the emergency scenario.

The high-level behavior of the external resources in the virtual environment is illustrated in the following by means of swim lane diagrams that provides an overview of the discrete-event sequence of actions.

In general, the request of resources comes from the accident site (for example from the telephone operator) or from another station or hospital that has not enough resources available. If the resources are not enough, other requests are sent to close stations or hospitals.

In the case of a fire station (illustrated in Figure 28), the resources are the tankers and firefighters. Once called, they prepare and then move to the accident site, where they first meet with the emergency manager for a general update about the situation. Next tankers do not need to meet the emergency manager but they can start fighting the fire immediately. The overall process is identical for the local police station (see Figure 29), which sends vehicles and police officers to surveil and secure the area surrounding the disaster zone. Slightly different is the behavior of the Carabinieri stations, depicted in Figure 30, because they may have at their disposal also helicopters to surveil the area from the top and to transport (if need be) red code-injured people to the closest hospital.

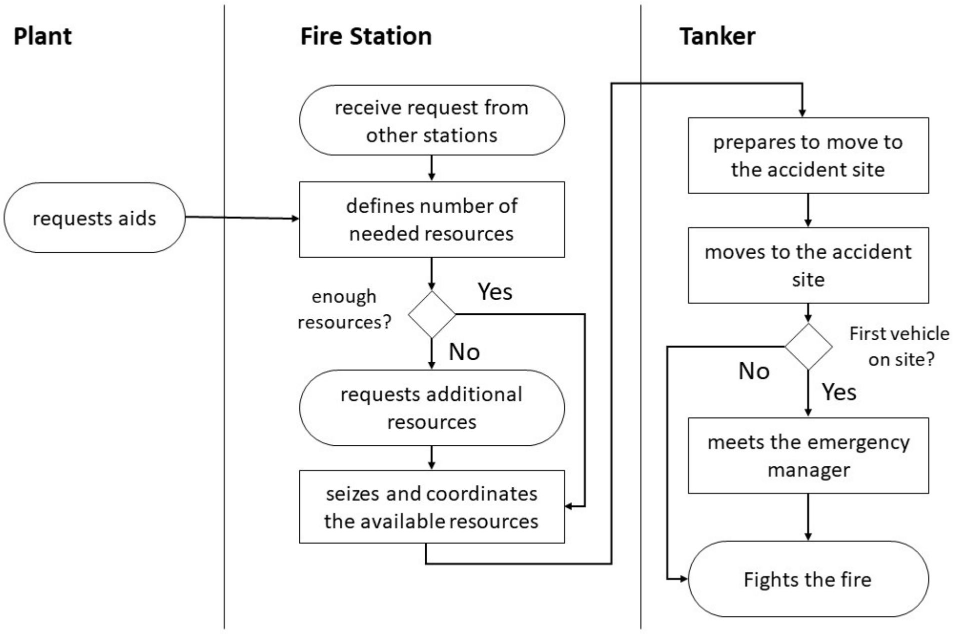


Figure 28: Fire station’s resources: swim lane diagram

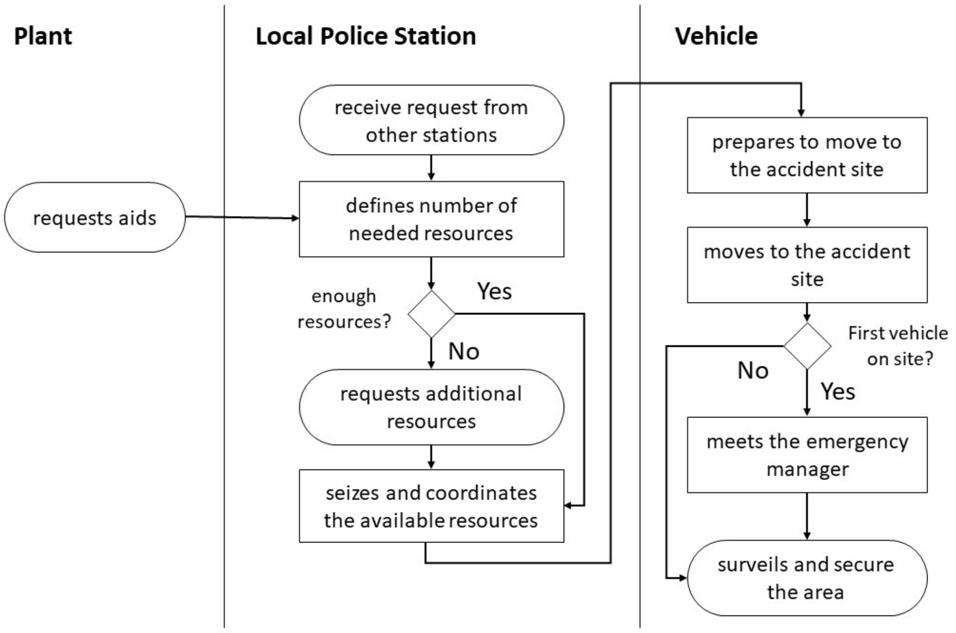


Figure 29: Local Police station’s resources: swim lane diagram

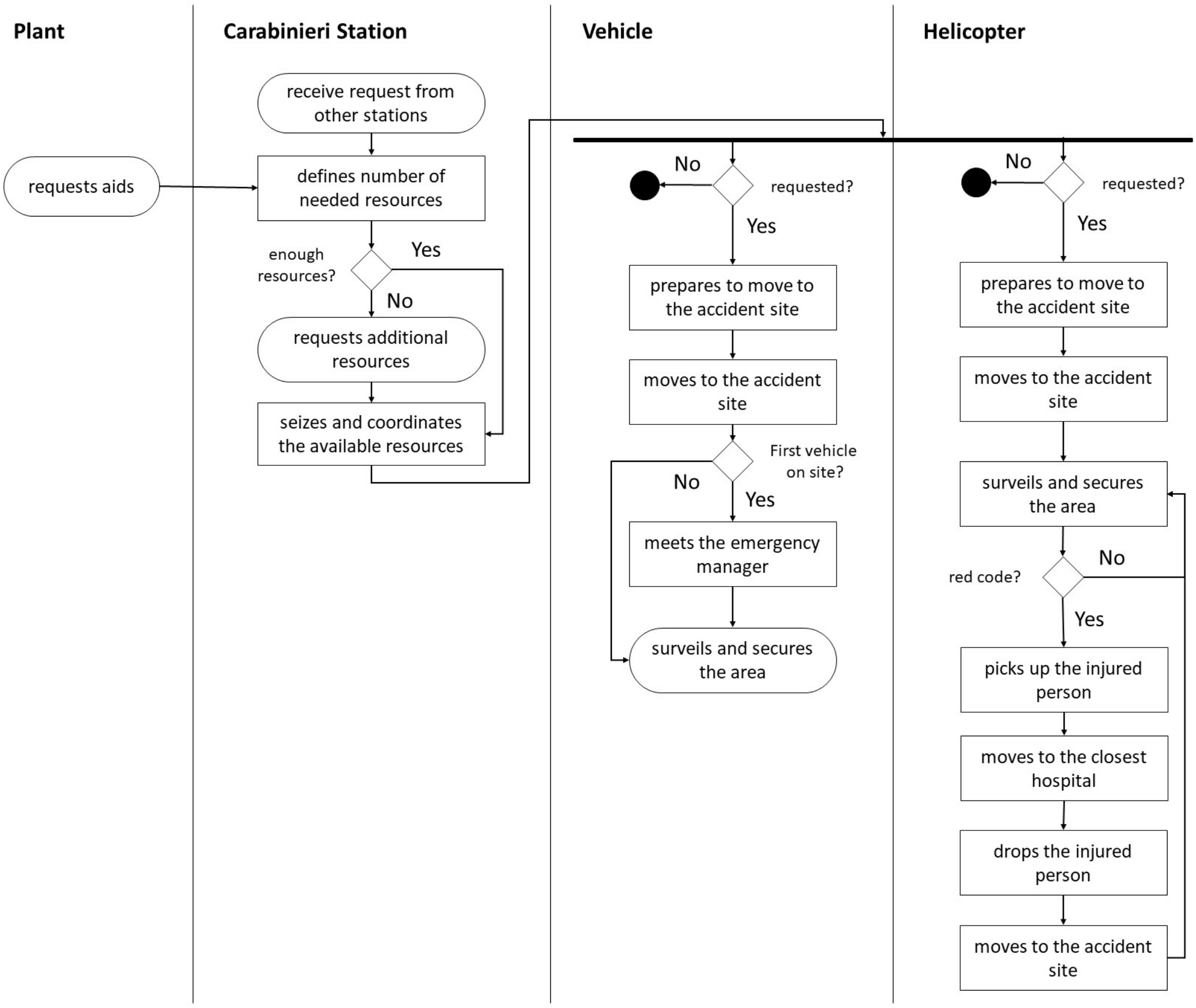


Figure 30: Carabinieri station's resources: swim lane diagram

Civil Protection headquarters and hospitals have instead ambulances and resources with medical skills to help the wounded and injured people at the accident zone. Ambulances and helicopters move to the collection area, next to the spot (the accident site), where it is possible to group the wounded people through Triage system. The Triage is the process of determining the priority of patients based on the severity of their condition:

- white code (no health or mobility issues);
- green code (secondary urgency);
- yellow code (primary urgency);
- red code (extreme urgency);
- black code (deceased).

Unlike the civil protection headquarters (that only have basic emergency vehicles), hospitals can have:

- Basic Emergency Vehicle that are assumed to treat only green codes;
- Basic Advanced Emergency Vehicle that are assumed to treat yellow codes first;
- Advanced Emergency Vehicle that are assumed to treat red codes first.

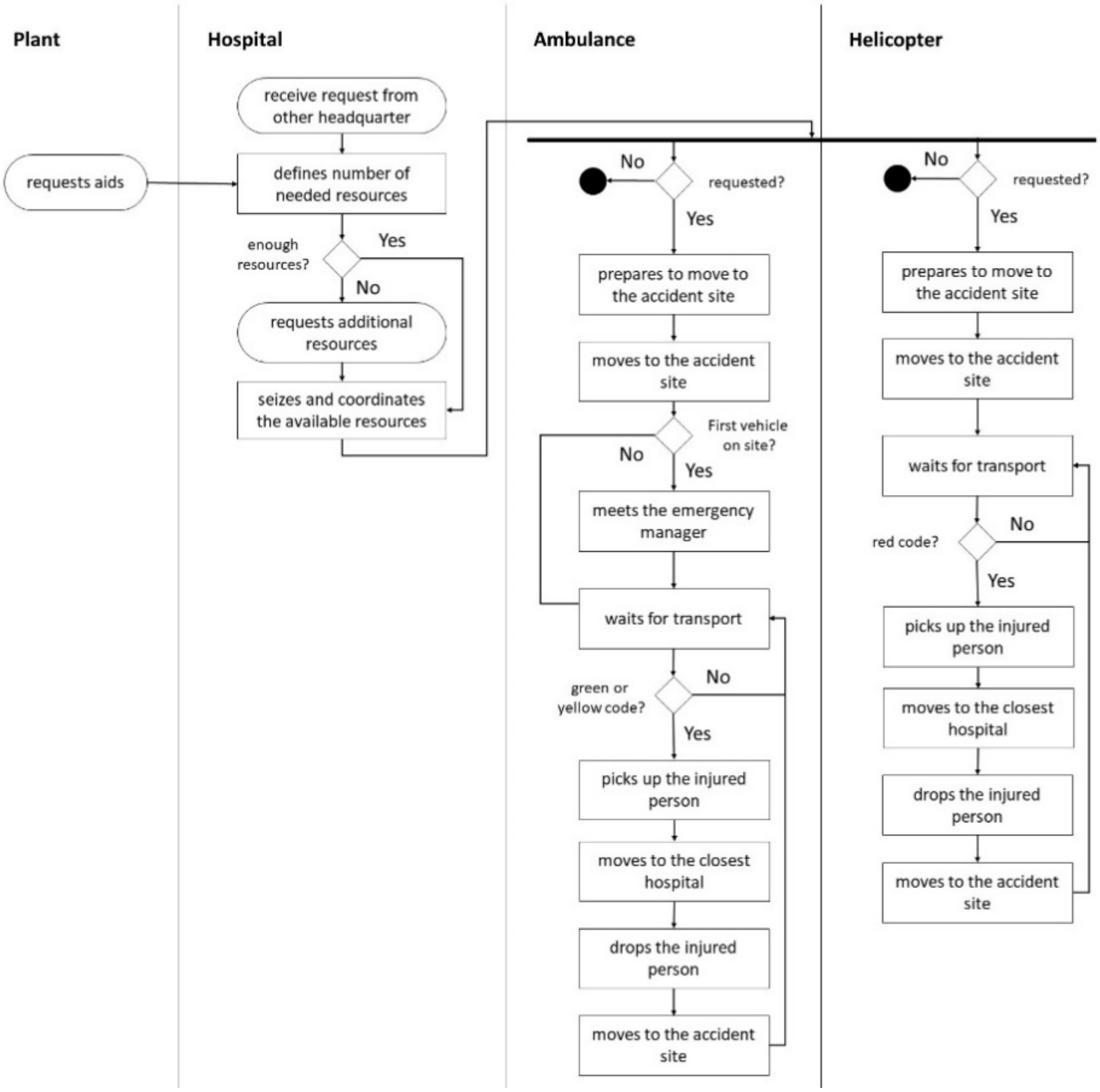


Figure 31: Civil Protection headquarter’s resources: swim lane diagram

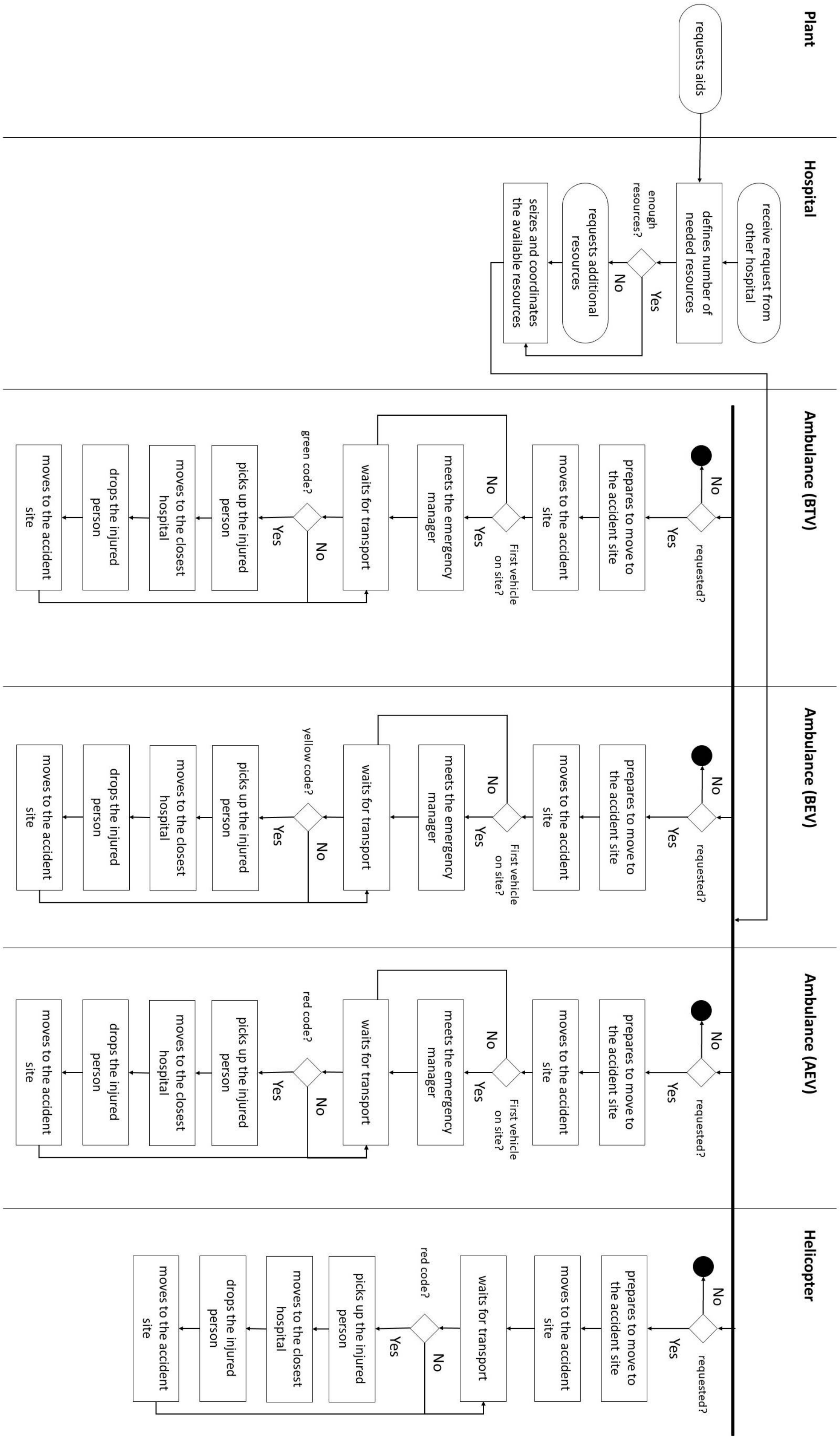


Figure 32: Hospitals' resources: swim lane diagram

All the agents representing a resource in the virtual environment will be placed in the GIS environment by giving the coordinates (latitude and longitude of the stations, hospitals or headquarters). By using GIS data, vehicles, ambulances and tanks can move along real-world streets and roads and can use traffic data for more realistic movements in the virtual environment (see Figure 33).

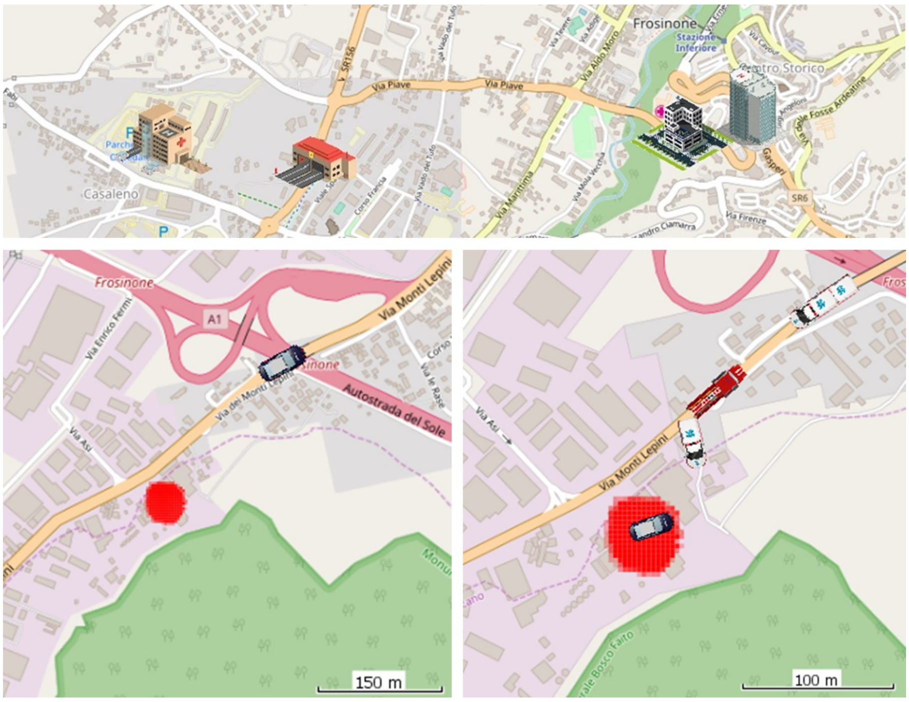


Figure 33: Placing agents in the GIS environment

4.3.3 Internal agents: integrating a multi-agent paradigm with social force modeling

In the developed training system, people are not considered as homogeneous individuals but are looked on as heterogeneous individuals. In addition to the agents already mentioned in the previous paragraph (e.g. law enforcement vehicles, ambulances, fire stations, civil protection headquarters), other agents have been created, namely:

- the emergency manager;
- the employer;
- the first aid team leader and members;
- the internal team (leader and members) that received firefighting training;
- the telephone operator;
- the emergency protocol officer;
- the systems security officer;
- the media relations manager;
- generic employees;
- generic visitors.

Their behavior and their interaction with the evolving accident scenario and with the other agents has been defined for every virtual agent according to their role and responsibilities above described.

In recent years, social force models have attracted great attention from researchers who applied Helbing's studies (Helbing & Molnar, 1995; Helbing et al., 2000) to several situations. However, a pure social force model does not allow simulating individuals and their interactions. Agent-based modelling allows instead each pedestrian to have unique behaviors, usually represented by conceptual models at a higher level, thus reproducing a more faithful evacuation scenario. For example, Wagner & Agrawal (2014) use agent-based modeling to simulate crowd evacuation in the presence of a fire accident, or Wang et al. (2015) propose a multi-agent based congestion evacuation model in which the effect of obstacles and panic behavior are also included. A reliable and realistic evacuation model should also take into account how the evacuation behavior is influenced by the source of danger, i.e. the evacuation cause. Wan et al. (2014) stated that 'almost all research studies are based on a hypothesis that there are no casualties, and only a few insert real emergency situations into evacuation models. It turns out that the existing models lacked veracity and vitality'. In their work, a social force model has been integrated with a Gaussian Puff Model representing the dispersion of a toxic gas. Radianti et al. (2015) proposed a spatio-temporal probabilistic model integrating crowd and hazard dynamics. However, a fire dynamics model has never been integrated with a social force model. In the context of this study, stochastic cellular automata model used to recreate the fire dynamics will be connected to the human behavior model here developed. In line with the current literature, which suggests that it is necessary to combine different kinds of approaches to model human behavior because each of them has its own advantages and disadvantages (Zheng et al., 2009), a multi agent-based and social force human behavior modeling approach has been developed and implemented.

With regard to the behavior of the agents above mentioned, in life-threatening situations like fires in a building, the following features appear to be typical:

1. individuals get nervous and they tend to develop blind actionism;
2. people try to move considerably faster than normal;
3. individuals start pushing and interactions among people become physical in nature;
4. moving and passing of a bottleneck frequently becomes uncoordinated;
5. at exits, jams are building up and sometimes, arching and clogging are observed;

6. people tend to show herding behavior, i.e. to do what other people do;
7. alternative exits are often overlooked or not efficiently used in escape situations.

All the agents representing humans are identified as heterogeneous population that share the same underlying structure characterized by a health status, a certain psychological type (represented by a nervousness factor during the emergency) and education & training level. Furthermore, as explained in the training strategy, the stochastic serious game logic should allow creating all the potential scenarios: it may happen (in the virtual environment as in reality) that some members of the emergency response team will remain injured in the accident. To this end, all the internal agents will be initially (at the beginning of the training session) located in the plant in a random location. Their health status is defined according to the level of lethality of the area where they are located and the area affected by the fire disaster. The disaster area has been subdivided in three concentric zones (as depicted in Figure 34) according to distances and limitations of the accident zones (defined by regulations and rule of thumbs) as reported in Figure 35.

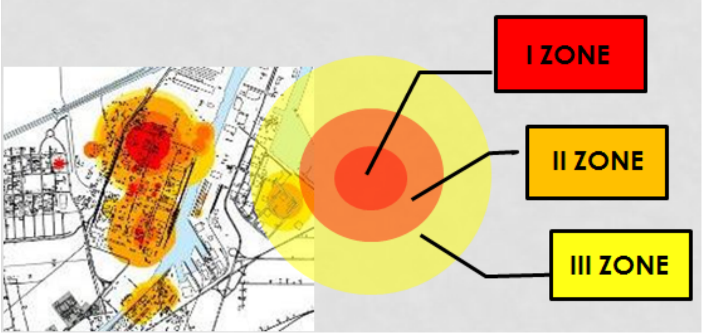
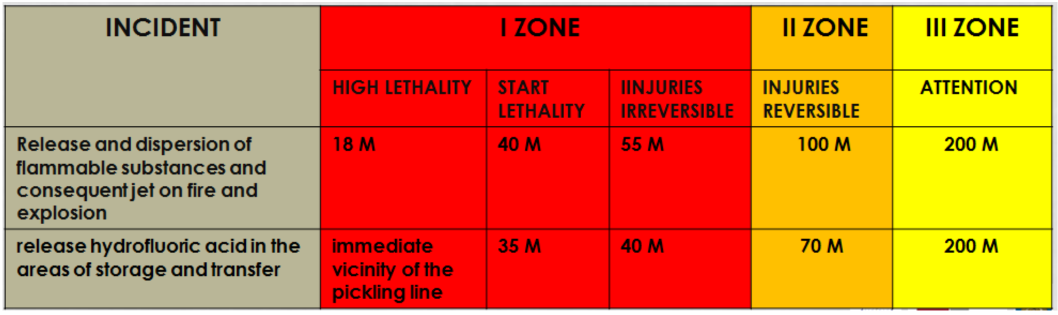


Figure 34: Disaster area's zone by level of lethality



INCIDENT	I ZONE			II ZONE	III ZONE
	HIGH LETHALITY	START LETHALITY	IINJURIES IRREVERSIBLE	INJURIES REVERSIBLE	ATTENTION
Release and dispersion of flammable substances and consequent jet on fire and explosion	18 M	40 M	55 M	100 M	200 M
release hydrofluoric acid in the areas of storage and transfer	immediate vicinity of the pickling line	35 M	40 M	70 M	200 M

Figure 35: Distances of accident zones and potential harms of agents' health

Besides the physical harms, in face of danger, people may reflect some negative psychological activities (i.e. tension, fear, panic). These activities may have a significant impact on the cognition, motion and decision behavior. If pedestrians are in negative condition, they may not make their decisions by themselves and conformity behavior may also occur. The fluctuating level of nervousness, $\eta_i(t)$, is assumed to influence the capability (and therefore the probability) of the person i to make the right choice according to the procedure, to execute quickly a task and the desired speed during the evacuation. In the context of this study, $\eta_i(t)$ depends on the distance d_{il} (in meters) between the closest cell l of the lattice belonging to the fire front $L(t)$ to the location of the person i and it is calculated as:

$$\eta_i(t) = 1 - \frac{d_{il}}{d_s} \tag{13}$$

where $d_s = 20$ meters is a safety distance between a person and the fire front at which the people are not getting nervous.

The education & training level, instead, is a parameter ξ_i ranging from 0 to 1 that is configured at the beginning of the training session by the training session facilitator for each intelligent agent i driving the behavior of the emergency manager and team members. While the nervousness level negatively affects the human performance, the education & training level positively affects the capability (and the probability) of a virtual agent to make appropriate decisions and to execute a task timely.

These two parameters affect the behavior of the intelligent agents:

- the nervousness level affects mainly the speed of the building evacuation (this is where the social force model is mainly implemented);
- the nervousness level and the education & training level affects the time needed to execute a task and, similarly, the probability to make the right choice within a set of potential courses of actions that are generated dynamically at run-time.

The description of these two aspects is provided to show the features of the human behavior here implemented.

The social force model is a well-consolidated approach that allows to simulate people as particles and to describe their evacuation behavior and motion as governed by the Newton's equations. According to the social force dynamics, the motion of a person is affected by two types of forces: social forces and physical forces. Social force is not directly exerted by the person's environment, but it is a measure of the motivation and the decision of the person to perform certain movements. A social force describes the psychological tendency of a person to have a personal space, or a person's desire to move to a certain location or to avoid certain objects or other people. In contrast to social forces, a person may also be subjected to physical forces. A physical force is described as the interaction between the person and another physical object.

As proposed in Helbing & Molnar (1995) and Helbing et al. (2000), the social force dynamics equation used in the proposed system is:

$$m_x \frac{d\vec{v}_x(t)}{dt} = \vec{F}_x(t) + \xi \tag{14}$$

$$\frac{d\vec{r}_x(t)}{dt} = \vec{v}_x(t) \tag{15}$$

where $\vec{r}_x(t)$ denotes the position of the pedestrian x at any time t of the simulation, $\vec{v}_x(t)$ is the velocity of that pedestrian and m_x is the mass of the pedestrian x, which is assumed to be 80 kg for men and 70 kg for women. $\vec{F}_x(t)$ is the total magnitude force – the sum of all the physical and social forces – acting on the pedestrian x and ξ is the (Gaussian) fluctuation term that represents random variations of the pedestrian behavior.

In the simulation, the pedestrians are represented by real avatars with an occupancy area whose radius ranges from 0.25 to 0.35 m. The diameters are chosen randomly and follow a uniform distribution. Two agents are considered to be in contact if the distance between them is less than the sum of their body radii. At start, pedestrians are randomly placed in predefined rooms within the plant. Then, each pedestrian starts the evacuation and decides to move towards a specific destination (an evacuation target or a safe area) pushed by the total magnitude force, $\vec{F}_x(t)$.

The various forces employed in this work to determine $\vec{F}_x(t)$ are the following:

- the time-dependent motivational force, $\vec{f}_x^{mot}(t)$, that drives the pedestrian x to the desired destination is

$$\vec{f}_x^{mot}(t) = m_x \frac{\vec{v}_x^0(t)\vec{e}_x^0(t) - v_x(t)}{\tau_x} \tag{16}$$

  The desire to adapt the actual velocity $\vec{v}_x$ to the desired velocity $\vec{v}_x^0$ into the desired direction $\vec{e}_x^0(t)$ within a certain relaxation time τ_x is reflected by the acceleration term $\vec{v}_x^0(t)\vec{e}_x^0(t) - v_i(t)/\tau_x$. Herein, the contribution $\vec{v}_x^0(t)\vec{e}_x^0(t)/\tau_x$ can be interpreted as a driving term. Under the application of this contribution, the pedestrians continuously accelerate and eventually reach unrealistic speeds. In addition, the other forces – such as the psychological, repulsive and compression forces – provide elastic interactions between the agents. Under the influence of these forces, the pedestrians would tend to collide violently, resulting in large accelerations and unrealistic motions. Therefore, the viscous damping term $-v_i(t)/\tau_x$ is introduced to prevent these effects and has the meaning of a friction term with friction coefficient $1/\tau_x$. Under the influence of dangerous source, pedestrians are always nervous or panic and are willing to move away from the dangerous source as fast as possible. The more alarmed the individuals are, the higher their desired speeds are. Therefore, the magnitude of the desired velocity $v_i(t)$ depends on the nervousness level, which has been formulated in Equation (17), and is assumed to be the linear combination of a minimal walking velocity $v_0 = 1.4\, m/s$ and maximal velocity $\vec{v}_x^{max} = 3.0\, m/s$.

$$v_i(t) = [1 - \eta_i(t)] \cdot v_0 + \eta_i(t) \cdot v_{max} \tag{17}$$

- the tendency of pedestrians to keep a certain distance to other pedestrians ('territorial effect') may be described by repulsive social force, $\vec{f}_{xy}^{soc}(t)$, which is expressed in Equation (18):

$$\vec{f}_{xy}^{soc}(t) = A_x \cdot e^{\left(\frac{\gamma_{xy} - d_{xy}}{B_x}\right)} \cdot \vec{n}_{xy}(t) \tag{18}$$

  Herein, the parameter γ_{xy} is the sum of the two persons' radius, d_{xy} denotes the distance between two pedestrians' centers of mass calculated as $\left\|\vec{r}_x(t) - \vec{r}_y(t)\right\|$, $\vec{n}_{xy}$ is the normalized vector pointing from pedestrian y to x as in Equation (19):

$$\vec{n}_{xy}(t) = \frac{\vec{r}_x(t) - \vec{r}_y(t)}{d_{xy}(t)} \tag{19}$$

The parameter A_x denotes the interaction strength (it is expressed in Newtonian units and generally equal to 2×10^3 N) and B_x the range of the repulsive interactions. It represents the distance at which two pedestrians have physical contact ($\gamma_{xy} \geq d_{xy}$) and is equal to 0.08 m.

- physical interaction forces come into play when pedestrians get so close to each other that they have physical contact ($\gamma_{xy} \geq d_{xy}$). In this case, which is mainly relevant to panic situations, we first assume a body force $k(\gamma_{xy} - d_{xy})\, \vec{n}_{xy}$ counteracting body compression. If the compressive force exceeds a certain value, one may use this as a criterion for pedestrian injuries. In this work, however, we do not consider injuries even when the compression forces are large. The direction of this physical force is along the line between the centers of the pedestrians. Moreover, a sliding friction force $K\left(\gamma_{xy} - d_{xy}\right)\Delta v_{xy}^t \vec{t}_{xy}$ is defined to impede relative tangential motion. Sliding friction represents the granular frictional sliding between pedestrians when they are in contact range. As with compression, friction is applied when the distance between two pedestrians is less than the sum of their body radii. The magnitude of the frictional force is considered proportional to the tangential relative velocity of the two agents. The force takes the direction of the tangent between the individual and the object of contact in the two dimensional plane. We assume therefore that the physical interaction force, $\vec{f}_{xy}^{ph}(t)$, between a pedestrian x and a pedestrian y is:

$$\vec{f}_{xy}^{ph}(t) = k\theta(\gamma_{xy} - d_{xy})\, \vec{n}_{xy} + K\theta(\gamma_{xy} - d_{xy})\, \Delta v_{xy}^t \vec{t}_{xy} \tag{20}$$

where $k = 1.2 \times 10^5 kg \cdot s^{-2}, K = 2.4 \times 10^5 kg \cdot m^{-1}s^{-1}, \vec{t}_{xy}$ means the tangential direction, $\Delta v_{xy}^t = \left(v_y - v_x\right) \cdot t_{xy}$ means the tangential velocity difference and $\theta(z)$ is equal to its argument z, if $z \geq 0$, otherwise 0.

- the repulsive force between pedestrians and other objects – such as walls or obstacles – are treated analogously to pedestrian interactions. If $d_{xb}(t)$ means the distance of the pedestrian x to the object b, $\vec{n}_{xb}(t)$ denotes the direction perpendicular to it and pointing toward the pedestrian x and $\vec{t}_{xb}(t)$ the direction tangential to it, the corresponding interaction force, $\vec{f}_{xb}(t) = \vec{f}_{xb}^{soc}(t) + \vec{f}_{xb}^{ph}(t)$, between the pedestrian x and the object b will be:

$$\vec{f}_{xb}(t) = \left[A_x \cdot e^{\left(\frac{r_x - d_{xb}}{B_x}\right)} + k\theta(r_x - d_{xb})\right] \cdot \vec{n}_{xb} - K\theta(r_x - d_{xb})\, (v_x) \cdot t_{xb}\, \vec{t}_{xb} \tag{21}$$

The direction of this physical force is along the line between the centers of the pedestrians or perpendicular to the wall and pointing toward the pedestrian x in the case of agent–wall interactions.

- the social repulsive forces between the pedestrians and the fire front can be expressed in a way similar to the forces between pedestrians or between a pedestrian and a wall, but they are much stronger. However, the physical interactions are qualitatively different. In the context of this work, the social repulsive force between the pedestrian and the fire front is only considered because as people are reached by the fire front (the person gets into contact with the fire) become injured and immobile, or even dead ($v_x = 0$). If l is the closest cell of the lattice to the person x belonging to the fire front $L(t)$, $d_{xl}(t)$ means the distance of the pedestrian x to the cell l, $\vec{n}_{xl}$

is the normalized vector pointing from the cell l to the pedestrian x, , the corresponding interaction force, $\vec{f}_{xl}(t)$, between the pedestrian x and the cell l will be:

$$\vec{f}_{xl}(t) = A_x \cdot e^{\left(\frac{r_x - d_{xl}}{B_x}\right)} \cdot \vec{n}_{xl}(t) \tag{22}$$

Herein, the parameter A_x denotes the interaction strength and it is considered in this case twice greater than the one in the case of the social repulsive force between two pedestrians.

- in addition, the model takes into account time-dependent attractive interactions towards special attractions k, such as leaders or friends, by using attractive social forces (as opposed to repulsive social forces). The joining behavior of people, which guarantee that acquainted individuals join again the group after the have accidentally been separated by other pedestrians, can be expressed by the formula below, where C_{xy} is a constant that includes the nervousness level of the pedestrian:

$$\vec{f}_{xy}^{att}(t) = -C_{xy}(t) \cdot n_{xy}(t) \tag{23}$$

Figure 36: Employees and emergency response team members evacuating the facility in the virtual environment

Other parameters for setting up the model can be retrieved at Lakoba et al. (2005). The evacuation ends (or stops) when all the evacuees reach a safe area or when 'mortal' environmental conditions affect the motion of some of them.

The way the time to execute a task has been assumed to be affected by the two parameters is below described. An identical approach has been also applied to calculate during run-time the probability to make the right decision within a set of potential courses of actions and therefore is not reported.

Each task is identified by an optimistic execution time (t_{opt}), a most-likely execution time (t_{lik}) and a pessimistic execution time (t_{pes}). Such times for every task have been collected through an extensive data collection phase in cooperation with subject matter experts: however, their opinion was rarely punctual and precise therefore a minimum and maximum value has been provided by them for each time component ($t_{opt_{min}}$ and $t_{opt_{max}}$ for the t_{opt}, $t_{lik_{min}}$ and $t_{lik_{max}}$ for the t_{lik}, $t_{pes_{min}}$ and $t_{pes_{max}}$ for the t_{pes}).

The education & training level of every person i has been assumed to influence such components as follows:

$$t_{opt} = \xi_i(t) \cdot t_{opt_{min}} + [1 - \xi_i(t)] \cdot t_{opt_{max}} \tag{24}$$

$$t_{lik} = \xi_i(t) \cdot t_{lik_{min}} + [1 - \xi_i(t)] \cdot t_{lik_{max}} \tag{25}$$

$$t_{pes} = \xi_i(t) \cdot t_{pes_{min}} + [1 - \xi_i(t)] \cdot t_{pes_{max}} \tag{26}$$

Such times are standard values that a person in a normal state (with no stress or nervousness) requires to execute a task. A triangular probability distribution with parameters t_{opt}, t_{lik} and t_{pes} would be used to calculate during the training session the time needed by every agent to execute a task. However, the nervousness level is assumed to influence this time too. It is assumed that, the greater is the nervousness level, the more the optimistic and most-likely values are expected to get closer to the pessimistic time by a factor given by the nervousness level $\eta_i(t)$. If we consider two different levels of nervousness, $\eta_i^1\ (t)$ and $\eta_i^2\ (t)$, with $\eta_i^1\ (t) < \eta_i^2\ (t)$, the triangular distribution will be modified as shown in Figure 37. In particular, the optimistic and most likely values will be ‘pushed’ towards the pessimistic value (that is assumed fixed).

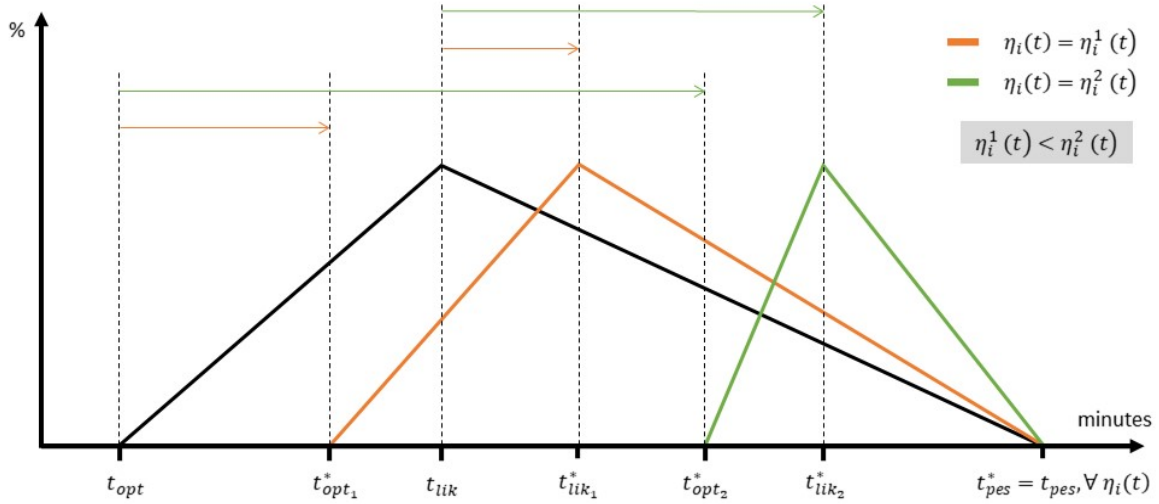


Figure 37: How the time to execute a task changes according to the nervousness level

The mathematical model to calculate this is given as follows:

$$t^*_{opt} = [1 - \eta_i(t)] \cdot t_{opt} + \eta_i(t) \cdot t_{pes} \tag{27}$$

$$t^*_{lik} = [1 - \eta_i(t)] \cdot t_{lik} + \eta_i(t) \cdot t_{pes} \tag{28}$$

$$t^*_{pes} = t_{pes} \tag{29}$$

Finally, the time to execute a given task is given by a triangular distribution with parameters t^*_{opt}, t^*_{lik} and t^*_{pes}. Table 1 shows a subset of tasks the emergency manager can perform with the related stochasticity.

Table 7. A selection of tasks of the emergency manager and expected durations

Task	Time (min)
Give the alarm and evacuation order	Triangular (1, 2, 3)
Coordination meeting with the internal firefighters team	Triangular (20, 40, 60)
Coordination meeting with the internal first aid team	Triangular (15, 20, 25)
Coordination meeting with the energy responsible	Triangular (25, 45, 70)
Coordination meeting with the systems responsible	Triangular (20, 25, 30)
Meet and update the external firefighters responsible	Triangular (10, 30, 60)
Check persons in the safety zone	Triangular (5, 7.5, 10)

This approach to calculate the time required to execute a task is applied for all the virtual human agents in the system. The first thing to highlight is that intelligent agents have been developed to drive not only the generic employees and visitors (that need to escape from the buildings and reach the safe zone) but also for the emergency manager and the emergency response team members. This may look contradictory because the emergency manager and the emergency response team members should be played by real players and not driven by intelligent agents.

Instead, on one side, the trainee playing the role of the emergency manager will be asked to act on the training environment and decide the order and timeliness of the decisions to be made or tasks to be assigned. The emergency manager will not be immersed hands-on in the plant (for example, by means of Virtual Reality helmets) but he/she will make a decision by clicking on the graphic user interface that trigger the actions of a virtual agent (this is where the intelligent agent comes into play). For instance, if the player decides to count the number of people still in the plant (and clicks on the corresponding button in the system interface), the virtual agent will require a certain amount of time to execute the task in the virtual environment (the time is calculated according to the procedure described above).

Unlike the emergency manager, that is the main figure of the proposed training system, the emergency response team members can be guided either by real players or by intelligent agents, depending on the trainees who participate to the training session. The trigger is always the emergency manager who assigns the tasks to the members of the emergency response team as explained in the diagram in Figure 38.

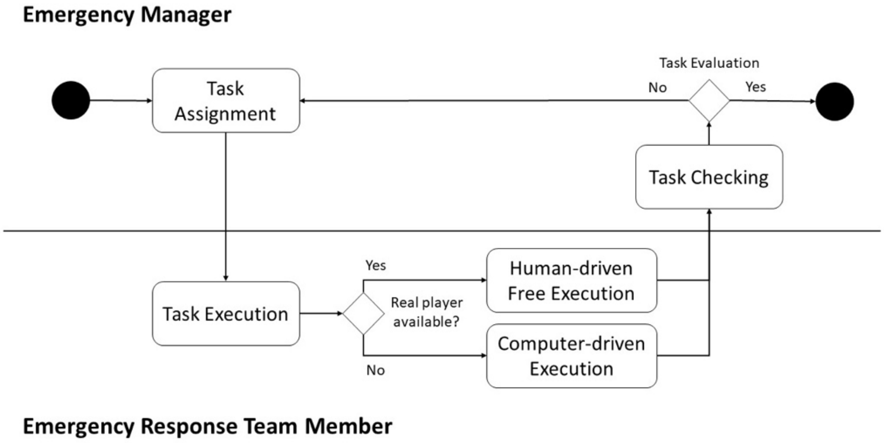


Figure 38: Task assignment diagram

After that, if the role is played by real trainees, no intelligent agents will be used in practice and the behavior will be entirely human-driven (the trainees are immersed in the virtual environment by means of Virtual Reality helmets). In case a specific role in the emergency response team is not covered by a real trainee, the agent will be entirely computer-driven with a certain level of intelligence. By using this approach, very flexible training sessions can be set up and a multi-player paradigm can be easily implemented in the serious game.

The behavior of the agents representing the emergency response team members can be described with flowcharts. Every rectangle in the flowchart represents the execution of a specific task, includes all the possible courses of action and therefore the sequence of tasks to be performed.

Some examples are provided in the following diagrams. The diagrams show that every member of the emergency response team can be (stochastically) injured because of the disaster. If the telephone operator is still able to move, then he/she evacuates and goes to the safe zone where medical aids are located, otherwise he/she will wait to be rescued. If the telephone operator is not injured, he/she will move to the coordination point only if he/she noticed the fire or heard the alarm. Once at the coordination point, his/her task is to control the phone and filter all the communications. Upon assignment of the emergency manager, he/she calls and keep updated the Carabinieri and law enforcement authorities (112), the firefighters (115) and the hospitals (118). The behavior of the telephone operator is illustrated in Figure 39.

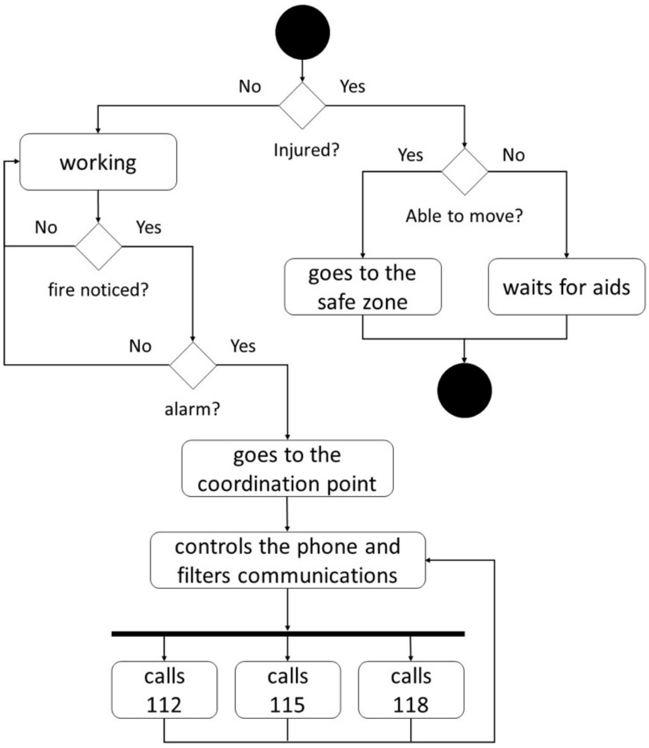


Figure 39: Main duties of the telephone operator: a high-level flowchart

High-level flowcharts clearly show the sequence of actions of the emergency response team members when they are tasked by the emergency manager. For example, the member of the internal fire brigade waits for being assigned a task when he/she gets to the coordination point. Examples of task reported in Figure 40 are ‘prepare a fire report’, ‘count the number of people in the safe zone’, ‘remove the obstacles from the emergency roads’, ‘carry out a tour in the plant to find missing people’.

Similarly, the behavior of the systems officer is represented in Figure 41, where the following tasks have been illustrated: ‘prepare a system status report’, ‘automatically shut off the systems’, ‘manually shut off the systems’.

What should be mentioned about this modeling approach is that the time to execute the task is very crucial for the success of the task. Indeed, the greater is the time, the greater is the probability to fail because the disaster scenario may get worse (e.g. a person can get injured, another area of the plant can catch on fire, a system may become too compromised and uncontrollable). Furthermore, the scenario is, again, stochastic: it means that the success of a task is not certain. When the system responsible tries to shut off the system automatically, the process may fail or succeed depending on an internal stochasticity (which takes into account the status of the system, the time needed to execute the task etc.). This way, a highly stochastic training scenario is obtained. It is up to the trainees to try to work the emergency out even if the scenario gets worse and worse by executing the right sequence of tasks in a timely way.

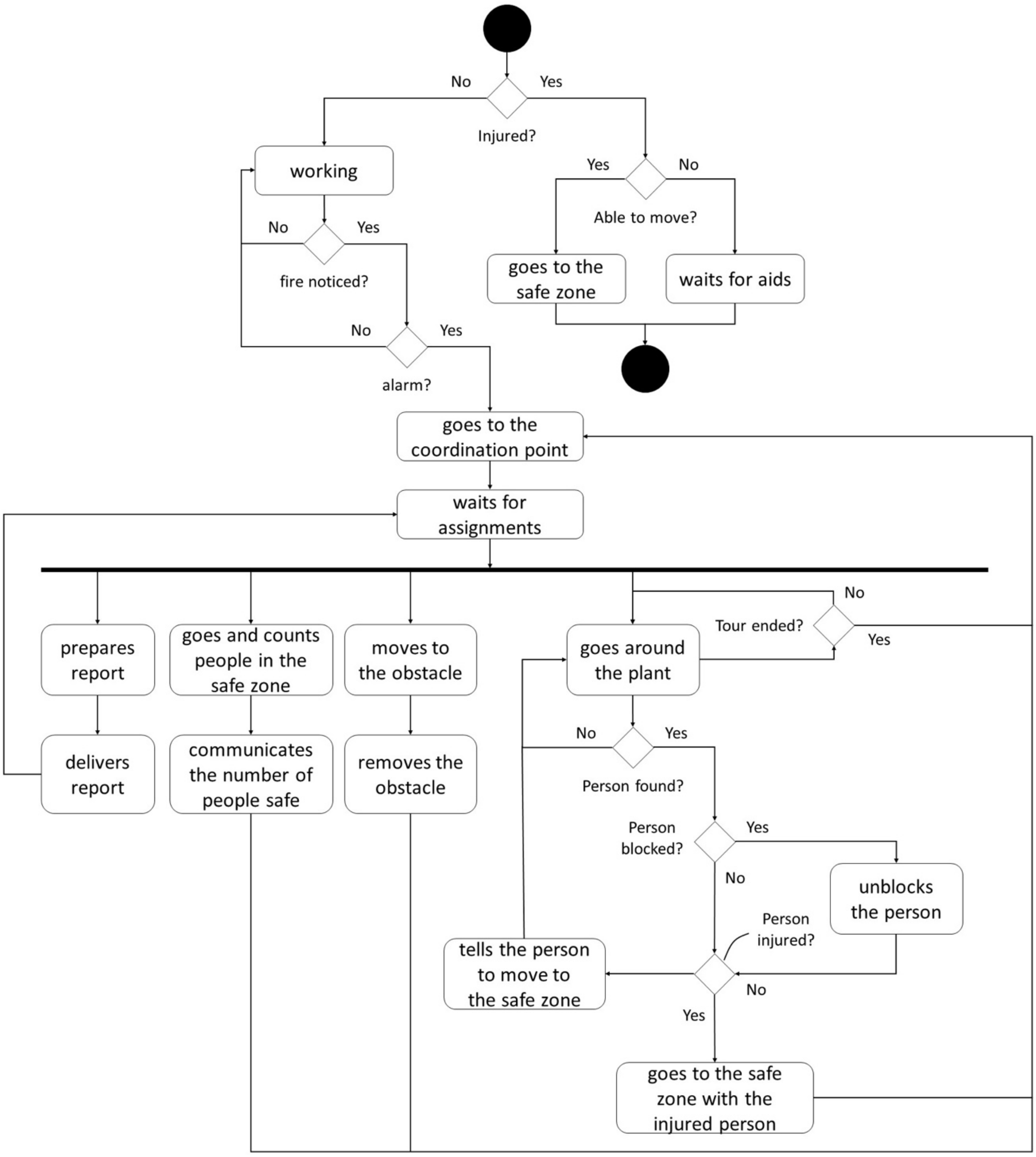


Figure 40: Main duties of the internal fire brigade member: a high-level flowchart

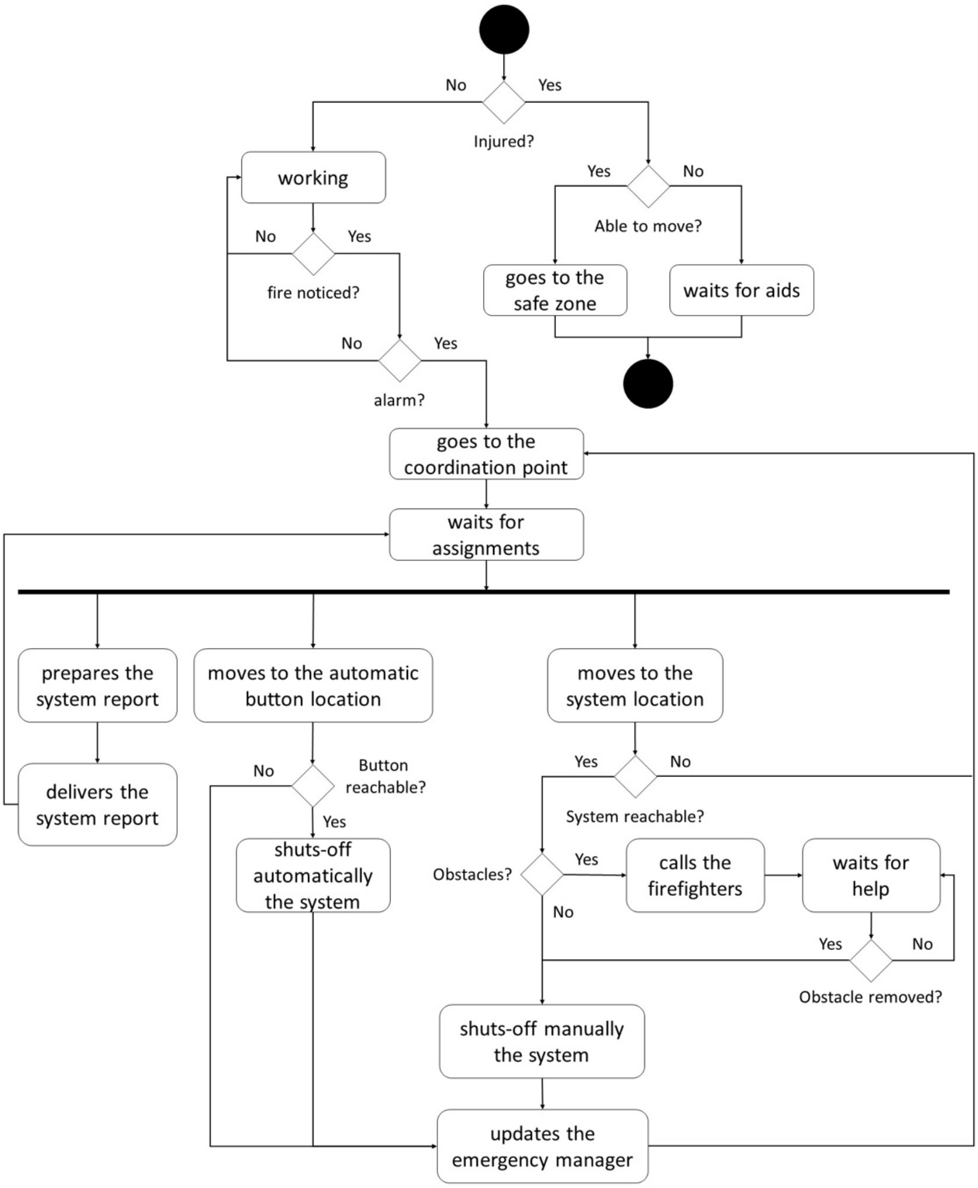


Figure 41: Main duties of the systems officer: a high-level flowchart

4.4 Design of a System of Systems architecture for the training system

Considering the designed training strategy and the developed training environment, multiple system components and technologies shall be implemented and shall interface efficiently. Before presenting the general architecture of the developed training solution, some research and implementation questions are presented and addressed in the following paragraphs.

4.4.1 Selection of software tools

Choosing the right software tools is certainly an important decision in order to get the best results out of the final prototype, to speed up the development phase and to get the best user experience.

Because simulation is such a powerful tool to assist in understanding complex systems and to support decision-making, a wide variety of approaches and tools exist. There is a variety of open-source or proprietary simulation tools and frameworks, e.g. AnyLogic[7], Arena[8], ExtendSim[9], Simio[10], each of them tailored for a specific type of problem. Most of these software tools are based on Java, which makes them very accessible even to beginners. After an initial screening of all the tools, AnyLogic has been selected as the best software for computer simulation. AnyLogic is a cross-platform multimethod simulation modeling tool developed by The AnyLogic Company (former XJ Technologies), which supports agent-based, discrete event, and system dynamics simulation methodologies. It is widely used in many industries as it offers great features and advantages compared to other tools:

- it supports all the three well-known modeling approaches: discrete-event simulation, agent-based modeling, system dynamics and any combination of them within a single model;
- the platform for model development environment is Eclipse, which is familiar to almost all the Java developers;
- it includes a graphical modeling language by means of a number of libraries that speed up the development lifecycle and also allows the user to extend simulation models with additional Java code;
- it supports interactive 2D and 3D animation as well as tile maps from free online providers, including OpenStreetMap. Tile maps allow the modeler to use map data in models and to automatically create geospatial routes for agents.
- an AnyLogic model can be exported as a Java application, that can be run separately, or integrated with other software.

AnyLogic University Edition 7.2.0 has been used in the context of this study.

Game engines are popular tools to code and plan out a VR application quickly and easily without building one from the ground up. Unreal[11], CryEngine[12] and Unity[13] are among the most predominant and leading game engines for creating advanced level VR applications. While CryEngine takes a bit time to be able to use this platform effectively and a bit harder to grasp for the beginners and Unreal is best suited for developing highly graphical and photorealistic games, Unity by Unity Technologies has been selected as

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[7] AnyLogic, The AnyLogic Company, https://www.anylogic.com/

[8] Arena, Systems Modelling Corporation, Rockwell Automation, https://www.arenasimulation.com/

[9] ExtendSim, Imagine That Inc., http://www.extendsim.com/

[10] Simio, Simio LLC, https://www.simio.com/

[11] Unreal Engine, Epic Games, https://www.unrealengine.com

[12] CryEngine, Crytek, https://www.cryengine.com/

[13] Unity, Unity Technologies, https://unity3d.com/

the most suitable tool for the development of the VR application. Unity 3D is considered as one of the best game engines as it offers its users a wide range of tools and features:

- it boasts of a robust asset store where game assets, scripts, functional extensions and ready-made solutions can be easily downloaded, which speed the development lifecycle up;
- it has a fairly easy to grasp interface even for beginners as, for example, a logic around an object can be created by dragging the codes in a built-in Integrated Development Environment (IDE);
- its editor framework is one of the best-documented and cleanest thanks to a wide and robust community of developers;
- it supports a number of file formats used in the leading 3D applications including 3D Studio Max, Blender, etc.;
- it provides cross-platform integration way ahead of its competitors, which makes it attractive also for future extensions and work.

Having said this, Unity is a complete package that lets you simultaneously play your game, edit it, and test it as well, create environments, add physics and lighting, manage audio and video, handle animation, profile GPU and CPU performance, and do multiplayer. The version Unity3d 5.3.4f1 has been used in the context of this study. Other supporting software tools used in the study are:

- Blender and 3D Studio Max for 3D modeling and computer graphics;
- Eclipse has been used as Java IDE.

4.4.2 Choosing the best standard for the distributed simulation

Despite HLA is the most popular architecture for distributed simulation in the industrial domain (in particular for training oriented purposes), it was also compared technically to the other standards in a preliminary phase. The ALSP and DIS have been discarded because they are prior to the HLA, which combines their benefits and strengths. TENA has been under study and compared to HLA. This architecture provides interoperability, reusability and modularity that are of huge importance of the development of the training system. Despite no problems have been identified in adopting one or another, the adoption trend of HLA in industrial domain has been crucial and has determined the choice of HLA as standard for integrating the systems that have been developed in the context of this work. This choice has been motivated by prospective reasons: the choice of the leading paradigm makes the architecture extremely scalable and modular and facilitates its extension with new components and functionalities. Further information about HLA implementation can be easily found in the literature or simply by checking the IEEE 1516-HLA 2010-evolved standards reported in the final list of references of this article (IEEE Std 1516 – 2010, IEEE Std 1516.1 – 2010, IEEE Std 1516.2 – 2010, IEEE Std 1516.4 – 2007). The version used in the context of this study is the IEEE 1516 High Level Architecture (HLA) 2010-Evolved. Commercial RTIs (MÄK High Performance RTI by MÄK Technologies and Pitch pRTI by Pitch Technologies) and non-commercial RTIs (Portico by the Open LVC Group) have been considered in this work and can be used.

4.4.3 A Java-based Unity-AnyLogic middleware for HLA connection

Unity3D and AnyLogic are not HLA compliant, meaning that they do not natively support the IEEE 1516 HLA standard for distributed simulation. An ad-hoc bridge to connect Unity3D and AnyLogic with

HLA has been designed and developed, the Unity-AnyLogic middleware. It integrates all the interfaces services provided by the HLA RTI (Run Time Infrastructure) under the version HLA-2010 evolved.

Figure 42 shows first an overview of the Unity3D-HLA Bridge that has been designed to connect multiple federates developed by using Unity3D (see the left part of figure 1). Unity3D Federates exchanges messages through the Unity3D Clients & Socket Interfaces. This module has been designed in order to let Unity3D Federates acting as clients and exchanging information through socket connections. The Unity3D Clients communicate (both directions, in-out) to a Java Server. The Java server, in turn, after translating the messages (e.g. from bytes to string, from string to other HLA types, etc.) calls the HLA services through the HLA Libraries therefore accessing (in both directions) the functionalities provided by the HLA Run-Time Infrastructure (RTI) to fully participate in the HLA federation. In order to use correctly the Unity3D-HLA Bridge it is first required to start the JAVA server and then let the server listening on a specific port in order to receive messages from Unity3D clients and sending them to the other federates through the Run-Time Infrastructures services (and vice-versa). Until a Unity3D client is not connected then the JAVA server stays in a loop; the exit condition is given by the connection of a Unity3D Client that will start sending messages.

The Unity3d-HLA middleware works for commercial RTIs (MÄK High Performance RTI by MÄK Technologies and Pitch pRTI by Pitch Technologies) and non-commercial RTIs (Portico by the Open LVC Group).

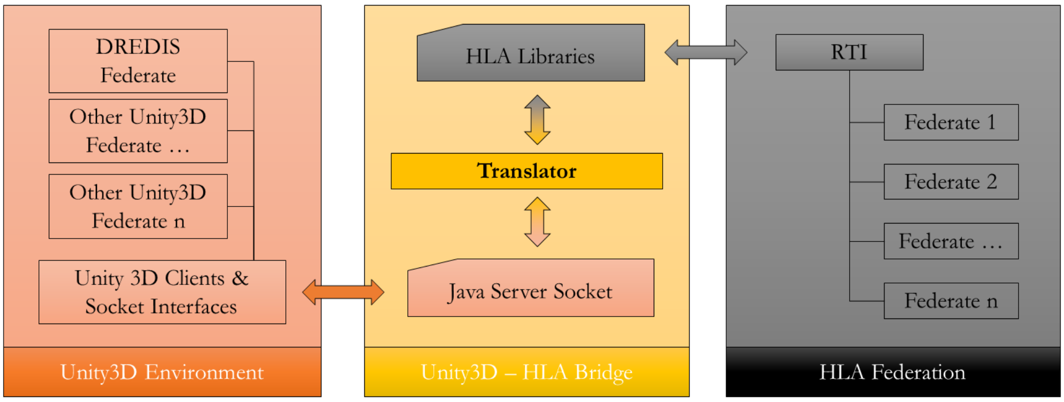


Figure 42. Unity3d-HLA middleware

The HLA interoperability in AnyLogic is supported by an HLA Support Module (HSM) class library (Borshchev et al., 2002). The HLA Support Module (HSM) enables a federate to invoke the RTI services by using the following classes: (1) supporting most of low-level RTI services (HLAHelpers), (2) publishing and subscribing objects and interactions (HLAObjectClass/HLAInteractionClass), (3) sending and receiving objects and interactions (HLAObject/HLAInteraction). The HLA Support Module (HSM) also presents two port classes which queue receiving objects and interactions as HLAObjectUpdatePort and HLAInteractionTranceiverPort, respectively. The HSM enables AnyLogic to support a wide range of RTI services such as Federation Management, Declaration Management, Object Management, and Time Management. The HSM uses a StepHook interface, which places specific methods on the engine that is performing the model's time steps. These methods enable models to exchange messages and synchronize local simulation times to the global time of the federation. StepHook interface allows the user to put a hook on engine performing model time steps. Special method Engine.setStepHook(com.xj.anylogic.StepHook) is used to set a time step hook. StepHook interface incorporates two methods:

1. double nextEvent (double time) This method is called by the engine just before each time step. The single method parameter is a time when the next event is scheduled. It can be Double.POSITIVE_INFINITY if there are no events scheduled. The method implementation can return another time moment, that must not be later than the time moment, so the system clock will be adjusted only to this time point.
2. void timeStepDone() The method is called by the engine right after the system clock has been adjusted to the time obtained from nextEvent().

The described above StepHook interface is used as an interaction interface between HLA Support Module and AnyLogic Model Engine. The structure of HLA federation with AnyLogic federate among other federates is shown in Figure 43.

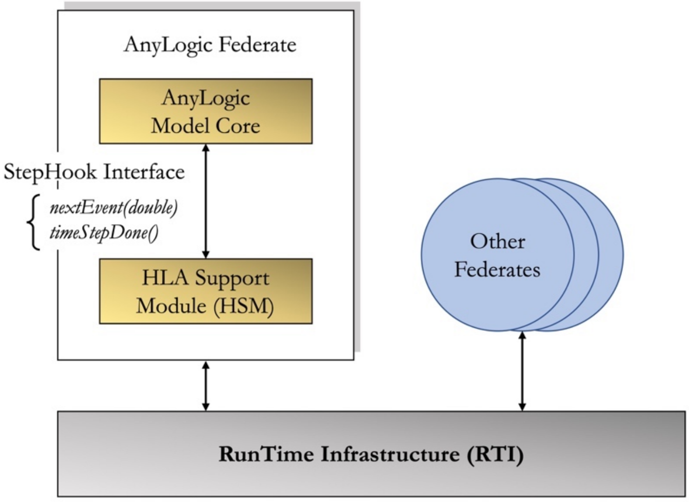


Figure 43. AnyLogic-HLA middleware

4.4.4 Integrating fast-time and real-time simulation

All the communication services are managed then by the HLA Run-Time Infrastructure. However, in order to use the HLA, a major problem arises. There is a need not only to guarantee communication among the different federates but also to let two different types of simulation paradigms (event stepped fast time simulation and virtual real-time simulation) to interact each other. Indeed, the training system includes trainees with different objectives:

- the Emergency Manager wants to make a sequence of decisions and understand only the effect of his decisions (its simulation can be considered event- or time-stepped);
- the Emergency Team Members, who are playing in a virtual environment as if it was in the real world, should play the simulation real-time.

To solve this problem and couple fast-time and real-time simulation, the HLA messaging protocol has been opportunely modified to provide the system with an additional capability to shift automatically from real-time to event-stepped execution.

The modification has been done by working on the Time Management Services provided by the HLA standard, in particular on the Time Advance Request Service and on the Time Advance Grant Service. Full description of the services is reported in the IEEE Std 1516.1 – 2010, in order to keep the time synchronization among the different federates, the HLA use the Time Advance Request Service: thanks to this service each federate may request an advance of its time. This request is passed to all the other federates and according to the times of all the other federates, the HLA uses the Time Advance Grant to indicate to the federate when the time advance is granted. Now, this approach works perfectly when the federates use the same time management approach (e.g. all the federates are involved in a real-time virtual simulation). Problems immediately arises when the time management approach is different among the federates (as in the case of the architecture proposed in this article) and, in particular, when virtual simulation (where, by definition, the time advances as the real clock) is coupled with event stepped simulation (where the time can jump from one time to another according to the next event in the queue). Neither the virtual simulation time management nor the event stepped simulation time management can be used. Indeed, using always the real time (as in the virtual simulation) means that a training session could last even some days (this is the time frame usually needed to solve disaster in industrial plants). This is obviously unacceptable, as a training session should last no more than 1 hour. Vice versa, using the fast time (as in the event stepped simulation) means that the emergency team members cannot experience the virtual environment and interact real time to perform their actions. This is also unacceptable. Therefore, as both time management approaches are needed because of the different training objectives for the emergency manager (fast time simulation, see immediately the consequence of the decisions taken) and for the emergency response team member (real time simulation, interact in a virtual environment as they do in the real environment), it is clear that both of them must be used at the same time. The problem has been solved by developing an additional service, called Time Advance Stand-by, located in the Unity3D-HLA middleware. The service receives through the RTI the Time Advance Request and works as follows:

- if there are interactions ongoing in the virtual environment (this means that there are emergency response team members interacting within the virtual environment) the time advance request will enter a while loop and the request will stand-by;
- if there are no interactions ongoing in the virtual environment, the Java-Unity middleware sends a request to the Scenario Evolution Engine to understand if there are already planned actions that must be executed by the emergency response team members. The actions that the emergency response team members must execute in the virtual environment are decided by the emergency manager. If there are already planned actions, then the time advance request will still stand-by;
- if there are no already planned actions that must be executed by the emergency response team members then a positive acknowledgement of the time advance request will be sent back through the Run Time Infrastructure that will grant the time advance to the federate that requested it.

By applying this procedure, the emergency manager will not be able to increase/reduce the simulation speed every time there are interactions ongoing in the virtual environment; this is also useful to let the emergency manager see how the team members are performing their duties in the virtual environment. When there are no interactions ongoing then the simulation time of the emergency manager jumps to the next relevant event (in order to speed up the training session).

4.4.5 A system of systems general architecture

After the definition of the technologies, standards for distributed simulation, software and tools that will be used to develop the system, the general technological architecture of the training system has been designed. It was conceived as a System of Systems architecture to provide high scalability, flexibility and multi-player experience. The architecture, depicted in Figure 44, comprises a group of independent systems that are hereunder described.

A Java-based training session configuration system enables the training session facilitator to configure the training scenarios via a dedicated interface. It basically acts upon the training session database defined with MySQL, one of the most common relational database management systems. As shown in Figure 20, MySQL tables have been created to store all the information and data related to the training environment, basic and static geometric 3D models (see the scenario tables), to the disaster's configuration parameters (see the accident tables) and to the user (see the user's tables). These tables directly feed another system, called Master Engine, developed by using AnyLogic, which consists of three modules:

- the Scenario Initialization Module initializes the stochastic training environment with the initial configuration parameter, generates the related virtual environment and initializes the training content according to the number and roles of the actual players;
- the Scenario Evolution Engine that includes all the mathematical models and the programming code that reproduce the scenario evolution, the fire dynamics, the employees' behavior and the serious game logic underlying the possible courses of action;
- the Event Generator Module monitor the scenario evolution, collects data about the current scenario evolution and injects accordingly different messages that trigger events.

Although the Master Engine operates independently, it must communicate and interoperate with the other systems (or federates, according to the HLA terminology) through the services provided by a middleware, called Run Time Infrastructure (RTI). The Master Engine represents the Federate 1 of the HLA-based federation, which is composed of other federates.

The first one (Federate 2) is a Java-based interface representing a scenario performance module, called Common Operational Picture (term especially used for the military distributed training systems) collects a seamless data flow from the master engine in a MySQL table and displays the real-time key performance indicators onto a user-friendly graphic interface, thus enabling the training session facilitator and/or a group of observers to monitor the evolution of the training session.

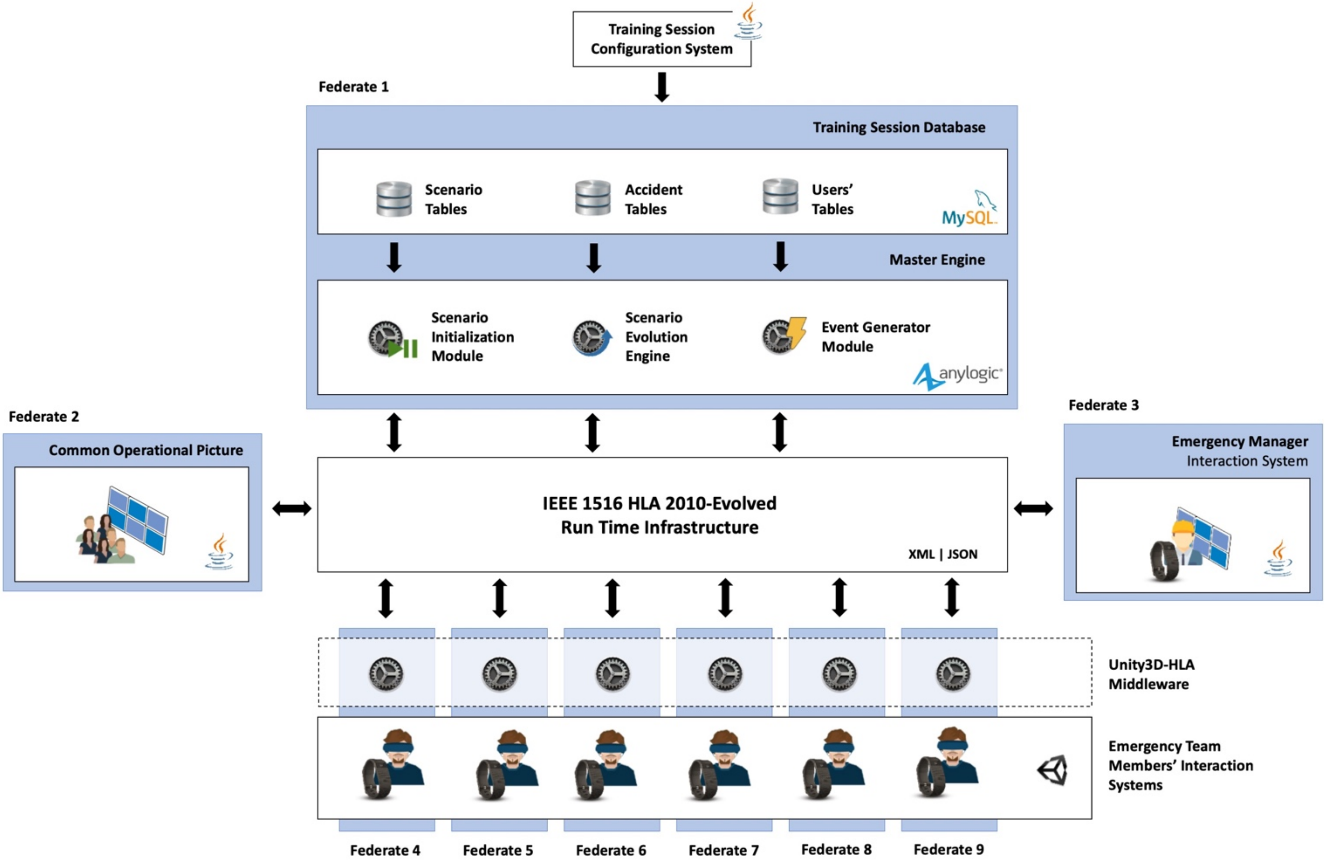


Figure 44: System of systems architecture of the training solution

The entire training scenario is coordinated and managed by the emergency manager that is considered to be the Federate 3 in Figure 44. A dedicated Java-based interface has been developed that can run on a touch screen or a traditional desktop computer. The emergency manager interaction system is then completed with a commercial smart watch and a surrounding audio & sound system to interact vocally with the emergency response team members.

At the bottom of the architecture, it can be observed that a variable number of emergency response team members can join simultaneously the training session (from Federate 4 to Federate n). Their interaction system consists of a headset (in the case of this research, an HTC Vive with motion controllers and joysticks), through which they are immersed into the virtual environment to maximize the sense of presence, a smart watch for the heart rate monitoring and an embedded microphone and audio straps to interact vocally with the other trainees (emergency manager and emergency response team members). The emergency response team members' interaction systems have been built in Unity 3D and connected to the other systems by using the ad-hoc developed Unity 3D-HLA middleware.

The overall framework to run such HLA-based architecture and the different federates is depicted in Figure 45. The training session facilitator is the one who will start the RTI and the Master Engine. The federate of the Master Engine will create the Federation since it is the first one connecting to the distributed network. Once the federation has been created the training session facilitator can also start the Common Operational Picture federate, which will join the federation just created. At the next step, the emergency manager will start his federate that will join the federation. This federate is necessary in the federation as the training session cannot run without at least the emergency manager coordinating the disaster scenario.

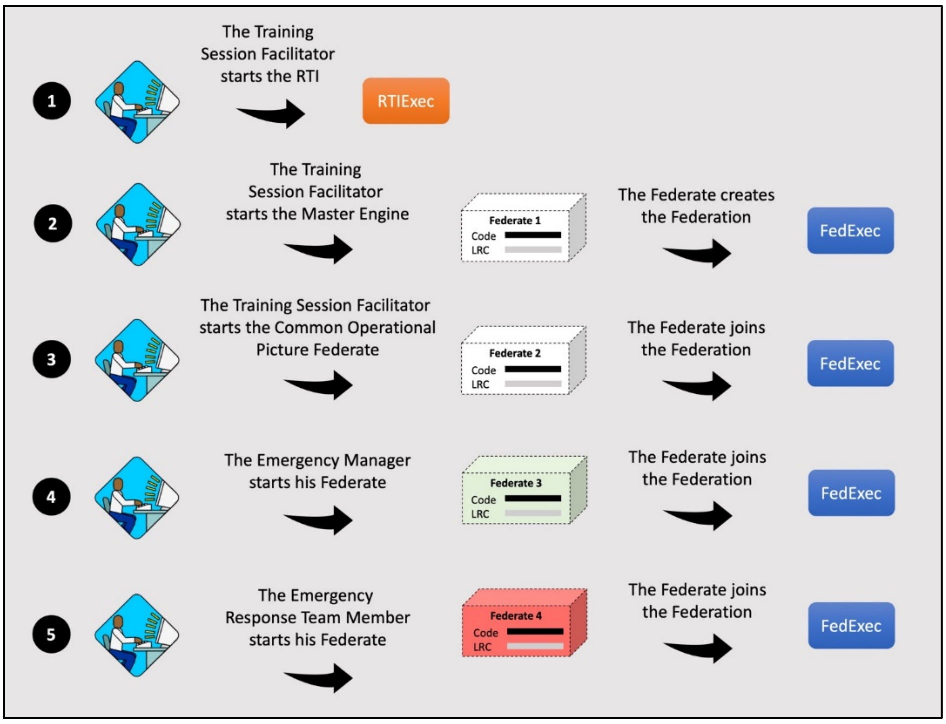


Figure 45: How to run the HLA-based architecture

After the emergency manager, one or more emergency response team members can start their federate, which will join the same federation, thus enabling the systems to interoperate with each other and all of the trainees to share the same virtual environment and collaborate.

One of the potentials of this architecture is in its scalability. The training session can be run in stand-alone mode by the only emergency manager (who will play in an emergency response team with intelligent agents driven members) or by the emergency manager and a variable number of emergency response team members. A multi-player training system is therefore enabled, which allows to carry out different types of training sessions even if all the real players are not available at the same time. Furthermore, the use of the HLA standard gives the opportunity to connect several other systems to the federation that may represent other people in an industrial emergency scenario or other mathematical models to enlarge the scope of the training system. Moreover, since the systems are executed on different workstations and interoperate over the internet (via LAN connection to ensure more stable networks), the computers can also be geographically dispersed. As an example, the training session facilitator can be in Italy, the emergency manager in the United States and the emergency managers in any other place. This architecture fully embodies the concept of distributed training system for a cooperative learning, a concept that would be very useful to big companies whose employees are often located in different plants or facilities. Therefore, it is usually hard to set up training session where the trainees are always in the same location (typically the employees go back to the headquarter, for example, for a ‘training period’). Real and intuitive communication among the trainees is also guaranteed by the system with audio & sound equipment embedded as a feature of the different federates.

4.5 The System Implementation

Images and screenshots from the proposed system vividly show how the developed training environment embraces the key modeling principles of configurability, reusability and feeling of realism. The following paragraphs illustrates the system's interfaces with reference to all the people involved in the training session:

- the training session facilitator, who configures the training environment and supervises the players during the training session;
- the trainee playing the role of the emergency manager;
- the trainee playing one of the emergency team member roles.

4.5.1 The training session facilitator interfaces

A dedicated graphical user interface introduces the training session facilitator to the different features of the system aimed at enabling the configuration of the training environment. It should be mentioned that these interfaces can be accessed only by the training session facilitator as they deal with configuring the training scenario that should remain unknown to the trainees until the training session starts. This home interface, depicted in Figure 46, enables the training session facilitator to access the different initial features:

- to play the training scenario with the default configuration of the settings;
- to configure the settings and information related to the plant where the training session will be set;
- to configure the settings and information related to the major industrial accident;
- to configure the settings and information related to the user experience;
- to close the training session.

If the training session facilitator push the 'Play simulation' button, the training session starts with default settings and the training session configuration can be skipped and the players will be introduced to the training environment (see next paragraph).

Figure 47 shows the interface that is accessed by selecting the 'Plant information' button. This interface enables the training session facilitator to configure a 'quasi-infinite' number of geo-referenced training scenarios by setting up the industrial plant general information as well as the characteristics and availability of the external resources. The industrial plant general information includes:

- an identification name of the plant;
- the city, the region and the geographical coordinates where the plant is located;
- the total extension of the plant area (m^2) and the terrain characteristics outside the plant (to be chosen among 'Urban', 'Grassy', 'Dry' as, with the weather, this parameter influences the dispersion speed of the fire);
- the number of employees and visitors at the moment of the accident.

This interface also requires the definition of all the external resources involved, including:

- fire stations
    - number of available fire stations;
    - an identification name per each fire station;
    - the geographical coordinates where each station is located;

    - the type of road connecting each station to the plant (‘Local’, ‘Urban’, ‘Extra-Urban’, ‘Highway’);
    - the number of available tankers at each station;

- traffic bureaus
    - number of available traffic bureaus
    - an identification name per each traffic bureau;
    - the geographical coordinates where each traffic bureau is located;
    - the type of road connecting each traffic bureau to the plant (‘Local’, ‘Urban’, ‘Extra-Urban’, ‘Highway’);
    - the number of available vehicles of the local police at each traffic bureau;

- Carabinieri stations
    - number of available Carabinieri stations
    - an identification name per each Carabinieri station;
    - the geographical coordinates where each Carabinieri station is located;
    - the type of road connecting each Carabinieri station to the plant (‘Local’, ‘Urban’, ‘Extra-Urban’, ‘Highway’);
    - the number of available vehicles at each Carabinieri station;
    - the number of available helicopters at each Carabinieri station;

- civil protection departments
    - number of available civil protection departments
    - an identification name per each civil protection department;
    - the geographical coordinates where each civil protection department is located;
    - the type of road connecting each civil protection department to the plant (‘Local’, ‘Urban’, ‘Extra-Urban’, ‘Highway’);
    - the number of available ambulances at each civil protection department;
    - the number of available helicopters at each civil protection department;

- hospitals
    - number of available hospitals
    - an identification name per each hospital;
    - the geographical coordinates where each hospital is located;
    - the type of road connecting each hospital to the plant (‘Local’, ‘Urban’, ‘Extra-Urban’, ‘Highway’);
    - the number of available ambulances (a given amount must be specified per each type of ambulance, i.e. basic transport vehicle, basic emergency vehicles, advanced emergency vehicle) at each hospital;
    - the number of available helicopters at each hospital.

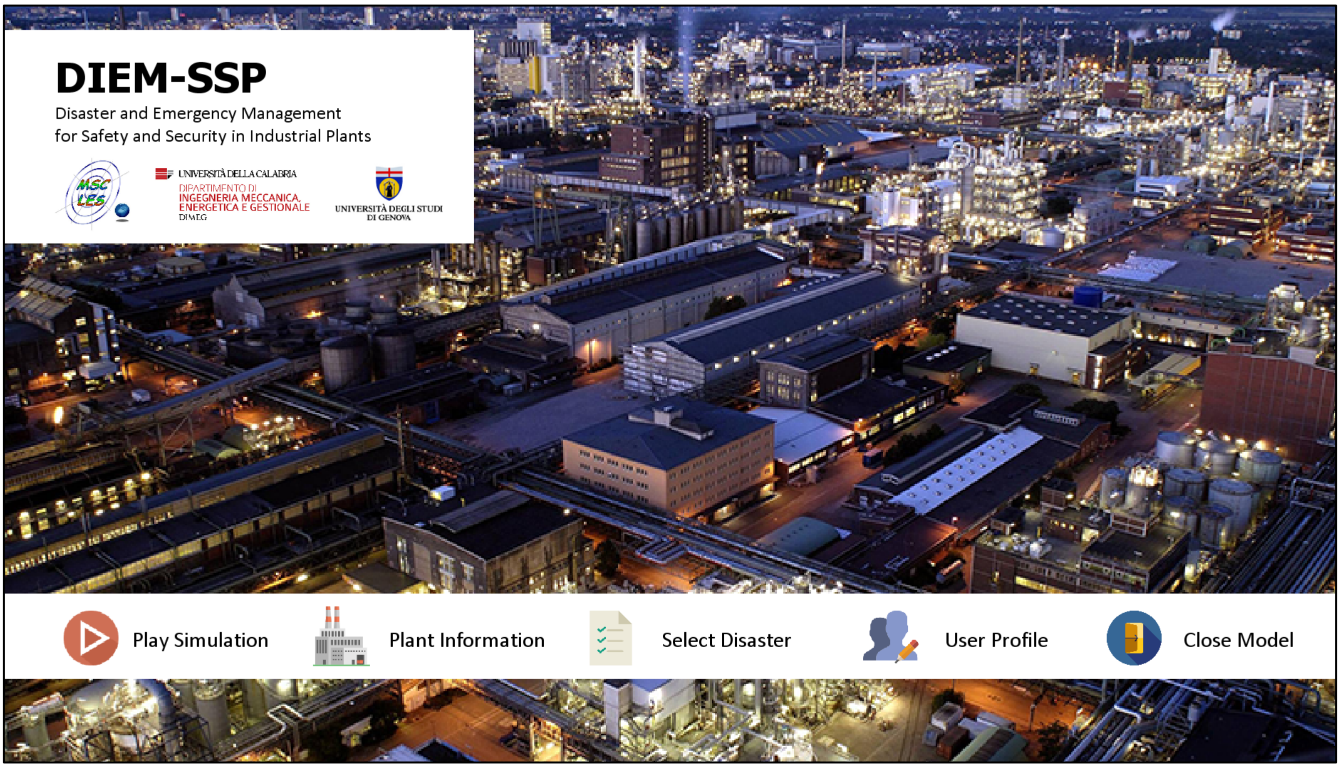


Figure 46: The system home interface

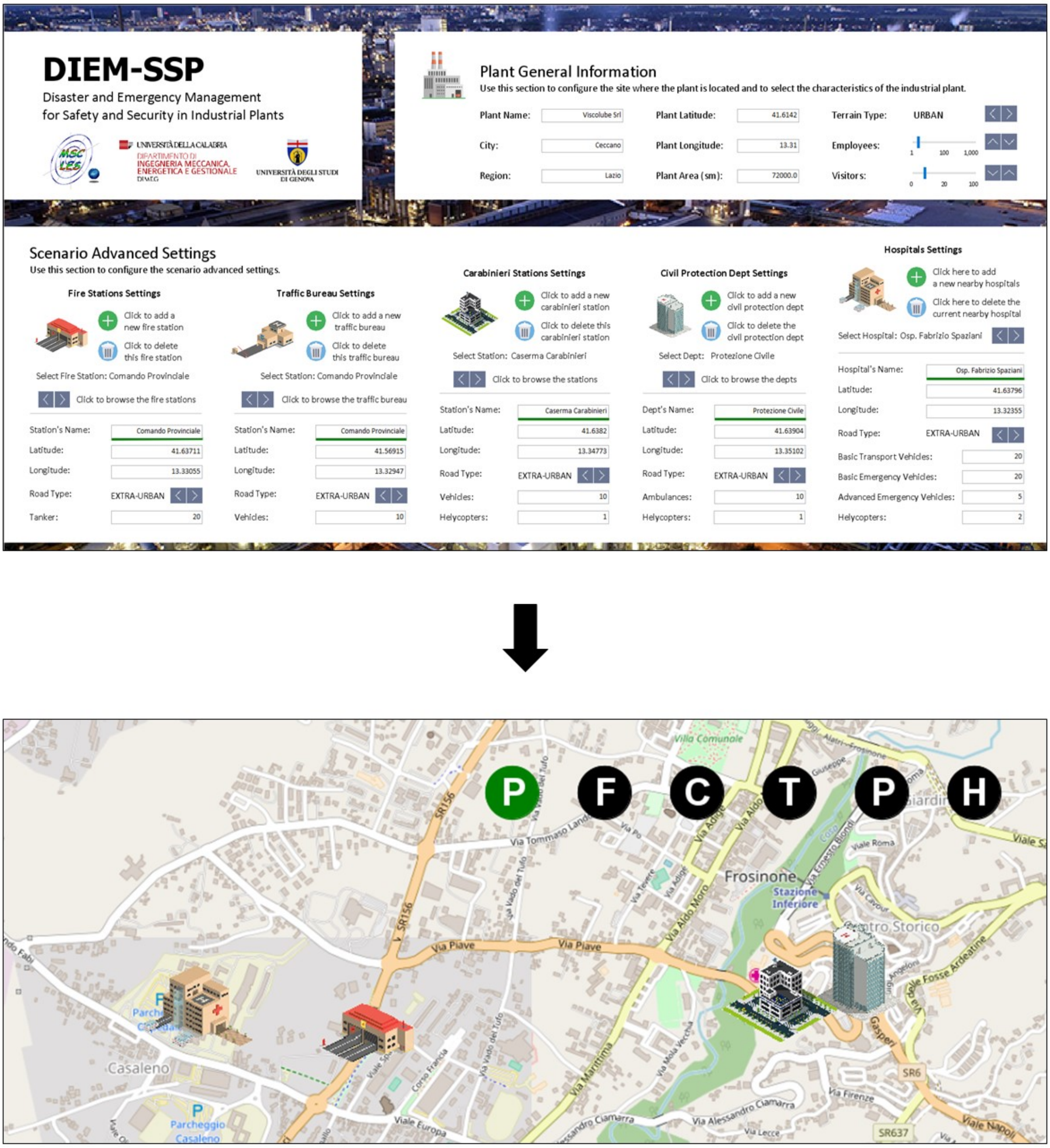
All these information will be used to set used to automatically the training environment and to locate it into a real-world scenario. Indeed, the plant and the external resources will be placed in a geo-referenced map provided by OpenStreetMap based on the provided coordinates (see Figure 47). Using a GIS map will allow to have real information about the available roads, the traffic conditions or the distances between the entities involved into the simulated industrial accident response scenario.

Once the industrial plant general information have been entered, the disaster scenario has to be configured. The interface illustrated in Figure 48 is divided in four sections. The fire general settings include:

- the bounds of the map that will be shown at the beginning of the simulation in the control panel of the emergency manager (it is supposed to be the area where the disaster will take place);
- the disaster's gravity, which represents a [0;1] parameter affecting the complexity of the scenario and the probability functions already depicted in the previous section;
- the fire seed, represented by the geographical coordinates of the location where the disaster (i.e. the fire) takes place.

Additional parameters affecting the fire dynamics can be set up in the next two sections:

- in the fire disaster advanced settings, the training session facilitator can configure
  - the warm-up area (m^2);
  - the fire model's precision, representing the length (in meters) of the cells in the stochastic cellular automata model (observe that the shorter is the edge length, the higher is the need of computational power as more cells will be generated.



DIEM-SSP

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Plant General Information

Use this section to configure the site where the plant is located and to select the characteristics of the industrial plant.

Plant Name: Viscolube Srl
City: Ceccano
Region: Lazio
Plant Latitude: 41.6142
Plant Longitude: 13.31
Plant Area (sm): 72000.0
Terrain Type: URBAN
Employees: 1 – 100 – 1,000
Visitors: 0 – 20 – 100

Scenario Advanced Settings

Use this section to configure the scenario advanced settings.

Fire Stations Settings

Select Fire Station: Comando Provinciale
Station's Name: Comando Provinciale
Latitude: 41.63711
Longitude: 13.33055
Road Type: EXTRA-URBAN
Tanker: 20

Traffic Bureau Settings

Select Station: Comando Provinciale
Station's Name: Comando Provinciale
Latitude: 41.56915
Longitude: 13.32947
Road Type: EXTRA-URBAN
Vehicles: 10

Carabinieri Stations Settings

Select Station: Caserma Carabinieri
Station's Name: Caserma Carabinieri
Latitude: 41.6382
Longitude: 13.34773
Road Type: EXTRA-URBAN
Vehicles: 10
Helycopters: 1

Civil Protection Dept Settings

Select Dept: Protezione Civile
Dept's Name: Protezione Civile
Latitude: 41.63904
Longitude: 13.35102
Road Type: EXTRA-URBAN
Ambulances: 10
Helycopters: 1

Hospitals Settings

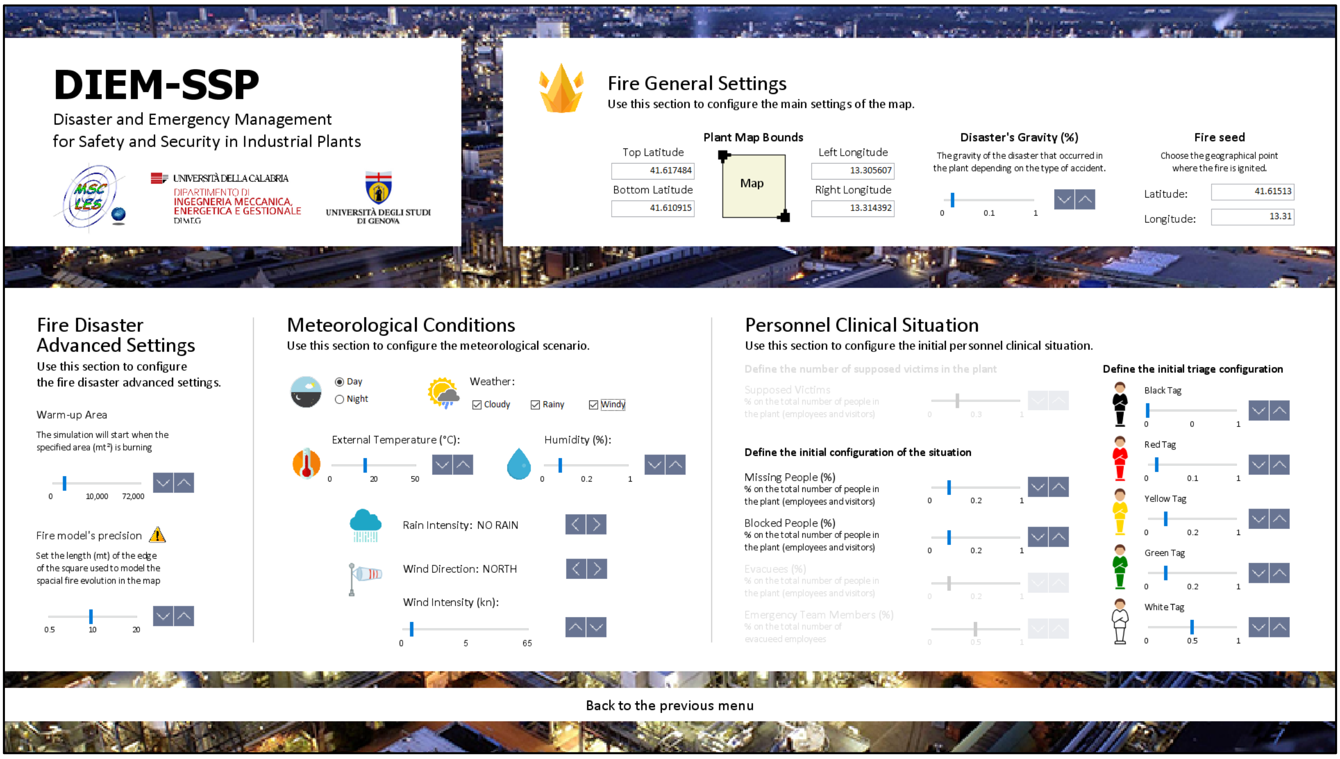
Select Hospital: Osp. Fabrizio Spaziani
Hospital's Name: Osp. Fabrizio Spaziani
Latitude: 41.63796
Longitude: 13.32355
Road Type: EXTRA-URBAN
Basic Transport Vehicles: 20
Basic Emergency Vehicles: 20
Advanced Emergency Vehicles: 5
Helycopters: 2

Figure 47: Scenario Configuration: plants and external resources information and GIS Connectivity

- in the meteorological conditions section, the training session facilitator can define:
  - whether it is day or night;
  - whether it is cloudy, rainy or windy;
  - the external temperature (°C);
  - the external humidity (%);
  - the rain intensity (in case of rain): ‘No rain’, ‘Light’, ‘Moderate’, ‘Heavy’, ‘Violent’;
  - the wind direction (in case of wind): ‘North’, ‘North-West’, ‘West’, ‘South-West’, etc.;
  - the wind intensity (in case of wind) in knots.

The last section of this interface is dedicated to the configuration of the initial personnel status. In particular, for the purpose of this study, the following parameters are needed:

- the percentage of missing people on the total number of people in the plant (employees and visitors);
- the percentage of people on the total number of people in the plant (employees and visitors) that are known to be blocked in a certain area;
- the initial triage situation in terms of percentages of people who are known to be black codes, red codes, yellow codes, green codes and white codes.



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Fire General Settings
Use this section to configure the main settings of the map.

Plant Map Bounds
Top Latitude: 41.617484
Bottom Latitude: 41.610915
Left Longitude: 13.305607
Right Longitude: 13.314392

Disaster's Gravity (%)
The gravity of the disaster that occurred in the plant depending on the type of accident.
0 0.1 1

Fire seed
Choose the geographical point where the fire is ignited.
Latitude: 41.61513
Longitude: 13.31

Fire Disaster Advanced Settings
Use this section to configure the fire disaster advanced settings.

Warm-up Area
The simulation will start when the specified area (mt²) is burning
0 10,000 72,000

Fire model's precision
Set the length (mt) of the edge of the square used to model the spacial fire evolution in the map
0.5 10 20

Meteorological Conditions
Use this section to configure the meteorological scenario.

● Day
○ Night

Weather: ☑ Cloudy ☑ Rainy ☑ Windy

External Temperature (°C): 0 20 50
Humidity (%): 0 0.2 1
Rain Intensity: NO RAIN
Wind Direction: NORTH
Wind Intensity (kn): 0 5 65

Personnel Clinical Situation
Use this section to configure the initial personnel clinical situation.

Define the number of supposed victims in the plant
Supposed Victims
% on the total number of people in the plant (employees and visitors)
0 0.3 1

Define the initial configuration of the situation
Missing People (%)
% on the total number of people in the plant (employees and visitors)
0 0.2 1

Blocked People (%)
% on the total number of people in the plant (employees and visitors)
0 0.2 1

Evacuees (%)
% on the total number of people in the plant (employees and visitors)
0 0.2 1

Emergency Team Members (%)
% on the total number of evacueed employees
0 0.5 1

Define the initial triage configuration
Black Tag: 0 0 1
Red Tag: 0 0.1 1
Yellow Tag: 0 0.2 1
Green Tag: 0 0.2 1
White Tag: 0 0.5 1

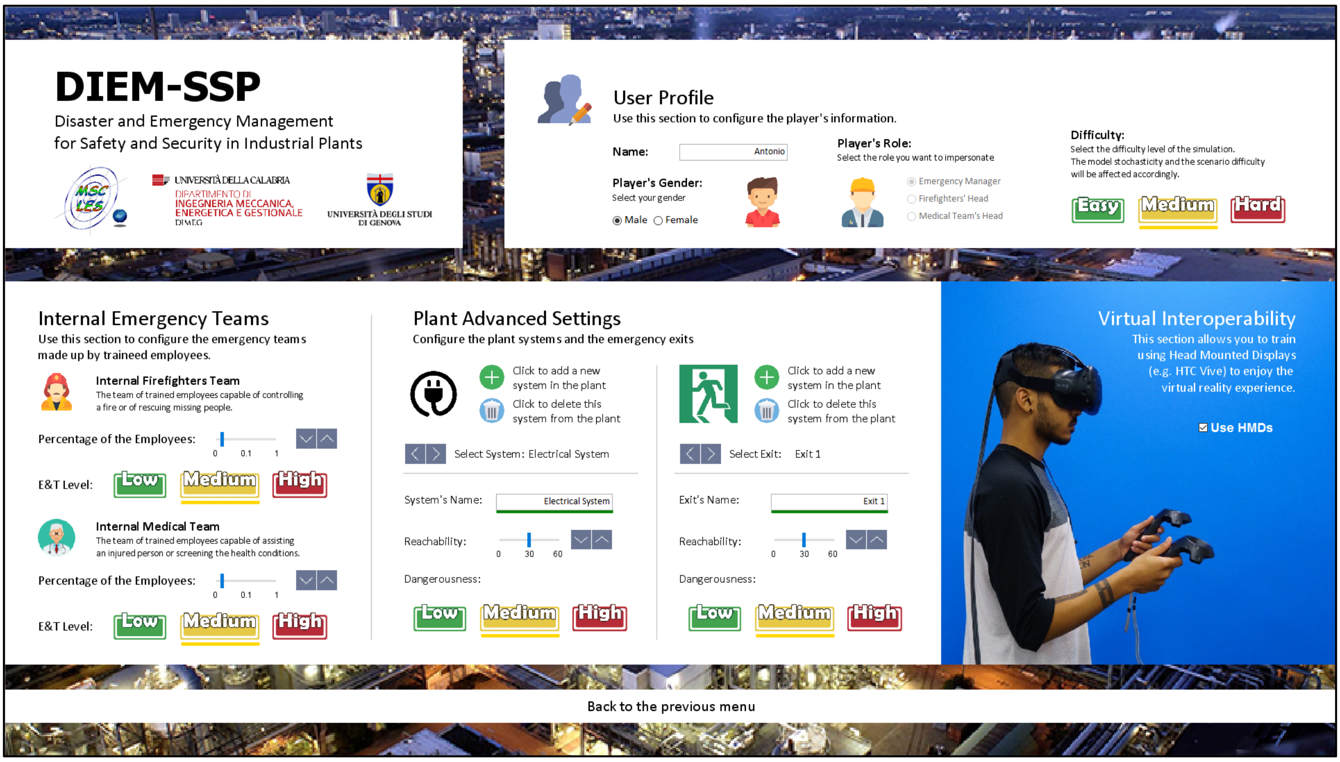
Back to the previous menu

Figure 48: Scenario configuration: disaster scenario

The last interface that has been implemented for the purpose of the training session configuration is illustrated in Figure 49. This interface is mostly related to the user experience. In particular, four sections can be identified. In the upper part, the trainee profile can be created: name, gender, role to be played in the emergency and difficulty level of the serious game ('Easy', 'Medium', 'High') affecting the models' stochasticity. In the lower-left part of the interface, the training session facilitator can define the number of people among the virtual employees of the plant who have been enrolled in the internal firefighters team or in the internal medical (or first aid) team. Indeed, the trainee that will play the role of the internal firefighters team responsible and of the internal first aid team responsible can count on a group of people (whose availability at the moment of the disaster is however stochastically determined by the system). Moreover, their expertise can also be set up ('Easy', 'Medium', 'High'): it will affect the probability of success of the teams when a task is assigned to them.

In the middle part of the interface, further configuration of the difficulty level can be done. Every system, machinery or equipment in the plant will be given a 'dangerousness' level ('Low', 'Medium', 'High') representing how much they have been damaged by the disaster. Therefore, the trainees will be asked to pay more attention to the systems and equipment that are more damaged than others and secure them as soon as possible.

To conclude, in the lower-right part of the interface, the training session facilitator can decide to carry out a joint and interoperable training session with the emergency team members (who are using virtual reality devices) or to carry out a standalone training session where there will be only the trainee playing the role of emergency manager and all the emergency team members will be driven by intelligent agents.


DIEM-SSP

Disaster and Emergency Management for Safety and Security in Industrial Plants

User Profile

Use this section to configure the player's information.

Name: Antonio

Player's Gender: Select your gender ● Male ○ Female

Player's Role: Select the role you want to impersonate ● Emergency Manager ○ Firefighters' Head ○ Medical Team's Head

Difficulty: Select the difficulty level of the simulation. The model stochasticity and the scenario difficulty will be affected accordingly.

Internal Emergency Teams

Use this section to configure the emergency teams made up by traineed employees.

Internal Firefighters Team: The team of trained employees capable of controlling a fire or of rescuing missing people.

Internal Medical Team: The team of trained employees capable of assisting an injured person or screening the health conditions.

Plant Advanced Settings

Configure the plant systems and the emergency exits

Click to add a new system in the plant

Click to delete this system from the plant

Select System: Electrical System

System's Name: Electrical System

Select Exit: Exit 1

Exit's Name: Exit 1

Virtual Interoperability

This section allows you to train using Head Mounted Displays (e.g. HTC Vive) to enjoy the virtual reality experience.

☑ Use HMDs

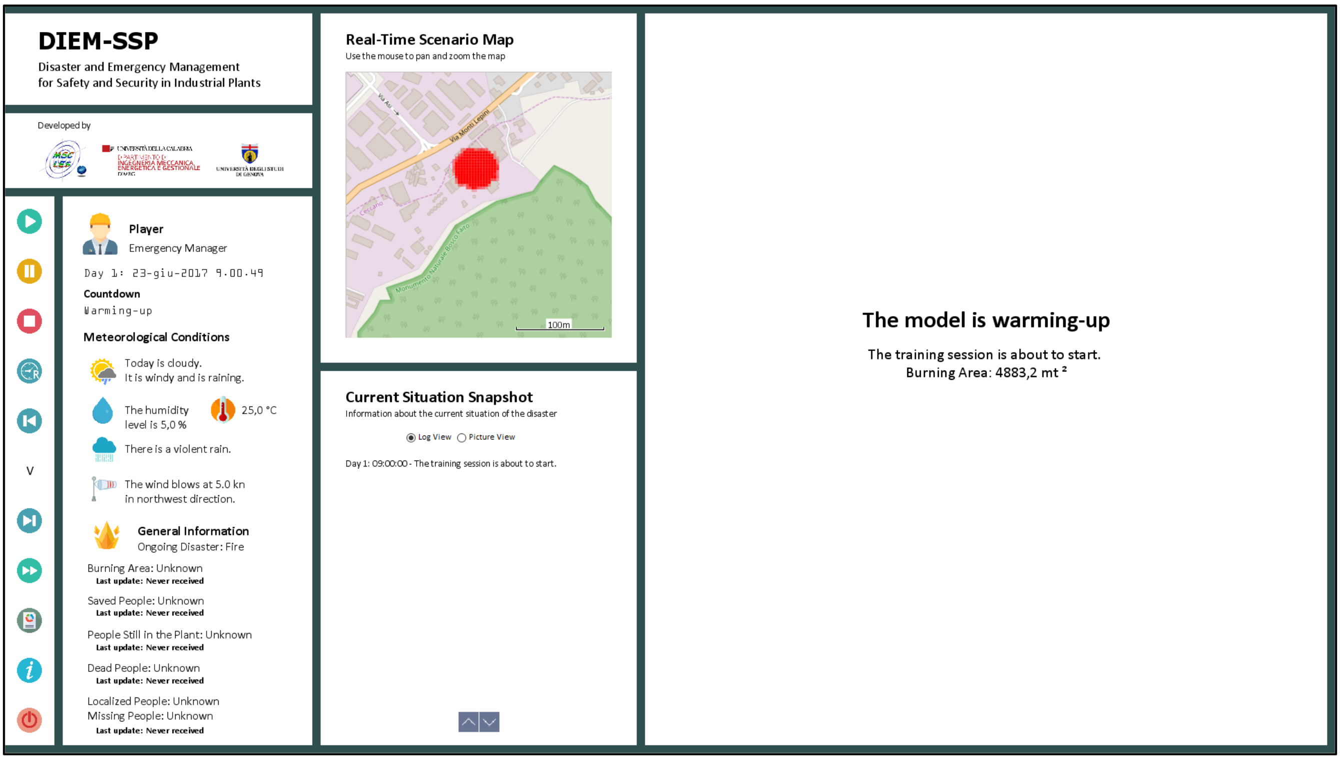
Figure 49. Scenario configuration: user experience and other settings

4.5.2 Players being introduced to the training scenario

After the scenario configuration, the training session goes through a warm-up process (as shown in Figure 50). A warm-up period (no more than 1 minute) is necessary, as the accident scenario is stochastically computer-generated in accordance to the initial configuration parameters and scenario requirements. At the end of the warm-up period, the emergency response team is updated about the ongoing disaster (as it happens in real-world situation) receiving all the most relevant information (situation in the plant, dimensions of the fire and areas interested, available resources nearby the plant, number of people involved, etc.). This information are explained through a text report and a GIS map as shown in Figure 51 and Figure 52. On-screen information is vocally delivered and consists of the following:

i. a map of the location of the accident accompanied by an introduction to the training session;
ii. the accident scenario and the textual description of plant;
iii. the 'theatre of operations', i.e. the sites where resources (e.g. firefighters, police, Carabinieri, hospitals) are located;
iv. the 'road to disaster', which is a summary of the main events leading to the actual disaster situation;
v. the 'operational conditions' (e.g. hypothetical number of injured people, meteorological conditions).

Please note that this is a dynamic report: it is initialized with the scenario data after the warm-up period and it is continuously updated as the time goes by (e.g., the number of people involved increases/decreases, the dimensions of the fire increases/decreases, etc.). This report represents the updated operational picture available for the emergency response team that can access this report at any time during the training session.



DIEM-SSP

Disaster and Emergency Management
for Safety and Security in Industrial Plants

Developed by

Player
Emergency Manager

Day 1: 23-giu-2017 9.00.49

Countdown
Warming-up

Meteorological Conditions

Today is cloudy.
It is windy and is raining.

The humidity level is 5,0 %

25,0 °C

There is a violent rain.

The wind blows at 5.0 kn in northwest direction.

General Information
Ongoing Disaster: Fire

Burning Area: Unknown
Last update: Never received

Saved People: Unknown
Last update: Never received

People Still in the Plant: Unknown
Last update: Never received

Dead People: Unknown
Last update: Never received

Localized People: Unknown
Missing People: Unknown
Last update: Never received

Real-Time Scenario Map
Use the mouse to pan and zoom the map

Current Situation Snapshot
Information about the current situation of the disaster

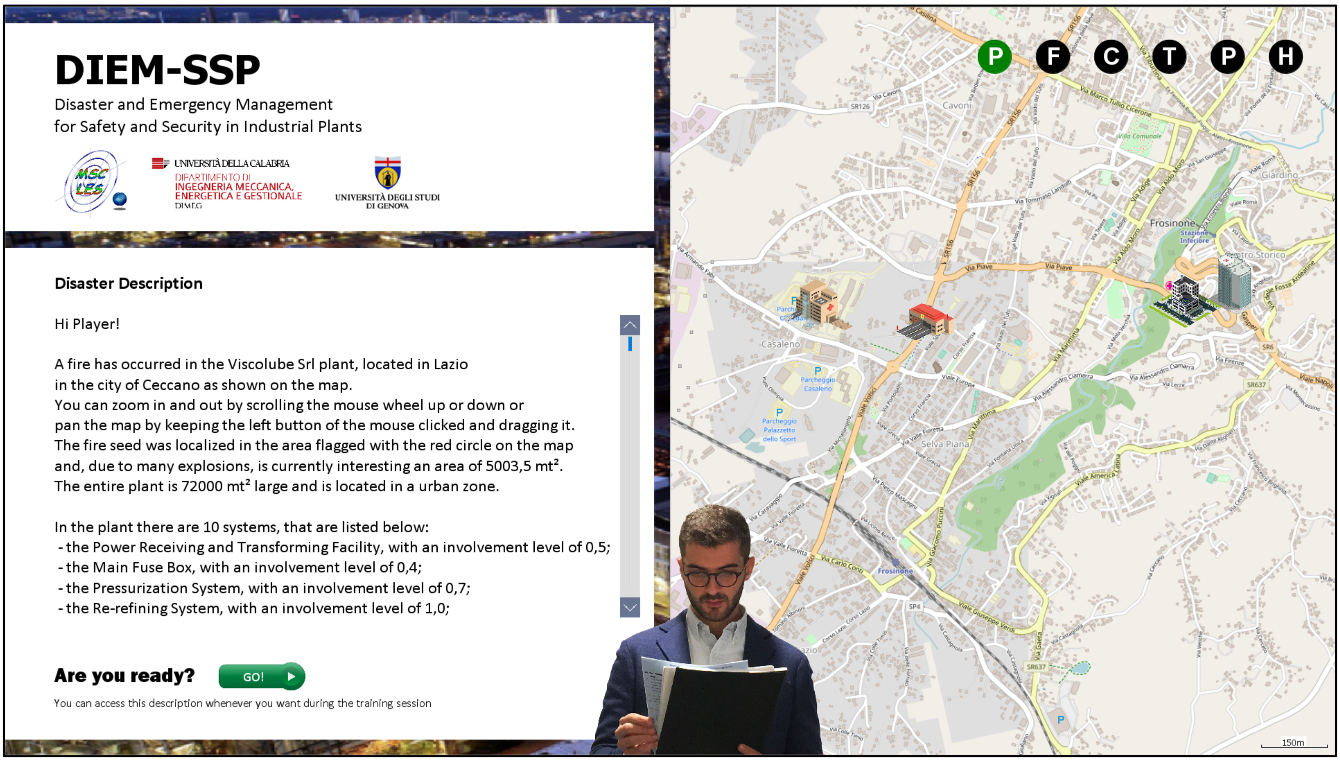
● Log View ○ Picture View

Day 1: 09:00:00 - The training session is about to start.

The model is warming-up

The training session is about to start.
Burning Area: 4883,2 mt^{2}

Figure 50. Warming-up the training scenario



DIEM-SSP

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for Safety and Security in Industrial Plants

Disaster Description

Hi Player!

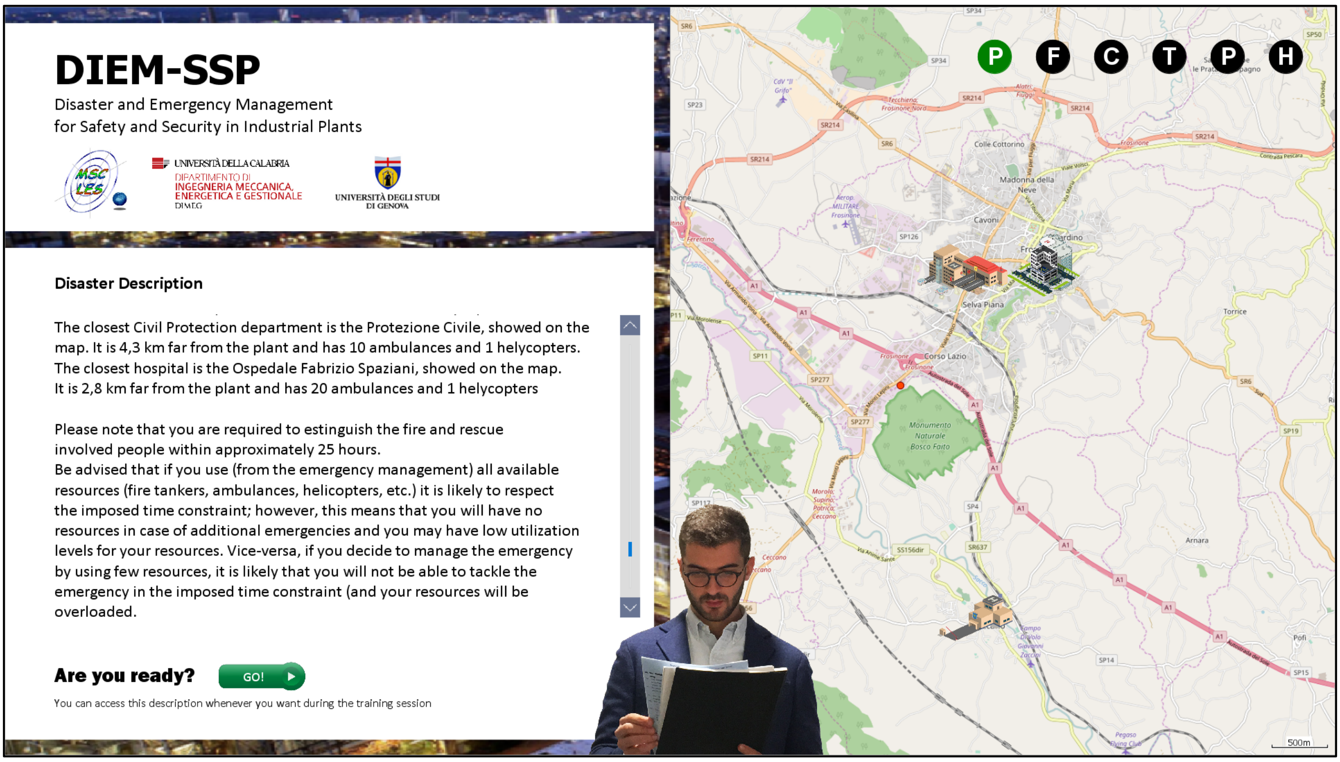
A fire has occurred in the Viscolube Srl plant, located in Lazio
in the city of Ceccano as shown on the map.
You can zoom in and out by scrolling the mouse wheel up or down or
pan the map by keeping the left button of the mouse clicked and dragging it.
The fire seed was localized in the area flagged with the red circle on the map
and, due to many explosions, is currently interesting an area of 5003,5 mt².
The entire plant is 72000 mt² large and is located in a urban zone.

In the plant there are 10 systems, that are listed below:
- the Power Receiving and Transforming Facility, with an involvement level of 0,5;
- the Main Fuse Box, with an involvement level of 0,4;
- the Pressurization System, with an involvement level of 0,7;
- the Re-refining System, with an involvement level of 1,0;

Are you ready? GO!

You can access this description whenever you want during the training session

Figure 51. Storytelling: introduction to the training scenario



DIEM-SSP

Disaster and Emergency Management
for Safety and Security in Industrial Plants

Disaster Description

The closest Civil Protection department is the Protezione Civile, showed on the
map. It is 4,3 km far from the plant and has 10 ambulances and 1 helycopters.
The closest hospital is the Ospedale Fabrizio Spaziani, showed on the map.
It is 2,8 km far from the plant and has 20 ambulances and 1 helycopters

Please note that you are required to estinguish the fire and rescue
involved people within approximately 25 hours.
Be advised that if you use (from the emergency management) all available
resources (fire tankers, ambulances, helicopters, etc.) it is likely to respect
the imposed time constraint; however, this means that you will have no
resources in case of additional emergencies and you may have low utilization
levels for your resources. Vice-versa, if you decide to manage the emergency
by using few resources, it is likely that you will not be able to tackle the
emergency in the imposed time constraint (and your resources will be
overloaded.

Are you ready? GO!

You can access this description whenever you want during the training session

Figure 52. Storytelling: training session details

4.5.3 The emergency manager: run-time interfaces

Once the trainees have read the scenario description thoroughly, the players are guided to the run-time interfaces, where they will be asked to act on the scenario and make decisions. Figure 53 shows the main graphical user interface of the emergency manager’s control panel.

It is organized as follows:

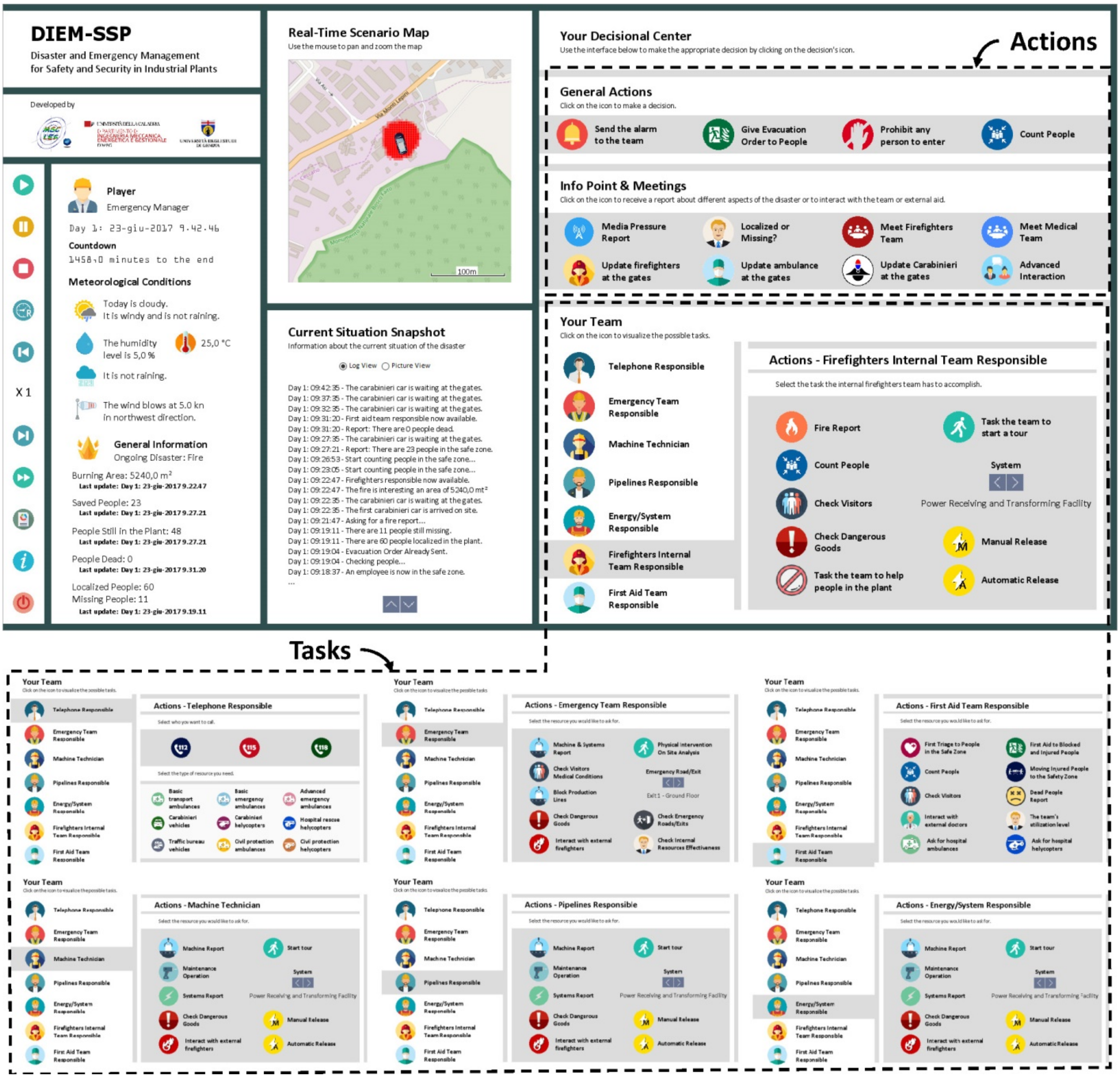
- In the very left part of the interface, the simulation control buttons are available. They enable the emergency manager to play the simulation, to pause it, to stop it, to set the simulation speed at the wall clock time, to set the speed at the maximum virtual speed or to increase/reduce the simulation speed values. It is also possible to access again the initial scenario description, to access the training system information or to close the model.
- Next to this section, the emergency manager finds synthetic information about the ongoing scenario. It includes the time into the training environment and the countdown to the end of the training session, the meteorological conditions and general summary information about the fire accident, such as the current burning area, the number of saved people, the number of people still in the plant, the number of people dead, the number of people that are still missing. It should be noted that this information is updated every time the emergency manager requests and receives an update by the emergency response team.
- The central section of the control panel shows a 2-dimensional GIS map that shows how the cellular automata representing the fire evolution grows (the red squares) and the movement of the animations of all the entities in the virtual environment (e.g. carabinieri, ambulances, etc.). The map represents a bird's eye view of the fire and is plotted as a grid of squares with the chosen edge length. The opaqueness value of the square with coordinates (lat, lon) is given by the temperatures in every cell of the cellular automata normalized in an interval [0;1] with the temperatures of the other squares. Below, a log of all the events happening in the virtual environment is produced in real-time. In particular, the time the event occurs and a description of the event is provided. The log gives the emergency manager an immediate feedback of the decisions made and action taken during the training session.
- In the right section of the control panel, the trainee playing the role of the emergency manager can click on the buttons to acquire information about the ongoing disaster, to perform strategic tasks (see the 'general actions' or 'info point & meetings' in the interface) or to assign a specific task to any member of the emergency team, namely the telephone operator, the systems responsible, the pipelines responsible, the machine responsible, the internal firefighters responsible and the internal first aid team responsible. The decisional center of the emergency manager is then composed of the following actions that the emergency manager can perform in first person:
  - General actions:
    - Send the alarm to the emergency response team
    - Give the people in the plant the evacuation order
    - Prohibit any person to enter the plant
    - Count the number of people in the safe zone
  - Info point & meetings
    - Media report
    - Detect localized and missing people
    - Meet the internal firefighters team
    - Meet the internal first aid team
    - Meet the external firefighters team

    - Meet the external medical team
    - Meet the carabinieri
    - Interact with the people in the plant

Right below the actions to be performed in first person, the emergency manager can assign a task to the people who belong to the emergency response team and are currently available. In the proposed prototype, the emergency manager's control panel include (among others) the following buttons:

- Telephone responsible:
    - Ask to call 112 (Carabinieri), 115 (Firefighters), 118 (Emergency Services)
    - Ask to keep active contact with the civil protection headquarter
- Evacuation responsible:
    - Ask to intervene on site with fire extinguishers
    - Ask to help people evacuating in a certain area of the plant
- Machine responsible:
    - Ask to secure the machines
    - Ask to check and secure dangerous goods
- Pipelines responsible:
    - Ask to secure a damaged pipeline
    - Ask for a pipeline status report
- Energy responsible:
    - Ask to check the emergency exits
    - Ask to shut off the electrical system
- Internal firefighters team responsible:
    - Ask for a fire report
    - Ask to start a search & rescue tour in the plant
- Internal first aid team responsible:
    - Ask to give you an update about the triage to the people in the safe zone
    - Ask to move injured people to the safe zone

The list of actions that the emergency manager can assign to an emergency response team member is rich and also includes unsuitable tasks for that role (e.g. ask to provide first aid to injured people in the plant). It is up to the emergency manager to assign correctly the tasks to the team members for an efficient and effective management of the situation.


DIEM-SSP
Disaster and Emergency Management for Safety and Security in Industrial Plants

Developed by

Player
Emergency Manager
Day 1: 23-giu-2017 9.42.46
Countdown
1458,0 minutes to the end

Meteorological Conditions
Today is cloudy.
It is windy and is not raining.
The humidity level is 5,0 %
25,0 °C
It is not raining.
The wind blows at 5.0 kn in northwest direction.

General Information
Ongoing Disaster: Fire
Burning Area: 5240,0 m²
Last update: Day 1: 23-giu-2017 9.22.47
Saved People: 23
Last update: Day 1: 23-giu-2017 9.27.21
People Still in the Plant: 48
Last update: Day 1: 23-giu-2017 9.27.21
People Dead: 0
Last update: Day 1: 23-giu-2017 9.31.20
Localized People: 60
Missing People: 11
Last update: Day 1: 23-giu-2017 9.19.11

Real-Time Scenario Map
Use the mouse to pan and zoom the map

Current Situation Snapshot
Information about the current situation of the disaster
● Log View ○ Picture View

```
Day 1: 09:42:35 - The carabinieri car is waiting at the gates.
Day 1: 09:37:35 - The carabinieri car is waiting at the gates.
Day 1: 09:32:35 - The carabinieri car is waiting at the gates.
Day 1: 09:31:20 - First aid team responsible now available.
Day 1: 09:31:20 - Report: There are 0 people dead.
Day 1: 09:27:35 - The carabinieri car is waiting at the gates.
Day 1: 09:27:21 - Report: There are 23 people in the safe zone.
Day 1: 09:26:53 - Start counting people in the safe zone...
Day 1: 09:23:05 - Start counting people in the safe zone...
Day 1: 09:22:47 - Firefighters responsible now available.
Day 1: 09:22:47 - The fire is interesting an area of 5240,0 mt²
Day 1: 09:22:35 - The carabinieri car is waiting at the gates.
Day 1: 09:22:35 - The first carabinieri car is arrived on site.
Day 1: 09:21:47 - Asking for a fire report...
Day 1: 09:19:11 - There are 11 people still missing.
Day 1: 09:19:11 - There are 60 people localized in the plant.
Day 1: 09:19:04 - Evacuation Order Already Sent.
Day 1: 09:19:04 - Checking people...
Day 1: 09:18:37 - An employee is now in the safe zone.
...
```

Your Decisional Center
Use the interface below to make the appropriate decision by clicking on the decision's icon.

General Actions
Click on the icon to make a decision.

Info Point & Meetings
Click on the icon to receive a report about different aspects of the disaster or to interact with the team or external aid.

Your Team
Click on the icon to visualize the possible tasks.

Actions - Firefighters Internal Team Responsible
Select the task the internal firefighters team has to accomplish.

Figure 53. Emergency manager's control panel

4.5.4 The emergency team member: run-time interfaces and virtual experience

In the collaborative training session mode, when the emergency manager clicks on the button of a specific task, the corresponding emergency team member will be signaled to perform the requested action. The request to perform the task will be received by the Emergency Team Member Interaction System that, as explained before, is based on the 3D virtual environment recreating the disaster scenario experienced by the trainees via a head-mounted display. Once immersed in this environment, the trainee (acting as one of the emergency response team members) is required to perform specific actions as he/she usually does in the real life in case of accidents. As shown in Figure 54, the emergency team members are required to execute the tasks as they really would do in the real environment by using the joysticks. For example, in case a gate valve has to be closed in the virtual environment, the trainee is required to grab the valve with the joysticks and rotate them as illustrated in the picture. The joysticks also provide haptic feedback to give the trainee the real feeling to grab the valve.

Figure 55 presents a selection of six tasks performed by some people playing the role of the emergency team members:

- Sending the evacuation alarm to the people in the plant;
- Delimit the dangerous area;
- Call the ambulances;
- Shut off remotely the pumping system;
- Close the gate valve of the oil pipeline;
- Prepare a report of the emergency manager.

For each of the six tasks, the location where the task is executed in the virtual environment is showed on the right while the trainee playing the role of the emergency response team member is showed on the left side. The figure also shows how the trainee is asked to perform all the necessary gestures (e.g. when using the phone, when delimiting the dangerous area with the PVC warning tape or when grabbing and moving down the lever to shut off the pumping system).

Figure 54: Immersive training sessions with gesture recognition

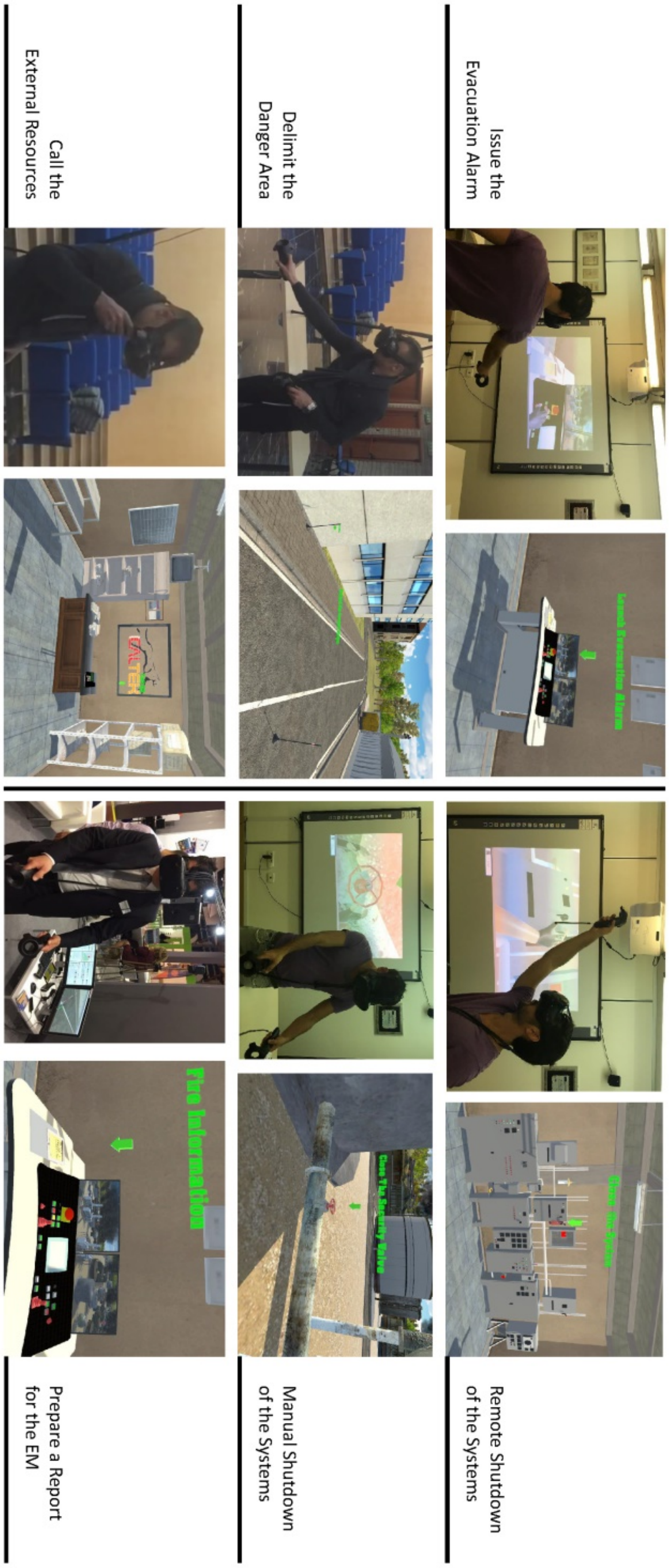


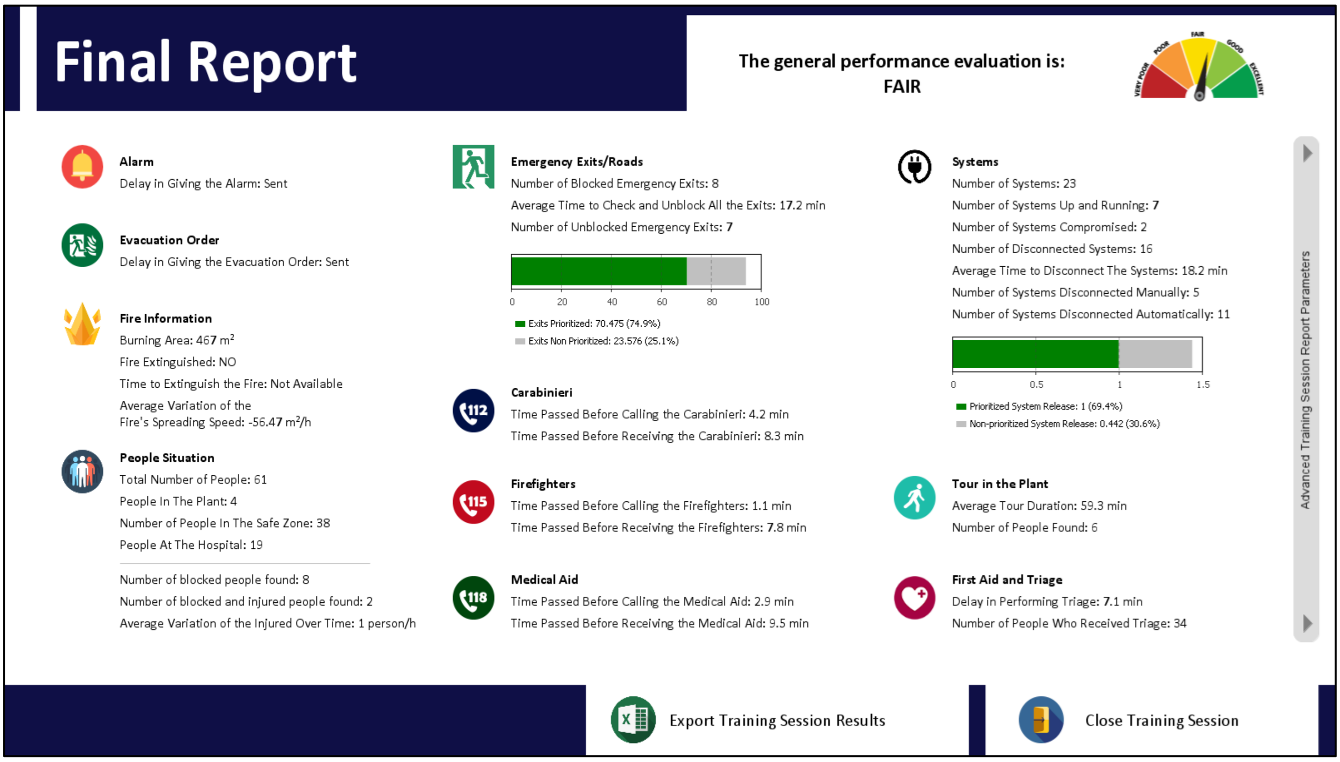
Figure 55. A selection of six tasks performed by the emergency team members

4.5.5 Training session report

The training session ends when the MIA has been worked out or when the given time runs out. A final report is provided to the trainees for further discussion and debriefing about their performance. The report (whose interface is shown in Figure 56) includes:

- a general performance dashboard based on a Likert scale (1: Very Poor; 2: Poor; 3: Fair; 4: Good; 5: Excellent) useful to get at a glance the result of the training session;
- the key performance indicators listed at the beginning of this chapter that will allow to focus on each aspects of the emergency response.

Result data can be exported as Excel worksheet to be used for post-training debriefing and analysis by clicking on the button at the bottom of the interface.



Final Report

The general performance evaluation is:
FAIR

Alarm
Delay in Giving the Alarm: Sent

Evacuation Order
Delay in Giving the Evacuation Order: Sent

Fire Information
Burning Area: 467 m²
Fire Extinguished: NO
Time to Extinguish the Fire: Not Available
Average Variation of the Fire's Spreading Speed: -56.47 m²/h

People Situation
Total Number of People: 61
People In The Plant: 4
Number of People In The Safe Zone: 38
People At The Hospital: 19

Number of blocked people found: 8
Number of blocked and injured people found: 2
Average Variation of the Injured Over Time: 1 person/h

Emergency Exits/Roads
Number of Blocked Emergency Exits: 8
Average Time to Check and Unblock All the Exits: 17.2 min
Number of Unblocked Emergency Exits: 7

Carabinieri
Time Passed Before Calling the Carabinieri: 4.2 min
Time Passed Before Receiving the Carabinieri: 8.3 min

Firefighters
Time Passed Before Calling the Firefighters: 1.1 min
Time Passed Before Receiving the Firefighters: 7.8 min

Medical Aid
Time Passed Before Calling the Medical Aid: 2.9 min
Time Passed Before Receiving the Medical Aid: 9.5 min

Systems
Number of Systems: 23
Number of Systems Up and Running: 7
Number of Systems Compromised: 2
Number of Disconnected Systems: 16
Average Time to Disconnect The Systems: 18.2 min
Number of Systems Disconnected Manually: 5
Number of Systems Disconnected Automatically: 11

Tour in the Plant
Average Tour Duration: 59.3 min
Number of People Found: 6

First Aid and Triage
Delay in Performing Triage: 7.1 min
Number of People Who Received Triage: 34

Figure 56: Training session final report

4.6 The human factors assessment methodologies

Stress and workload are the two human factors considered in this study as relevant determinants of human performance. The respective assessment methodologies used during the training sessions to detect stress and workload levels of the emergency response staff under training are here described.

4.6.1 The heart beat as a measure of stress

Since stress is also associated with physiological changes, such as higher heart rate and lowered heart rate variability, the heart beat detection has been proposed as indicator for investigating the physiological effects of stress. The heart rate measures the number of times per minute that the heart contracts or beats. The use of Apple Watches Series 2 to monitor the heart rate of the participants along the replications has been considered accurate enough for the purpose of this study. Indeed, the ultimate goal is not to measure accurately the heart rate but to monitor the trajectory of the heart rate along the training sessions and to assess the potential differences of the average heart rate between pairs of replications. The heart beat rate has been registered every 5 seconds both under idling conditions and during the different training sessions.

4.6.2 The X-NASA-TLX as a measure of the workload

The eXpanded NASA Task Load Index (X-NASA TLX) extends the traditional six dimensions of the NASA-TLX to twelve with the aim to include the peculiar aspects of the application domain (i.e. industrial emergency management) and of the way the tasks are executed in the scenario (i.e. VR and SG). The workload contributing factors have been defined to increase proportionally the perceived workload. The first three ones refer to the "scenario's demands imposed on the subject", while the next three ones refer to the "subject's interaction with the scenario":

- **F_1 – Mental Demand:** How much mental and perceptual activity (e.g. thinking, deciding) did the tasks require?
- **F_2 – Physical Demand:** How much physical activity (e.g. walking, running, pushing, pulling, etc.) was required?
- **F_3 – Temporal Demand:** How much time pressure did you feel due to the rate or pace at which the tasks occurred?
- **F_4 – Failure:** How unsuccessful do you think you were in accomplishing the goals set by the experimenter?
- **F_5 – Effort:** How hard did you have to work (mentally and physically) to accomplish your level of performance?
- **F_6 – Frustration:** How insecure, discouraged, irritated and stressed did you feel while performing the tasks?

The first two differences with the NASA-TLX are the following. First, F_2 is not intended in terms of physical movements because the emergency scenario is experienced through VR equipment but can be deduced by the *level of realism* – "how much real did the scenario look?", the *level of interactivity* – "how much involved did you feel in the scenario?" – and the *level of fatigue* – "how much discomfort did you feel using the hardware?" – generated by the VR experience. Secondly, the "Performance" factor of the NASA-TLX was converted into "Failure" in order to establish a proportional relation (if the operators feel unsuccessful in accomplishing the goals set by the experimenter, they probably perceive a high workload).

Six additional workload contributing factors related to teamwork aspects (and therefore to the collective sphere) which are crucial in an emergency management, have been then included. Indeed, it is widely recognized that people need to cooperate at different levels in daily activities and team working is crucial especially in case of emergencies. Any delay due to cooperation or misunderstanding or dissatisfaction with the team's support might lead the situation to a breakdown. The first three factors refer to the "scenario's demands imposed on the team", while the other ones to the scale "Team's interaction with the scenario":

- **F_7 – Coordination Demand:** How much coordination activity (e.g. synchronization, adjustment) was required?
- **F_8 – Communication Demand:** How much hard was the communication (e.g. discussing, negotiating, sending and receiving messages) to accomplish the tasks?
- **F_9 – Cooperation Demand:** How much cooperation with other virtual team members was needed to accomplish the tasks? How difficult was it to work as a team?
- **F_{10} – Ineffectiveness:** How unsuccessful do you think the team was in working as a team to accomplish the goals?
- **F_{11} – Lack of Support:** How difficult was it to provide and receive support from other team members?
- **F_{12} – Dissatisfaction:** How unsatisfied were you with working as a team? Was it emotionally draining and irritating or emotionally rewarding and satisfying?

The participants have been first asked to provide responses to pair-wise comparisons to assess the degree to which each factor generally contributes, in their opinion, to increase the perceived workload in a generic emergency situation. In order to answer the questions "how much does factor A influence the perceived workload compared to factor B?", the paradigm of the Fuzzy Analytic Hierarchy Process turned out to be very useful to rank the scales by developing a numerical score on the basis of linguistic preference judgements provided by the experts. The linguistic terms with their corresponding triangular fuzzy numbers are reported in Table 8.

Table 8: Linguistic preference judgements

Linguistic Variable	**Fuzzy Number**		
Absolutely Less Important Than	2/9	1/4	2/7
Strongly Less Important Than	2/7	1/3	2/5
Fairly More Important Than	2/5	1/2	2/3
Weakly Less Important Than	2/3	3/4	1
Equally Important	1	1	1
Weakly More Important Than	1	4/3	3/2
Fairly More Important Than	3/2	2	5/2
Strongly More Important Than	5/2	3	7/2
Absolutely More Important Than	7/2	4	9/2

Thereafter, the linguistic terms were converted into a symmetric fuzzy pairwise comparison matrix with (1, 1, 1) on the main diagonal. Once all pair-wise comparisons have been obtained, the judgments have been synthesized into a single group pair-wise comparisons matrix, where the generic element is calculated by using a geometric mean. The use of the geometric mean keeps the group pairwise comparisons matrix reciprocal and conservative. The fuzzy weights for every workload contributing factor are then derived as in Ramík and Perzina (2014) and then converted in crisp numbers by calculating their Centre of Gravity (CoG).

Another computerized questionnaire was created to be submitted to the subject to obtain the subjective workload ratings for the performed and specific emergency scenario that has been experienced. The scale of values which were used to rate the subject's perception of the contribution of the given factor to the overall workload is divided into 21 tick marks (Low/-10, Balanced/0, High/+10). If the given value is between -10 and 0, it means that the test subject does not feel very overloaded on that specific factor (e.g. mental demand); a value between 0 and 10 implies an operator's workload on that specific factor.

Once all sessions have been conducted, the pairwise judgments have been synthesized into a single group pair-wise comparisons matrix, where the generic element is calculated by using a geometric mean. The fuzzy weights for every workload contributing factor are then derived and converted in crisp numbers by calculating their Centre of Gravity. Instead, the ratings of every workload contributing factor referred to the specific emergency scenario experienced by the subjects were converted from the [-10; 0; +10] scale to a [-1; 0; +1] scale and synthetized into a group mean rating. An Overall Workload Judgement (OWJ) index is eventually calculated as the algebraic sum of all the weighted scores. As a result, the OWJ will range from -100% and +100%.

4.6.3 Linking the stress and workload ratings to the emergency response KPIs

In the final stage of this study, the correlation between the variables of interest has been statistically investigated. In particular, the relationships between workload (OWJ) and stress (Heart Rate), workload (OWJ) and KPIs, stress (Heart Rate) and KPIs have been analyzed (see Figure 57).

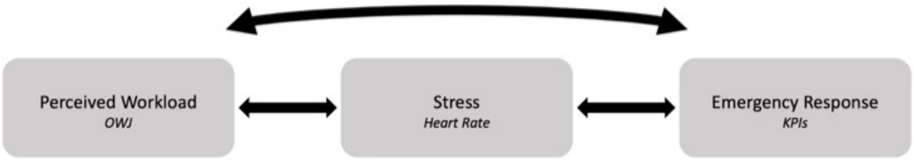


Figure 57: Relationships under investigation

A second order polynomial regression curve has been adopted to highlight the latent Yerkes-Dodson effect in the available data and the R^2 and p-value are calculated to assess how well the model fits the data. If the p-value is less than the significance level (0.05), then we conclude that the regression curve fits properly the available data and the derived insights can be considered relevant.

5 Experimental setup and case study

This chapter introduces to the experimental campaign conducted to test the effectiveness of the developed training system prototype. The experimental aims have been clearly stated in Chapter 3 to serve as guidance for the design of the experimental campaign.

Experimental campaign aims

Study Aim #2: To demonstrate whether the developed industrial emergency response training system is capable of enhancing significantly the personnel rate of retention and emergency preparedness technical (i.e. procedural) and non-technical (e.g. leadership, decision-making, team-working, stress management) skills.

Study Aim #2.1: To design an experimental campaign that could potentially highlight the personnel improvement rate of technical and non-technical skills and capture (if any) the effects on performance and psychological pressure of replacing the partner.

Study Aim #2.2: To carry out structured experimentations and analyze the training results to assess after repeated training sessions.

- how the performance of the emergency manager and of the emergency team member evolve along the replications (see the Mission Fulfillment KPIs);
- to which extent the proposed training approach is effective in delivering procedural knowledge to emergency managers and emergency team members (see the Procedural Compliance KPIs);
- whether it is realistic enough to think that the training experience produces psychological stress in those people that are trained with it (the emergency managers and emergency team members) and how they cope with stress over the repeated replications (see the Psychological Stress KPIs);
- whether and to which extent human factors, such as stress and perceived workload, are correlated to the capability of the emergency manager to coordinate and monitor the execution of all the measures and actions intended to deal with an industrial accident and its effects.

A brief description of the participants to the experiments and of the hardware used is then provided. The experimental campaign setup and conduct that can allow us to address the experimental aims is described and, at the end, the case study used to configure the training environment is depicted.

5.1 Participants

The experimental campaign has been carried out hiring 80 volunteers (between 22 and 60 years) among operators working in industrial plants and excluding actual emergency response team members. The rationale for this choice is that involving people with a previous background in emergency management could have biased the analysis. No specific competence or skill is then requested. Given the use of virtual reality devices that can provoke nausea, people have been asked to confirm that they had no physical or cardiovascular problems or concerns.

5.2 Selection of hardware

A proper selection of the hardware to run the system is crucial to avoid problems in terms of processing and computational requirements and graphics. To the purpose, the following devices have been used:

- three commercial ASUS G11CB with a processor Intel Core i7-6700 CPU @ 3.40 GHz, Graphics: NVIDIA GeForce® GTX 970, Memory 16GB with Windows 10;
- one HTC Vive with Audio and Motion Sensors;
- two Apple Watches Series 2.

5.3 Experimental campaign setup

The participants were clustered in two groups (depending on the role played in the training sessions): 40 emergency managers and 40 emergency team members. Consider for example two emergency managers (indicated with A and B) and two emergency team members (indicated with C and D) from the two groups of participants. For the sake of simplicity, the cooperation pattern over four replications of the training session is depicted in Figure 58, where the symbol ǁ indicates that the two participants (e.g. an emergency manager and an emergency team member) are playing together in a single training session. The first two replications of the training session (indicated with R1 and R2) are carried out by A ǁ C and B ǁ D, as showed in Figure 58. In order to capture (if any) the effects on performance and psychological pressure of replacing the partner, the next two replications (R3 and R4) are carried out as follows with inverted partners: A ǁ D and B ǁ C. Eventually, each trainee carried out four training sessions, 160 training sessions were conducted in total.

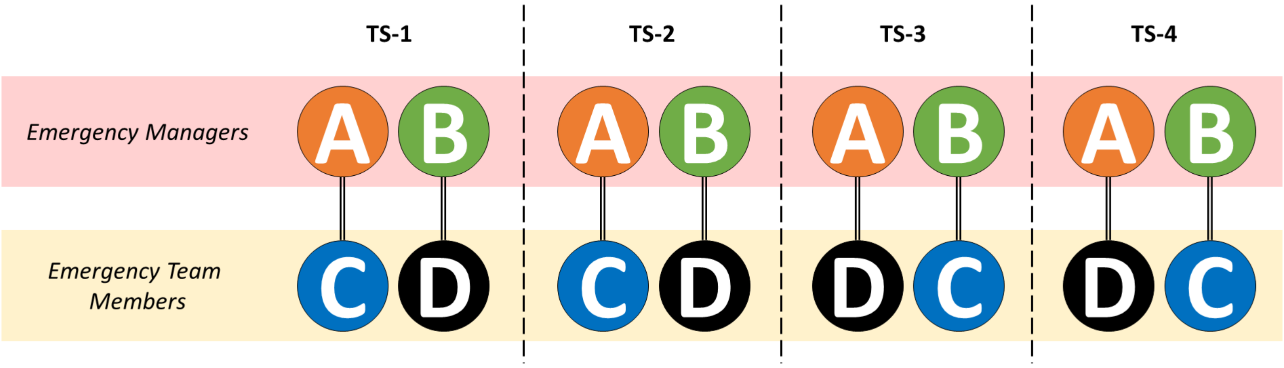


Figure 58: Cooperation pattern among four participants over four replications of the training session

Besides the emergency manager and the emergency team member that are real players, each training session is populated by other emergency team members driven by Intelligent Agents. The emergency manager is then called to coordinate a team of people (a real emergency team member and the others driven by intelligent agents). The actual emergency team member is asked to cooperate not only with the emergency manager but also with other emergency team members driven by intelligent agents by means of digital equipment, e.g. microphones or sound equipment. The configuration of a single training session is illustrated in Figure 59.

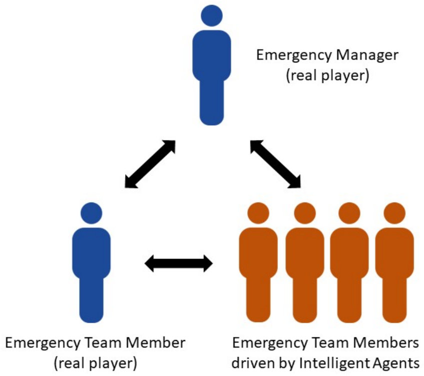


Figure 59: Players in a training session

5.4 Experimental campaign conduct

Experiments are conducted in accordance to the lifecycle that encompasses three major steps:

Stage 1. Preparation. Once everything is ready for the training session, participants were welcomed to the training facility, thanked for their participation and shown to seats in the experiment room. At the very beginning, the steady-state heart rate of the participants in beats per minute (bpm) was recorded with the assistance of two training session facilitators from the research team for 1 minute for calibration purposes. The two training session facilitators spoke then to the group. On one hand, they emphasized that the format of the experiment would differ from that of the traditional training sessions. As participants have little or no knowledge of emergency management, a traditional 1-hour class was conducted to present the procedures and plans the participants are expected to apply. On the other side, the facilitators also introduced the system and discussed the elements of the computer interface and virtual reality devices, thus allowing the participants to manipulate the interface and devices smoothly. The preparation stage concluded once participants seemed to be comfortable with the system. What is relevant to stress is that, in the first replication of the training session, the experiment personnel stayed in the room to provide support with the emergency procedures and with the system interface if need be. In the remaining replications, all experiment personnel were in a separate room out of participants' view, as they should have acquired enough experience with the system and procedures. Participants were then told that all information about the disaster would be presented to them as soon as the training session starts. They are however warned that the information given may be inadequate or misleading as happens in reality, which makes even more difficult to work the emergency out. The subjects who were going to play the role of the emergency manager were also trained on the connotation of the factors of the X-NASA-TLX and initially asked to provide responses to pair-wise comparisons to collate the degree to which each factor generally contributes, in their opinion, to the perceived workload. Stage 1 finally concluded with supporting participants in finding their seats and wearing the virtual reality devices and watches. While the first two steps are executed once and for all the participants, the next two stages are executed in cycles per each replication.

Stage 2. Conduct. The training session starts with the training scenario warm-up. When the scenario has warmed-up, participants were presented the scenario via an automatically generated vocal storytelling. At the end of this presentation, participants were informed that the situation would have irreversible effects on the plant and the surrounding community if the MIA is not worked out within the proposed time limit (25 simulated hours). Participants played until the MIA was worked out or until time ran out. Constant monitoring from the experiment personnel is ensured to provide immediate support in the case of health problems or issues with virtual reality devices.

Stage 3. Evaluation. After each session, a 60-minute break for relaxing from the use of the system is given to the participants and for an informal debriefing with the training session facilitators to elicit participants' opinions on the basis of the final summary report automatically generated by the system. Only after the first training session, another computerized questionnaire was submitted to the subjects who played the role of the emergency manager to obtain the subjective workload ratings for the performed scenario. Data were exported as Excel worksheet to be used for post-training debriefing and analysis.

Figure 60: Experimental campaign – pictures of the emergency managers

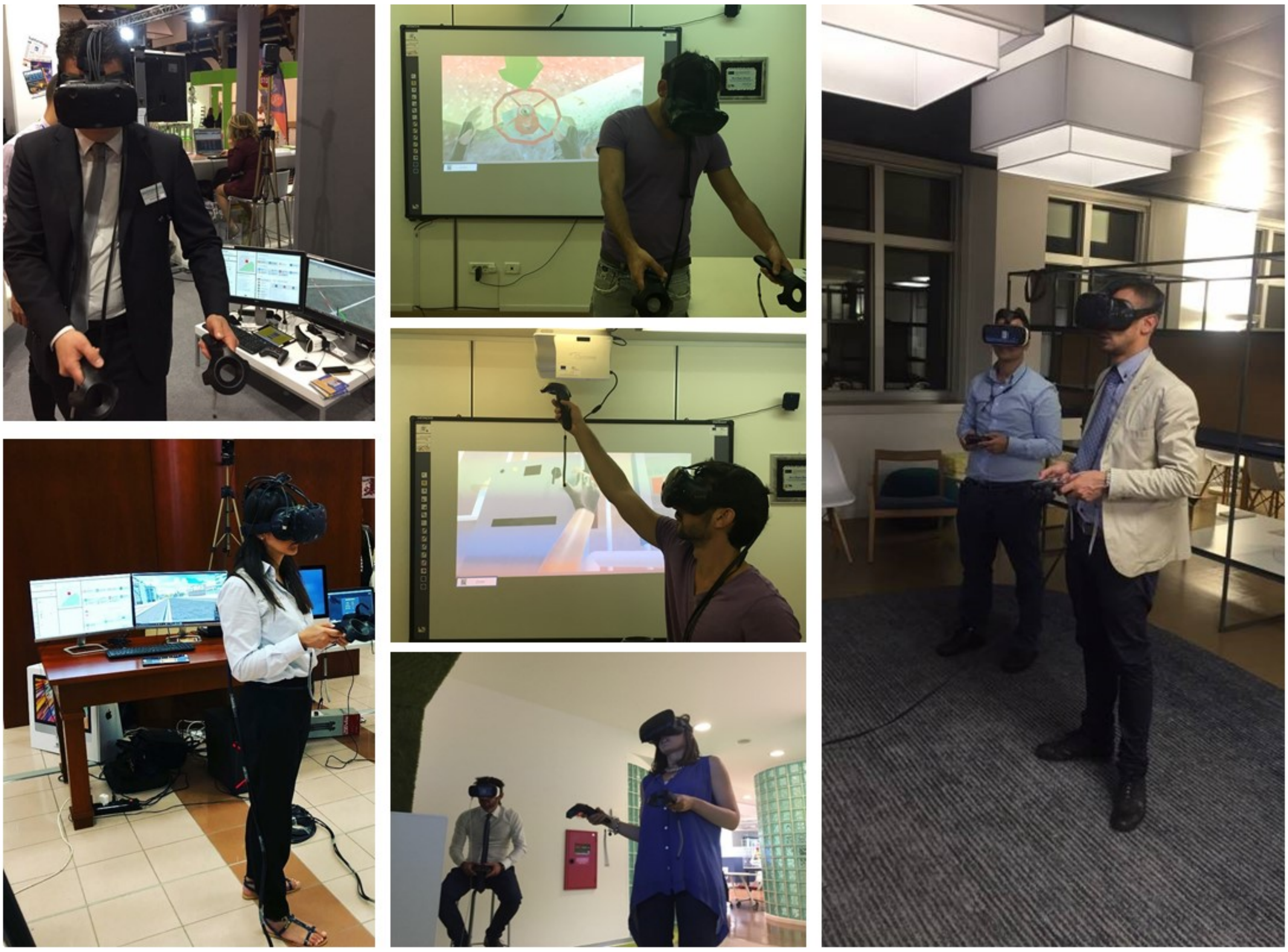


Figure 61: Experimental campaign – pictures of the emergency team members

5.5 Training environment configuration

The case study for experimentations is based upon a leading company in re-refining of waste lube oil and in the collection of special waste. The production facility, whose area is about 72.000 m^2 wide and whose maximum production capacity of 60.000 tons/year of used oils, is located in an urban area in Italy as depicted in the aerial view in Figure 62. A fire blasted in correspondence of an oil storage tank and, at the moment of the intervention of the EM, it covers about 40.000 m^2. The weather is cloudy, the temperature is 25°C, the humidity level is set up to 5% and a 5-knots wind is blowing in northwest direction. In the facility, there are 61 employees and an average number of 10 visitors was hypothesized. The layout includes two buildings where most of the employees are located with 8 emergency exits in total and 10 high-risk systems to be properly maintained or disconnected (a power receiving and transforming facility, a main fuse box, a pressurization system, a re-refining system, a special waste treatment system, a pumping system, an oil pipeline's main valve and three secondary valves).

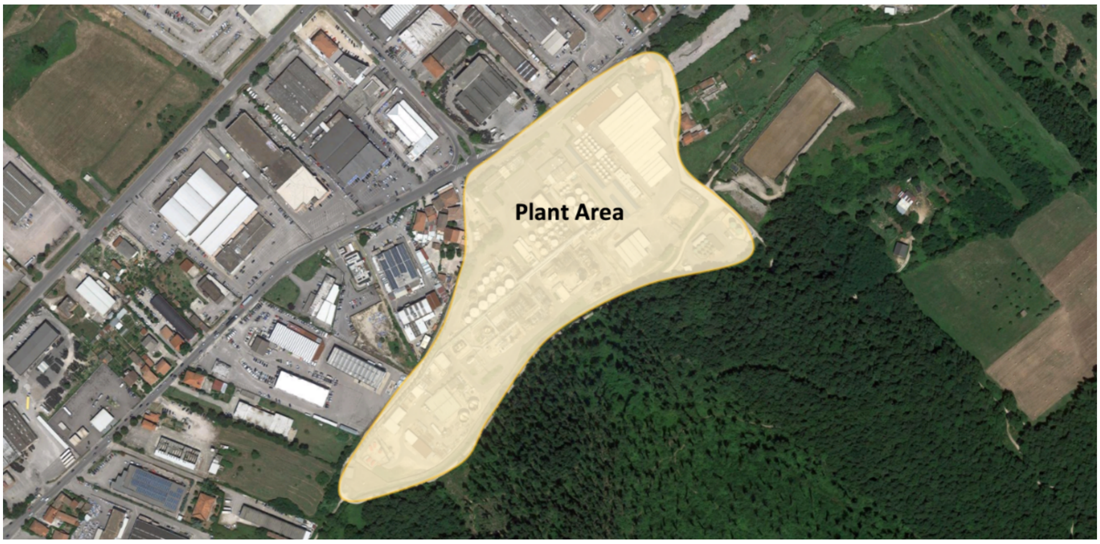


Figure 62: Aerial view of the plant

Different emergency and public authorities can get to the plant by extra-urban roads:

- a Firehouse with 15 tankers;
- a City Police Station with 10 available vehicles;
- a Carabinieri Station with 15 vehicles and 1 helicopter for emergency transport;
- a Civil Protection Department with 10 vehicles and 1 helicopter for emergency transport;
- a hospital with 10 basic transport vehicles (mounting Emergency Medical Technicians only), 10 basic emergency vehicles (mounting nurses), 5 advanced emergency vehicles (mounting medical personnel) and 1 helicopter.

An oil storage plant has been recreated in 3D by using models from scratch (with Blender and 3D Studio Max) but also with ready-to-use assets imported from the Unity Asset Store. The experimental campaign has been designed by using a worst-case approach based on the Buncefield disaster (an image of the terrible Buncefield disaster is shown in Figure 64). Figure 64 shows the real-world conflagration whereas Figure 65 shows the conflagration and the surrounding environment recreated virtually.

Figure 63: Real-world oil tanks, pipelines and pressurized valves

Figure 64: The Buncefield conflagration

Figure 65: The Virtual Training Environment

6 Results and discussion

Data analysis was done using Minitab 17. KPIs are presented in terms of interval plots (IP) with 95% confidence intervals (CI) calculated by using individual standard deviations. Lastly, to compare the means of the IP between a couple of replications of the training session, the Games-Howell post-hoc test (GH-test) is used with $\alpha=0.05$, as it appears to do better than the Tukey HSD when variances are very unequal (or moderately so in combination with small sample size).

At the end of every replication, a complete report on the response of the participants (the emergency manager and the emergency team members) is outputted to enable a statistical analysis of the KPIs listed as part of the training strategy and derive general remarks. The ultimate goal of this chapter is to understand:

- how the performances of the emergency manager and of the emergency team member evolve along the replications (see the *Mission Fulfillment KPIs*);
- to which extent the proposed training approach is effective in delivering procedural knowledge to emergency managers and emergency team members (see the *Procedural Compliance KPIs*);
- whether it is realistic enough to think that the training experience produces psychological stress in those people that are trained with it (the emergency managers and emergency team members) and how they cope with stress over the repeated replications (see the *Psychological Stress KPIs*);
- whether and to which extent human factors, such as stress and perceived workload, are correlated to the capability of the emergency manager to coordinate and monitor the execution of all the measures and actions intended to deal with an industrial accident and its effects.

To emphasize and explain the results, comments and sentences that the trainees provided during the post-training analysis are also given in the discussion.

In order to get at a glance how the four replications turned out, Figure 66 shows the overall success rate of the emergency response team over the four replications of the training session. As explained in the teaching strategy, the overall success rate of the emergency response team is defined as the percentage of the emergency managers that were able to completely extinguish the fire and evacuate all the people involved. What can be noticed immediately is that the average success rate increases from 12.5% to 77.5% within only four replications, thus showing the rapid high-level improvement that can be achieved. Moreover, a short-term slight decrease in the average success rate can be observed between R2 and R3. This is largely justified by the fact that collaboration issues were encountered due to the new partner. Indeed, some trainees reported on the ‘difficulty in understanding clearly and quickly what the emergency manager was asking’ and ‘slow communication of the results of an assigned task’. Such collaboration issues appear to be mitigated already in R4 as demonstrated by the results reported in Figure 66. As the black dotted curve in Figure 66 comes up very often in the analysis of the results, it will be referred to as ‘chaise longue’ profile. It is characterized by an overall growing or decreasing trend – depending on the considered KPI – and a more or less accentuated loss in performance between R2 and R3 because of the effects explained above.

Figure 67 shows the overall mean training performance of the entire emergency response team over the four training replications. The overall mean training performance increases from 14.45% to 67.53%. To analyze such differences and verify that data collected from the experimental campaign provide sufficient statistical evidence of the means differences, the Games-Howell post-hoc test has been used. Such results show that in all cases the mean differences are statistically different therefore, as the number of replications increases, the overall performances of the emergency response team improves.

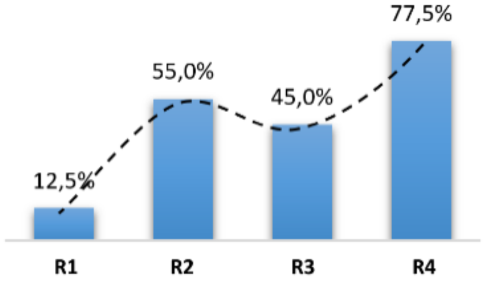


Figure 66. Success rate of the emergency response staff over the 4 replications

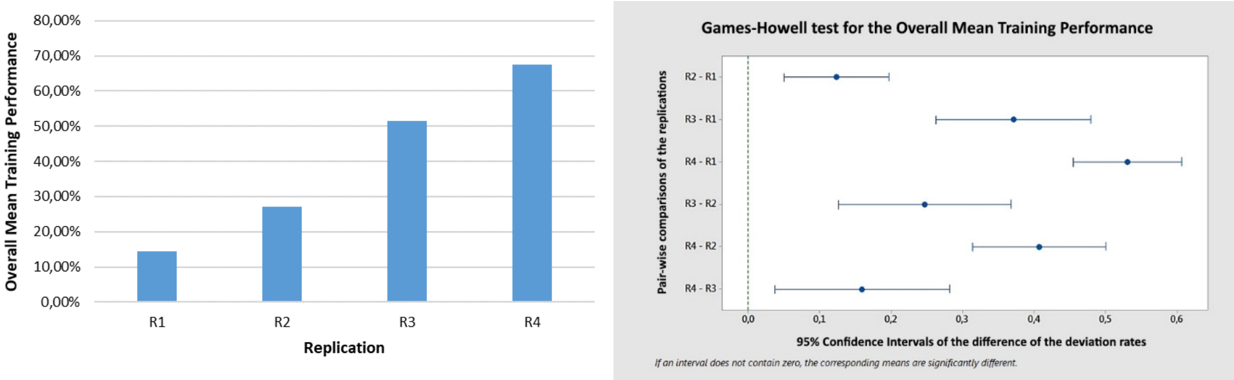


Figure 67: Overall Mean Training Performance and Games-Howell Test

To assess the potentials of the training system in relation to its knowledge transfer capabilities concerning procedures and compliance to emergency plans, procedural KPIs have been analyzed. In particular, for a general evaluation, the analysis has been focused on tracking and analyzing for each member of the emergency response team how deviation rates evolve from one replication of the training scenario to another. Deviation rate has been taken as a reference for evaluating the system potentials to deliver procedural knowledge. Essentially, this KPI is an appraisal of procedures and plans observance and within the training system, it is tracked for all the key figures that are involved in emergency management processes. For these reasons it has been deemed a good representation to assess:

i. to which extent procedures are learned by each involved actor;
ii. whether the training system has greater impacts on specific figures compared to others.

Deviation rates have been collected along the four replications for all persons that have been involved in the experimental campaign and then data have been grouped by role. Results, as shown in Table 9, confirm that the mean deviation rate related to performance at team level by replication and the mean deviation rate related to performance at individual level decrease as the number of replications increases. It means that the proposed training system has not negligible effects on trainees' learning outcomes: as the confidence and the experience with the training system grows (from one replication to another), people concentrate on their performance and are less error-prone. Moreover, it is possible to notice that the emergency manager and the evacuation officer have a great deviation rates in the first replications and a substantial decrease between the third and fourth replication. It suggests that these actors are involved in more complex tasks/procedures and that, in such cases, the proposed training solution keeps contributing to performance enhancement.

Table 9: Average Procedural Compliance Results

	R1	**R2**	**R3**	**R4**	**Mean by person**
Emergency manager	34.00%	32.00%	20.00%	8.00%	**23.50%**
First aid officer	17.00%	16.00%	7.00%	5.00%	**11.25%**
Evacuation officer	26.00%	18.00%	9.56%	4.45%	**14.50%**
Firefighting officer	10.57%	9.13%	4.26%	4.62%	**7.15%**
Protection and prevention officer	19.23%	14.40%	8.71%	3.21%	**11.39%**
Mean by replication	**21.36%**	**17.91%**	**9.91%**	**5.06%**	

To support such considerations by statistical evidence, the Games-Howell test has been carried out for the main roles within the emergency response system. In general, results show that for all the key members of the emergency response team, average deviation rates are significantly different from one replication to the next, thus proving that the training system has real effects on procedural compliance. However, this is not completely true for first aid officers, emergency officers and firefighting officers. For such roles, results should be analyzed on a case-by-case basis. As a matter of facts, for first aid officers, the Games-Howell Test shows that there is not a significant difference between results from R2 and R1. The rationale behind these results has been detected after analyzing the reports of the debriefing sessions carried out after R1 and R2. Such reports have highlighted that most of the people had never experienced a virtual environment before and it caused a lack of attention and focus on procedures. This issue has been fully recovered in the next replications (R3 and R4) where people have declared to feel themselves more involved in the scenario and more focused on their own performance. A similar situation has been recorded for Emergency Manager. Results from the first two replications are not significantly different but the situation changes after the second replication. In this case, from the debriefing reports it has been noticed that at the beginning people involved as emergency managers where totally overwhelmed by the complexity of their role with detrimental effects on their performance. This is even truer considering that people involved in the experimental campaign where equally inexperienced in emergency management procedures to ensure meaningful results and an unbiased analysis, statistically speaking. As for firefighting officers, the deviation rates of R2 are not significantly different from those of R1. Even in this case the distracting factor was the novelty of virtual reality environments. However in this case, it can be noticed also that difference between R3 and R4 is not meaningful. It happens because after two replications and debriefing sessions where people became familiar with the training system and with firefighting emergency procedures, they reached a very low average deviation rate in R3 (4.26%) meaning a good maturity level in procedures understanding and plans observance. In this situation, given that performances have already reached a good maturity level and that the complexity of firefighting officers procedures is not so high, it is acceptable to have not considerably different results in R4.

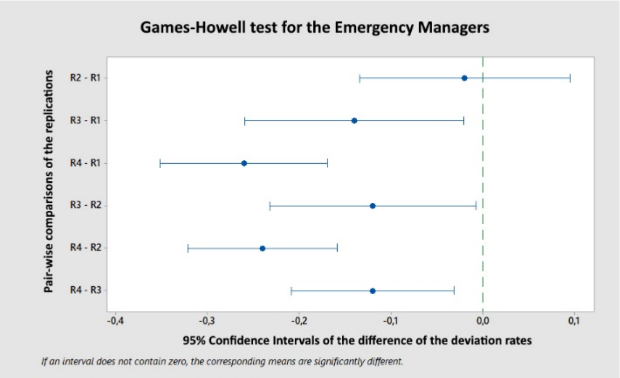


Figure 68: Games-Howell Test for the Emergency Managers over the 4 replications

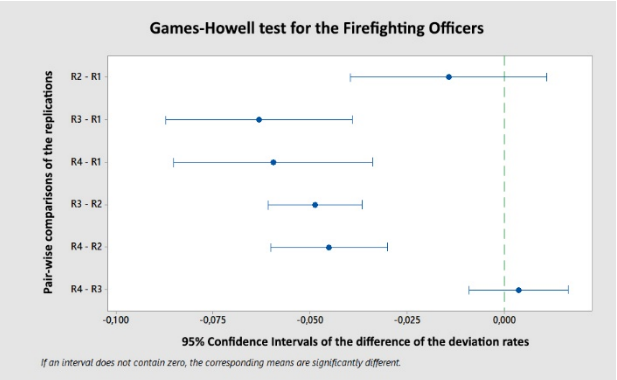


Figure 69: Games-Howell Test for the Firefighting Officers over the 4 replications

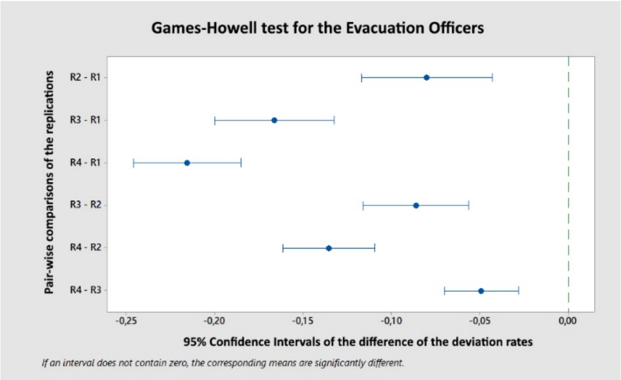


Figure 70: Games-Howell Test for the Evacuation Officers over the 4 replications

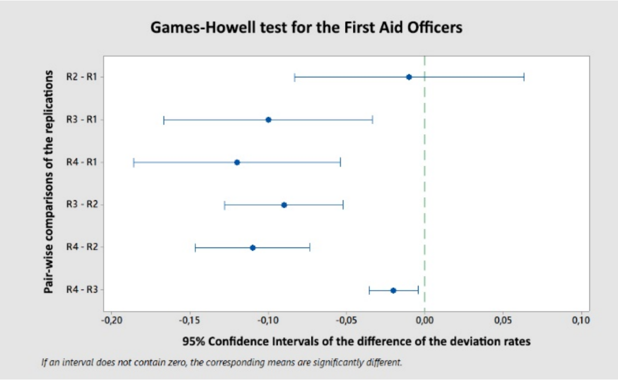


Figure 71: Games-Howell Test for the First Aid Officers over the 4 replications

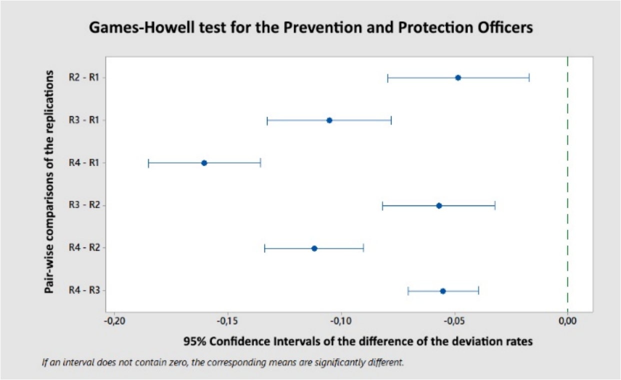


Figure 72: Games-Howell Test for the Prevention and Protection Officers over the 4 replications

6.1 Emergency manager: mission fulfillment KPI results

A complete analysis of the emergency manager's mission fulfillment KPIs, which relies upon the interval plots and the Games-Howell tests is hereafter provided to give much more evidence on the effectiveness of the developed system.

The first two KPIs refer to the duration of the replications in terms of both real training time and virtual training time. The red dotted line in the graphs reported in Figure 73 and Figure 74 indicates that the duration of a training session is upper bounded (after 60 'real' minutes or 25 'virtual' hours) as the training session ends automatically. A 'chaise longue' profile can be easily recognized: trainees have indeed commented that replacing the partner seems to have a detrimental effect on the overall performance in terms of capability to move up actions and share information quickly. The average values of the real training time over the 4 replications are 59.87 min, 58.51 min, 59.05 min, 57.86 min, which corresponds to 24.94 h, 24.38 h, 24.6 h, 24.11 h in terms of virtual training time.

The IP in Figure 73 shows how unlikely succeeding within the given limit is in R1. Indeed, the real training time fluctuates around 60 minutes (please note that the intervals do not exceed the upper bound of 60 minutes) and the disaster did not turn out positively in most of the cases. A learning outcome can be also observed: the width of the CI tends to decrease (from R2 on) because trainees are learning how to deal with the emergency. A good performance is registered in R4 that has been completed before the time limit. The same observation applies to the virtual training time (see Figure 74 as a reference).

As shown in the GH-tests of Figure 73 and Figure 74, a significant difference between the average values is obtained only between R1 and R4 (p-value = 0.004 both for the real and virtual training times). This proves that four replications are necessary to start achieving significant improvements in time.

As far as the firefighting operations are concerned, the average probability of extinguishing the fire over the 4 replications evolves from 7.5% to 95.0%. This is reflected in the IPs of the burning area at the end of the training session and of the time to extinguish the fire. In particular, Figure 75 shows the rapid decrease down to almost zero (the means are 13196 m^2, 4393 m^2, 945 m^2, and 143 m^2) of the burned area as well as a gradual reduction of the width of the CI over the 4 replications. In this case, a significant improvement is obtained between R1 and R3 (p-value = 0.032) and between R1 and R4 (p-value = 0.025). Similarly, the time to extinguish fire (Figure 76) decreases from 24.86 h, 24 h, 23.43 h, to 21.45 h, with a very small CI in correspondence of R1 because in most of the cases the R1 ends without having extinguished the fire. A wider CI is likely to characterize the next replications though their sizes gets smaller as the emergency manager repeats the training session. However, a significant difference between the mean is guaranteed only between R1 and R4 (p-value ≈ 0) and between R2 and R4 (p-value = 0.043), meaning that trainees are able to improve their time to extinguish the fire significantly only on the fourth occasion.

As far as the search & rescue operations are concerned, a first KPI to be considered is the number of people left in the plant, whose IP and GH-test are depicted in Figure 77. A 'chaise longue' profile can be recognized although the KPI's performance decrease is not very accentuated. The means of the number of people left in the plant over the 4 replications are 11, 4, 4, 1 persons and the CI's width decreases as well. Results here are truly meaningful because, apart the importance of every single life, significant difference are registered between R1 and R2 (p-value = 0.034), R1 and R3 (p-value = 0.028), R1 and R4 (p-value = 0.003) and R3 and R4 (p-value = 0.009). Similar results have been obtained for the number of rescued people as shown in Figure 78.

We move therefore to the analysis of the Rescue Operations Duration, which presents a decreasing 'chaise longue' profile, with small differences between the first three means (10.036 h, 8.03 h and 8.85 h) and a significant decrease only between the 1st and 4th mean (5.78 h), with a p-value = 0.002, as showed in Figure 79. Figure 80 shows the number of people found during a reconnaissance tour that does not increase substantially (the mean values over the 4 replications are 22, 16, 27, 25 persons) although an unexpected increase is registered between R2 and R3 and a very small difference in statistical terms can be recognized between TS.2 and R4 (p-value = 0.041). This is probably due to a greater attention from the emergency manager to task the emergency team to carry out repeated reconnaissance tours in the plant to search for people. Although scarce improvement seems to affect the rescue operations, relevant results are actually achieved in terms of number of blocked and/or injured people rescued, considered as a subset of person found during the reconnaissance tour, which presents a very accentuated 'chaise longue' profile (Figure 81). The blocked and/or injured people rescued grows initially from 3 to 13; then, after a strong reduction between R2 and R3 (from 13 to 8) due to the difficulty to coordinate actions and set up action strategies quickly when two unknown trainees are immersed together in the same scenario, the KPI goes through a rapid growth from 8 to 18. What is worth noticing is that in the case of this KPI most of the pairs of means are significantly different from each other (no statistical difference is registered between R3 with R1 or R2), thus showing how this KPI is highly sensitive to significant changes in experience and knowledge of the emergency procedures acquired after repetitive training.

To conclude the observations on the rescued people, one last KPI, the number of people who received triage at the arrival in the safe zone, shows that little consideration has been paid to this aspect, with consequent delays in the hospitalization. Indeed, a totally stationary trend is observed (see Figure 82).

The discussion now gets to the point on how the emergency manager has managed the emergency exits and the systems in the plant over the 4 replications. As depicted in Figure 83, the average time to check/unblock the emergency exit presents a faint 'chaise longue' profile with means ranging from 0.52 h to 0.48 h, and from 0.50 h to 0.48 h. No significant difference is identified between pairs of means, proving that this KPI is little sensitive, at least initially, to repetitive training (further training may lead to further decrease in the KPI and achieve statistical significant improvement). This is even more confirmed by the number of unblocked exits, which has a steady trend between 2 and 3, where 3 is the maximum number of emergency exits that are required to be unblocked during the training (Figure 84). We can therefore observe that the emergency managers took enough care of the emergency exits during the training, but the time to check/unblock them does not depend on the emergency manager.

Similarly, if we look at the following systems-related KPIs, the way the emergency manager look at the plant systems does not change substantially over the 4 replications. In particular, the number of plant systems still up and running at the end of the replications undergoes a large improvement between R1 and R2 and presents the typical 'chaise longue' profile (Figure 85). However, the means over the 4 replications (4, 1, 2, 1) are not significantly different, excerpt for a very small difference between the means of R1 and R2 (p-value = 0.035) and R1 and R4 (p-value = 0.035).

A steady trend is also shown by the number of compromised systems, with means (4, 4, 2, 3) that are not statistically different in pairs (see Figure 86). Instead, the number of disconnected systems presents an ever-growing trend with the means over the 4 replications (3, 5, 6, 6) that are statistically different only between the R1 and R4 (p-value = 0.013), as shown in Figure 87. The way the systems are disconnected (manually or automatically) does not vary considerably over the 4 replications. A stationary trend is showed by both the number of systems disconnected manually and the number of systems disconnected automatically and no difference between the means has been identified (see Figure 88 and Figure 89 respectively).

Finally, the average time to disconnect these systems presents an unexpected evolution over the 4 replications (see the IP in Figure 90). It seems increasing rather than decreasing and the width of the CIs grows more and more. This is due to the emergency manager's negligence towards switching off the systems and secure them in the R1 (trainees commented that they were more focused on collaborating with the firefighters and search & rescue the people, without considering the worsening factor that keeping the systems switched on had on the disaster evolution, e.g. further explosions). The emergency manager started indeed to take care of this aspect from R3 on (a decrease in this time and a very small reduction of the width of the CI is registered in R4).

The results above presented show the potentials of the proposed system to investigate not only the overall training performance but to focus on specific aspects of the emergency management. To this end, the system can be also used to let the emergency managers improving specific skills (e.g. be sure to 'save' specific company assets, be sure to minimize the remaining people in the plant, etc.) according to the company needs. However, mission fulfillment capabilities are only one part of the training 'equation'; the emergency managers must be able to respect the emergency procedures adopted by the company as if they are timely and correctly executed, the accident should move towards a resolution. To this end, the next section presents the procedural compliance KPIs for the emergency managers.

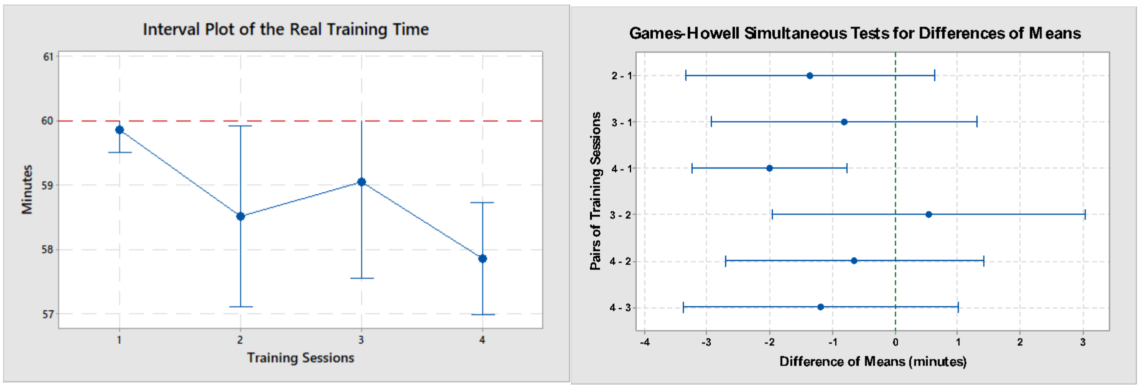


Figure 73: KPI-EM1 - Interval Plot and Games-Howell Tests

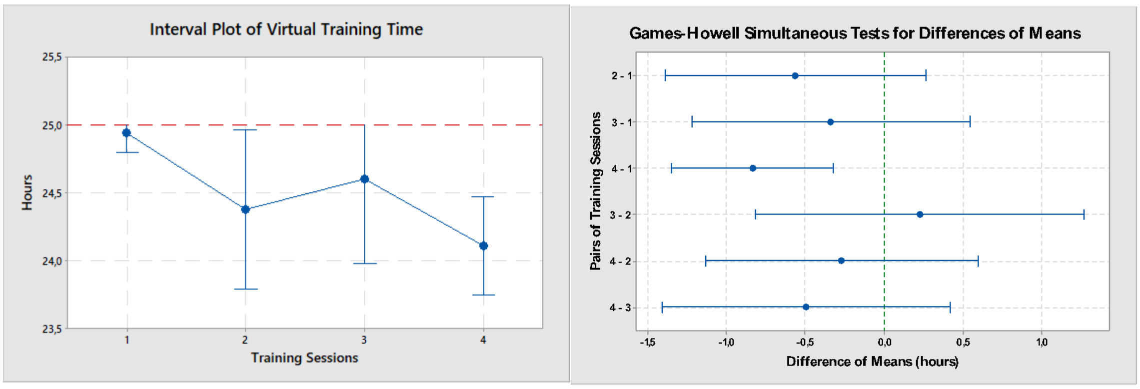


Figure 74: KPI-EM2 - Interval Plot and Games-Howell Tests

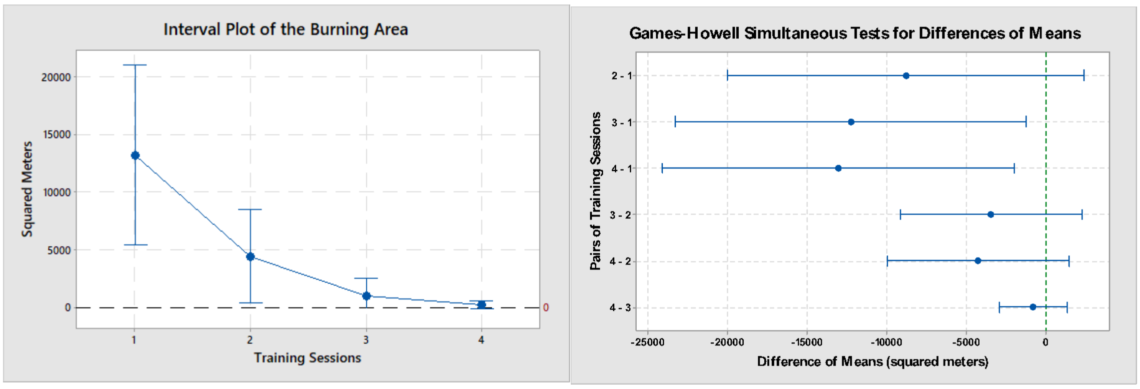


Figure 75: KPI-EM3 - Interval Plot and Games-Howell Tests

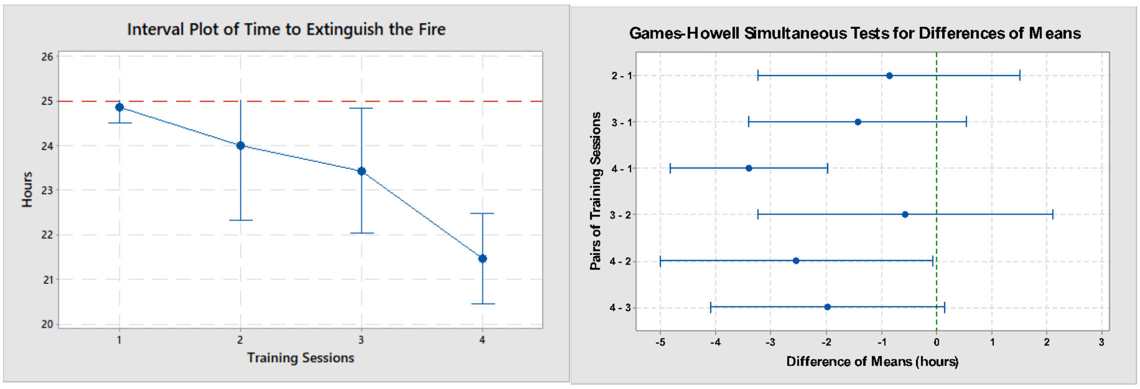


Figure 76: KPI-EM4 - Interval Plot and Games-Howell Tests

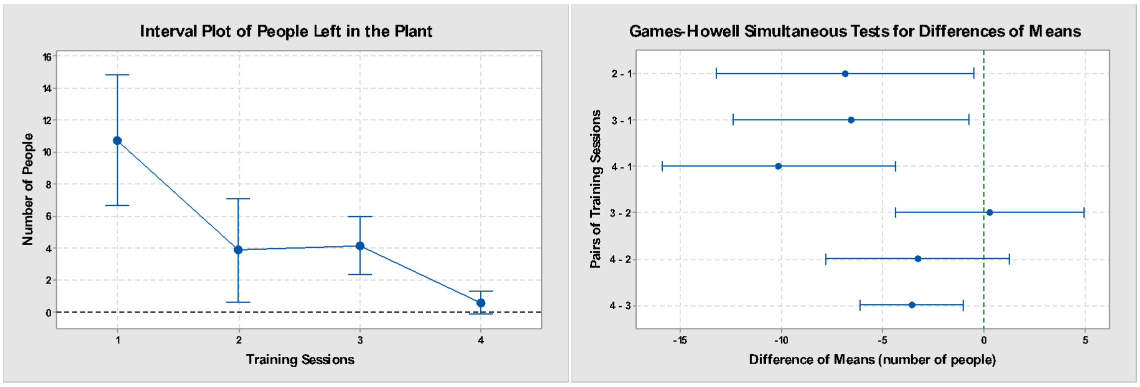


Figure 77: KPI-EM5 - Interval Plot and Games-Howell Tests

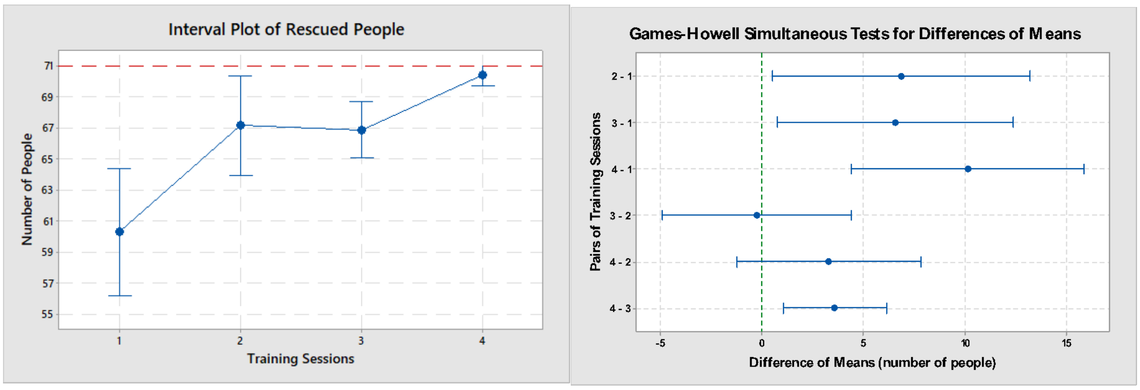


Figure 78: KPI-EM6 - Interval Plot and Games-Howell Tests

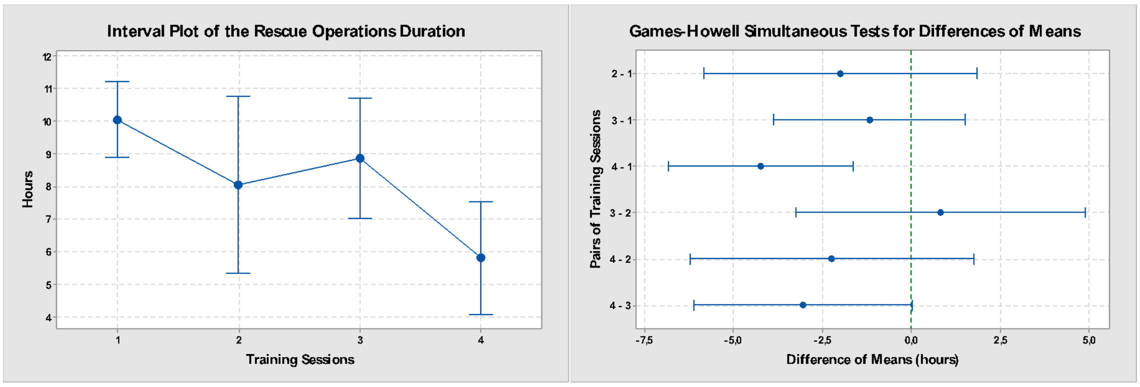


Figure 79: KPI-EM7 - Interval Plot and Games-Howell Tests

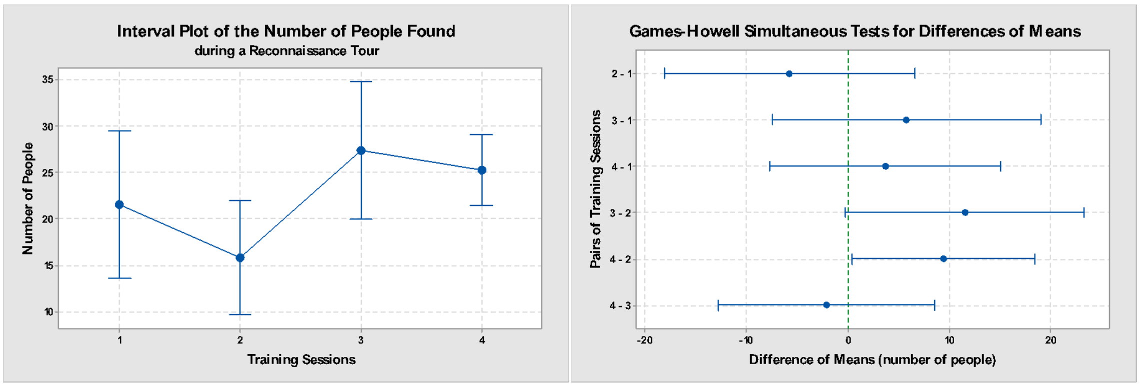


Figure 80: KPI-EM8 - Interval Plot and Games-Howell Tests

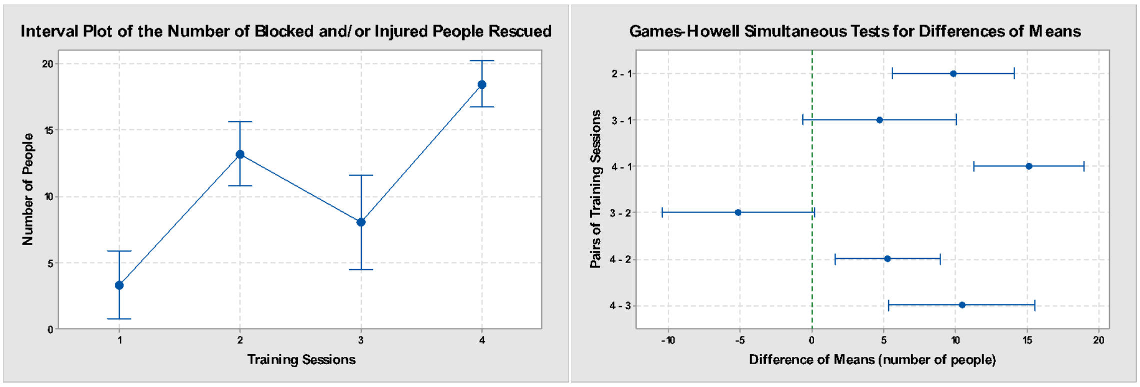


Figure 81: KPI-EM9 - Interval Plot and Games-Howell Tests

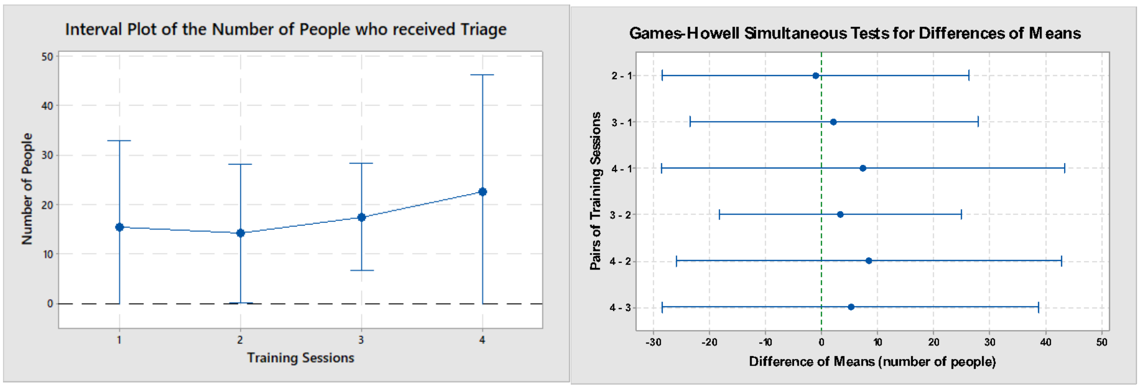


Figure 82: KPI-EM10 - Interval Plot and Games-Howell Tests

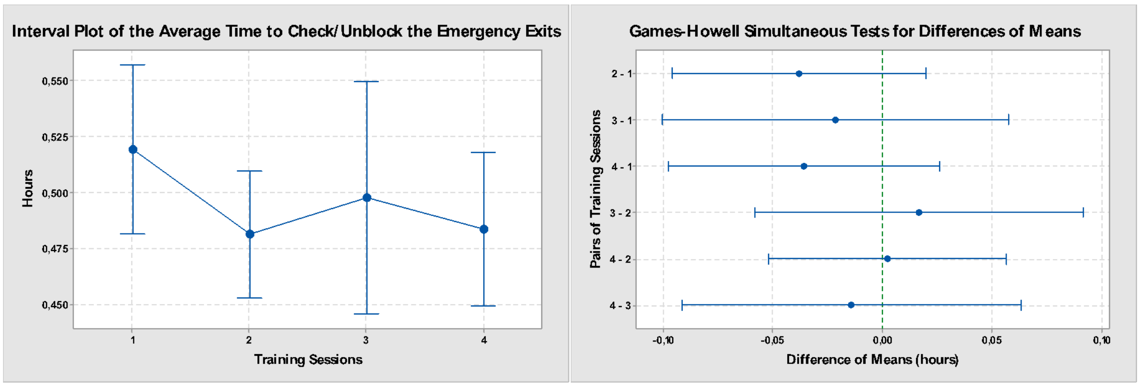


Figure 83: KPI-EM11 - Interval Plot and Games-Howell Tests

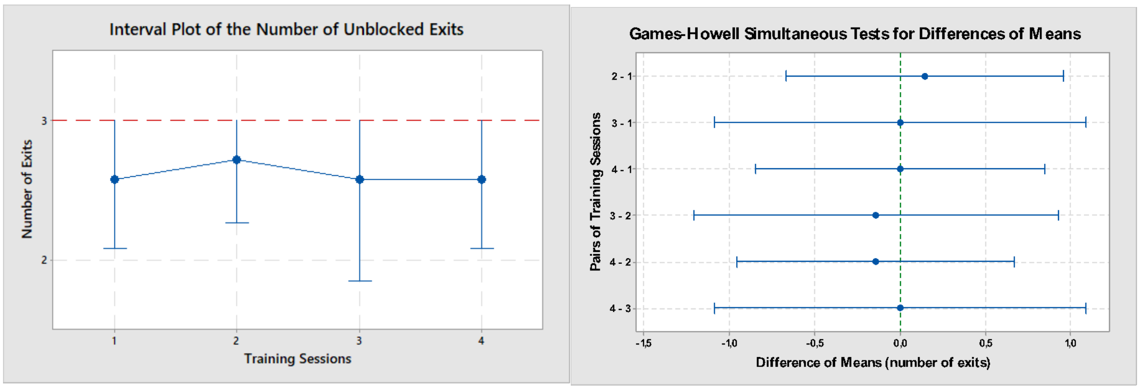


Figure 84: KPI-EM12 - Interval Plot and Games-Howell Tests

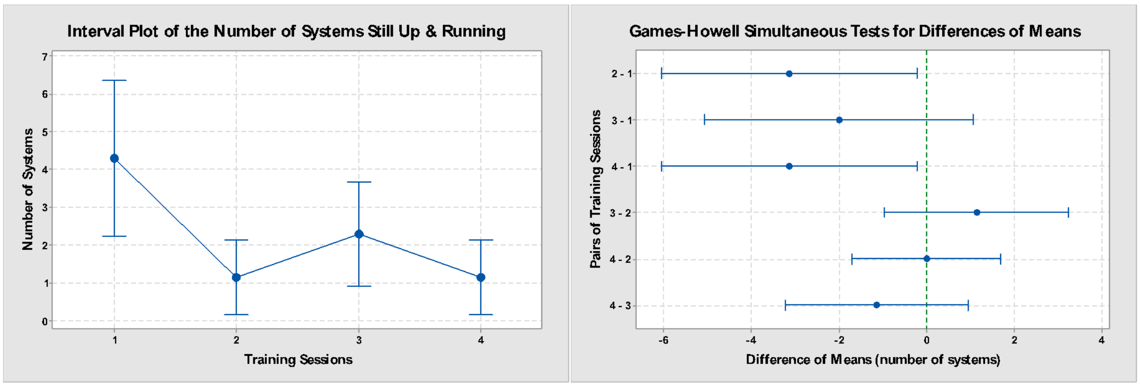


Figure 85: KPI-EM13 - Interval Plot and Games-Howell Tests

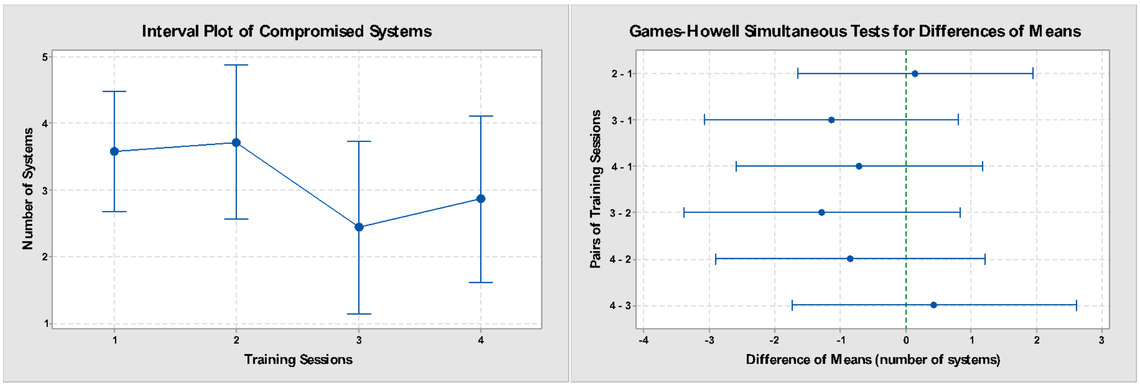


Figure 86: KPI-EM14 - Interval Plot and Games-Howell Tests

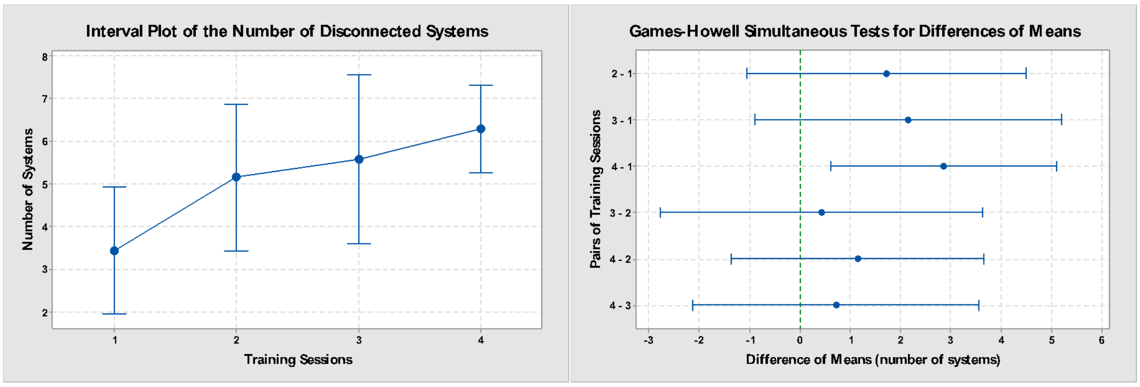


Figure 87: KPI-EM15 - Interval Plot and Games-Howell Tests

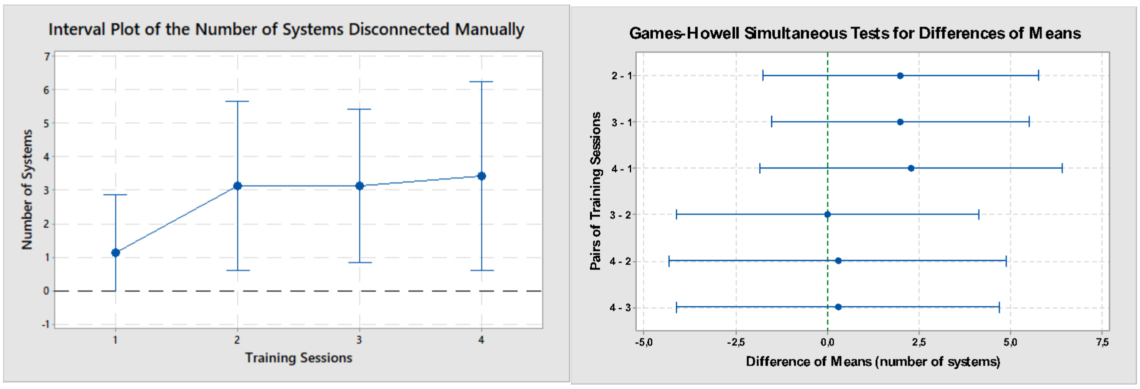


Figure 88: KPI-EM16 - Interval Plot and Games-Howell Tests

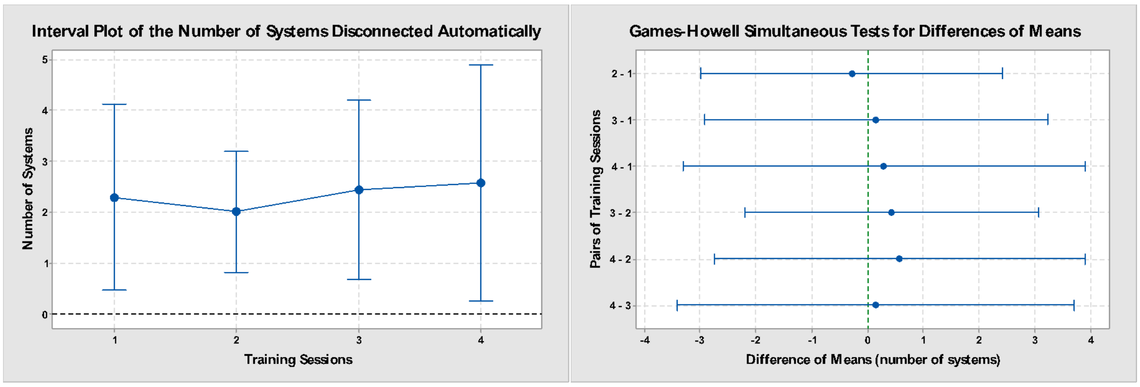


Figure 89: KPI-EM17 - Interval Plot and Games-Howell Tests

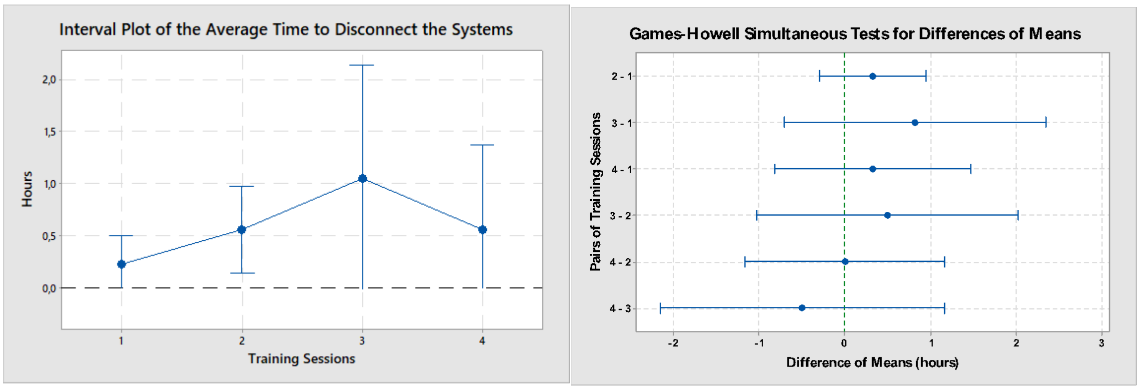


Figure 90: KPI-EM18 - Interval Plot and Games-Howell Tests

6.2 Emergency manager: procedural compliance KPI results

The proposed system allowed extrapolating interesting results related to the actions performed by the emergency managers and on the tasks they assigned to the emergency response team members.

The most executed actions are reported in Figure 91, which presents a clear predominance of the emergency managers' 'obsession' with counting and checking the people who reached the safe zone as well as check 'who is still missing' or who is still in the plant. Immediately following are the emergency managers' meetings with both the firefighters and medical aids throughout the emergency that are, ultimately, carried out as often as the emergency managers' requests to collect information about what the mass media are telling about the disaster. This last result shows that the emergency managers are generally worried about the image of the company and use to focus on time-consuming activities rather than redirect their full efforts on effective actions. On the other hand, the ten most assigned tasks are reported in Figure 92. In this case, the two most recurring tasks refer to the firefighting team that is asked to report about the fire and to help the emergency managers in counting the number of rescued people. Next, the medical team is also tasked to execute first aid on injured people, to move them to the safe zone and to help the emergency managers in counting the number of rescued people. Then, the firefighters team is also frequently asked to carry out reconnaissance tours in the plant to find missing people and to rescue localized people. Finally, in the last positions in this ranking, we find the task 'Call the emergency number 115', which proves a continuous communication with the fire stations. Asking for a report on dead people and asking the emergency team to check the emergency exits closes this ranking.

Figure 91: Five most executed actions

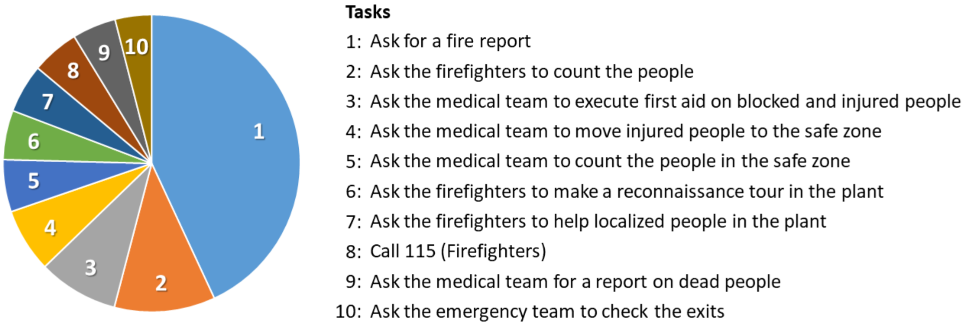


Figure 92: Ten most assigned tasks

Along the replications, the emergency managers were able to reduce the inactivity time, perform more actions and assign more tasks, as showed in the IP of Figure 93 (the number of performed actions and assigned tasks are 102, 103, 133, 147). However, because of the large variability, these means are not statistically different from each other as demonstrated by the GH-test whose results are reported in the same figure. This could be also an indication that additional replications are perhaps required to significantly reduce variability and significantly increase the number of tasks performed by the emergency managers.

The first issue to be highlighted is related to the promptness with which the Emergency Team is alarmed and the evacuation order is issued. Initially, it seems that the emergency managers forget to alarm the Emergency Team and to send the evacuation order. These two actions are heavily delayed in the game as showed in Figure 94 and Figure 95. This behavior has been later justified by the trainees themselves that have said they totally forgot about issuing the alarms because overwhelmed by the facts and more concerned about the fire and rescuing people immediately. Therefore, it was like the Alarming phase shifted after the Reconnaissance or even the Response phase. Moreover, calling the external aids (especially the firefighters) seemed to have a priority on the other tasks of the Alarming phase. In quantitative terms, a very large variability in the delay in giving the Emergency Team alarm affects the R1, which decreases more and more down to almost zero (because the emergency managers have finally understood to send immediately the alarm to the Emergency Team) in R4. As confirmed by the IP in Figure B.2, the reduction of the delay is relevant (even because the width of the CI decreases and the alarm is sent increasingly earlier), and from a statistical perspective there is a significant difference between R1 (8.57 h) and R4 (0.09 h). Similar considerations can be made for the delay in issuing the evacuation order, average values (9.95, 4.35, 1.50, 0.67 h).

As just mentioned, calling the external aids (police authorities, firefighters and medical aids) is performed very early compared to other actions, however in the R1 external aids are not called timely as expected. Furthermore, external aids used to wait at the entrance gates and they did not start acting because the emergency managers usually forgot to meet and update them about the situation and what has been already done (this action is required by the procedures). Calling and receiving the external aids is a strategic element in the disaster management. Evidences of this behavior and related improvements are provided in:

- Figure 96 for the delay in calling the police authorities with the following improvements over 4 replications: 2.58 h, 1.08 h, 0.74 h, 0.34 h (statistically significant differences also provided by the GH Test);
- Figure 97 for the delay in receiving the police authorities with the following improvements over 4 replications: 1.81 h, 1.05 h, 0.43 h (statistically significant differences also provided by the GH Test);

A similar improvement is obtained for the delay in calling the firefighters as shown in Figure 98 and Figure 99. It is worth noticing that the delay in calling the firefighters shows a significant decrease between the first two replications (from 2.21 h to 0.49 h) – because the emergency managers quickly understand the necessity to call the firefighters no later than the first 30 minutes – and then remains quite steady (no differences are identifiable). The delay in receiving the firefighters instead goes through a constant decrease (3.79 h, 1.41 h, 0.49 h, 0.27 h). Ultimately, for the sake of completeness, analogous considerations apply to the analysis of the delay in calling the medical aids and in receiving them whose results are summarized in Figure 100 and Figure 101.

Additional information on the emergency managers' capability to comply with the correct emergency procedures can be gathered from the system. Interesting data refer, for example, to the number of exits that are checked/unblocked in the correct order (prioritized exits) and to the number of systems that are disconnected with the right priorities (prioritized systems). Figure 102 highlights the little consideration paid by the emergency managers to checking order of the emergency exits (the exits should be checked according to their level of involvement in the disaster). This is recovered over the 4 replications as shown by the high-inclined learning curve in Figure 102 (similar behavior for the way the systems are disconnected, see Figure 103).

One last consideration included in this section refers to the capability of the emergency managers to lead well-timed triage activities on the people reaching the safe zone. If we consider the sum of the delays in performing triage (see Figure 104), this KPI does not exhibit an improvement. A high variability affects the mean values, which fluctuates around 1 h, therefore no statistically significant improvement is achieved in this case.

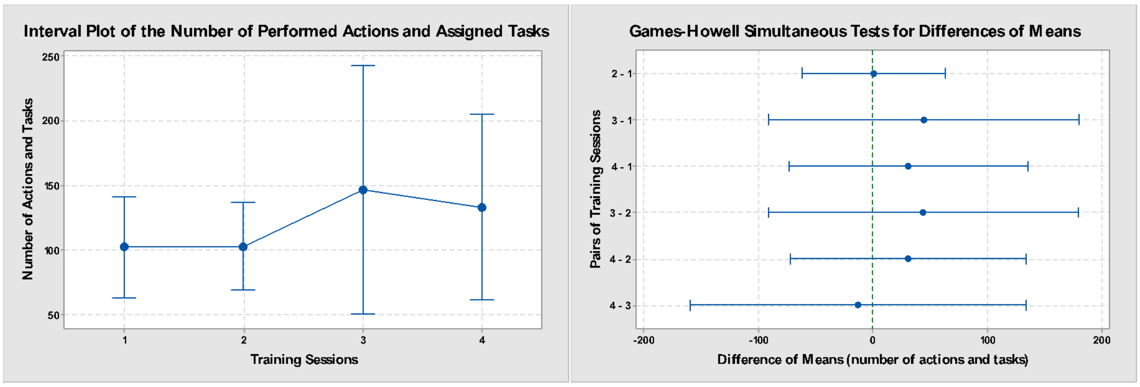


Figure 93: KPI-EM19 - Interval Plot and Games-Howell Tests

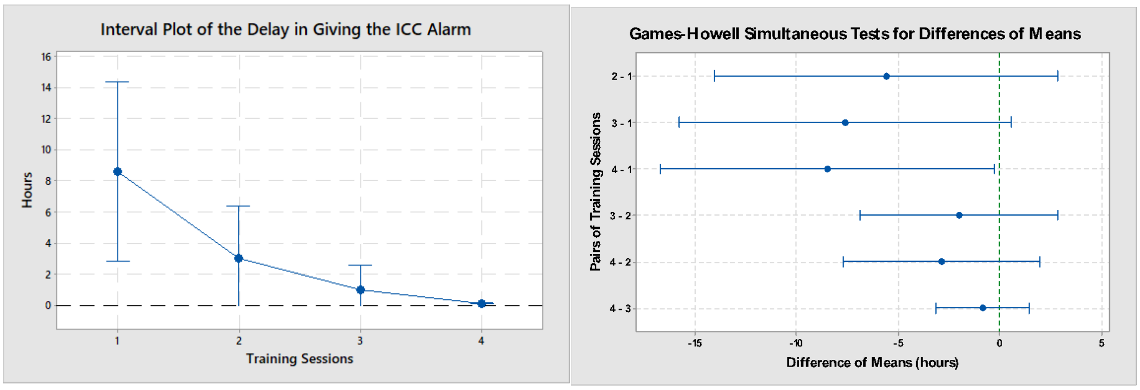


Figure 94: KPI-EM20 - Interval Plot and Games-Howell Tests

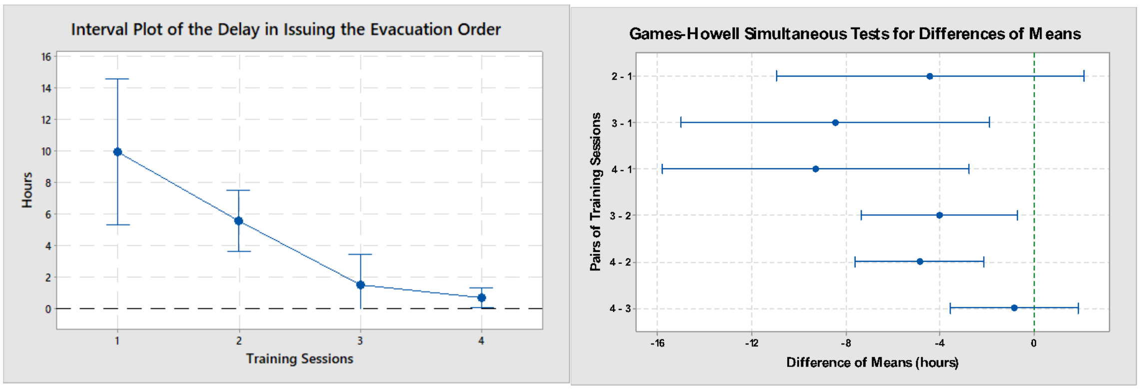


Figure 95: KPI-EM21 - Interval Plot and Games-Howell Tests

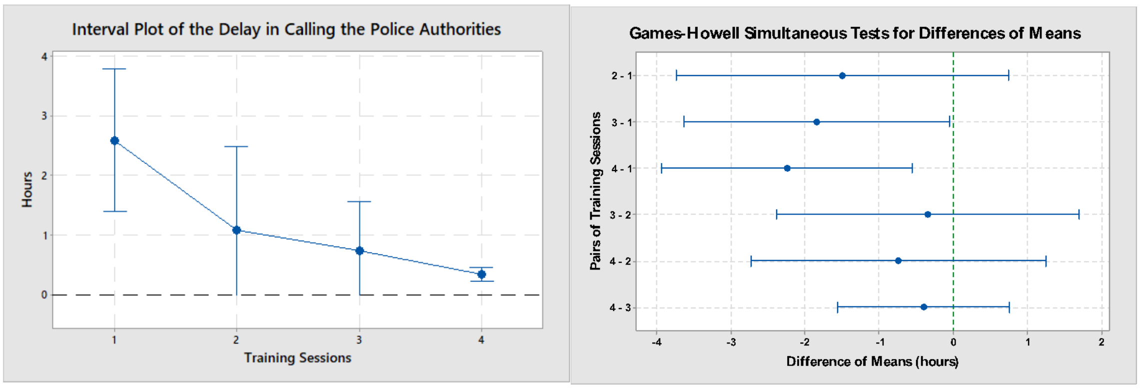


Figure 96: KPI-EM22 - Interval Plot and Games-Howell Tests

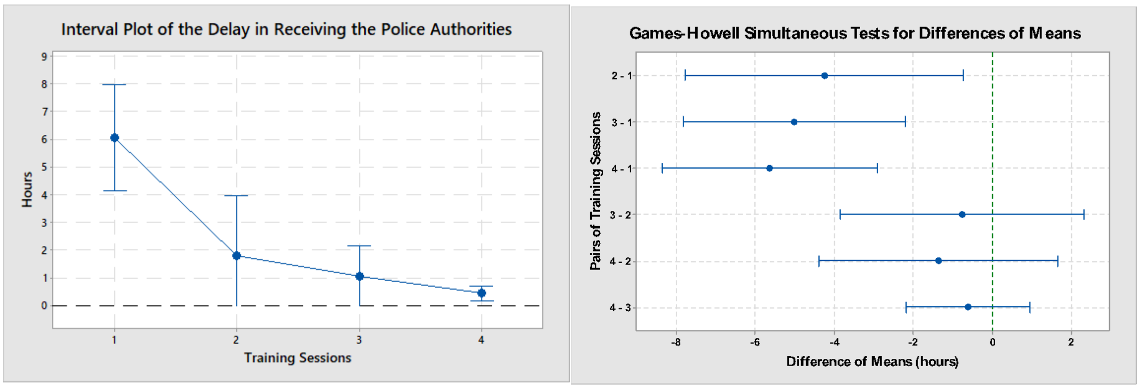


Figure 97: KPI-EM23 - Interval Plot and Games-Howell Tests

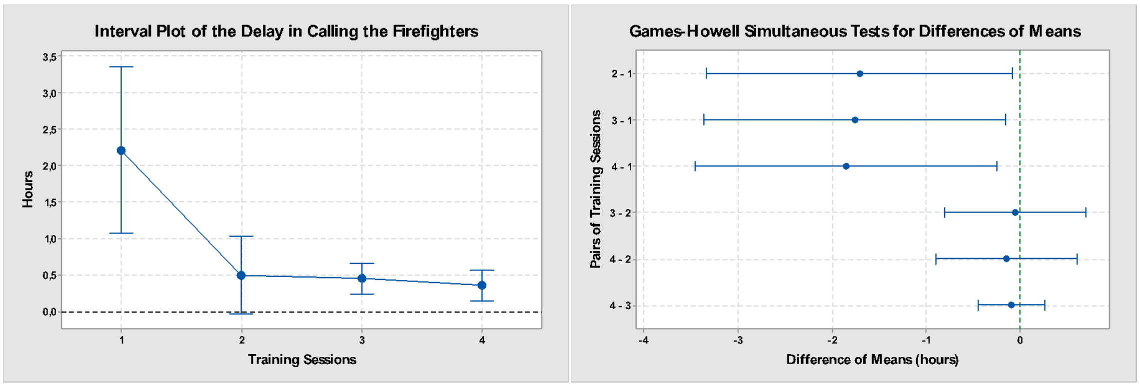


Figure 98: KPI-EM24 - Interval Plot and Games-Howell Tests

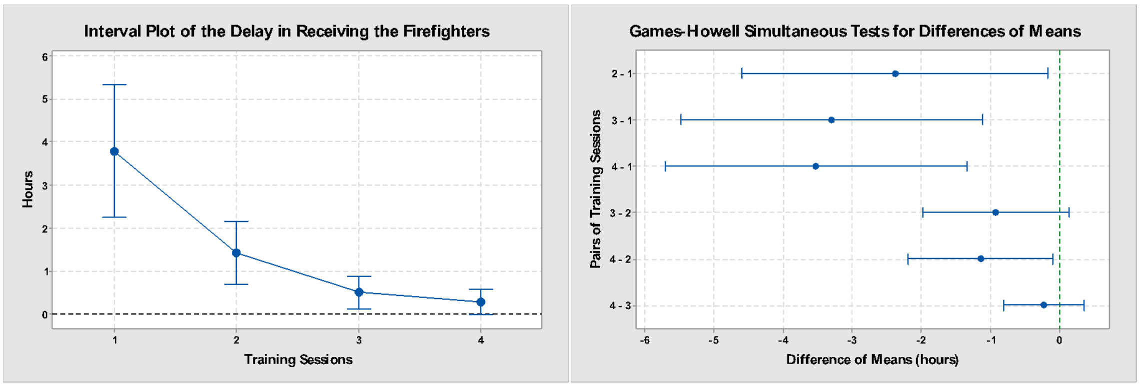


Figure 99: KPI-EM25 - Interval Plot and Games-Howell Tests

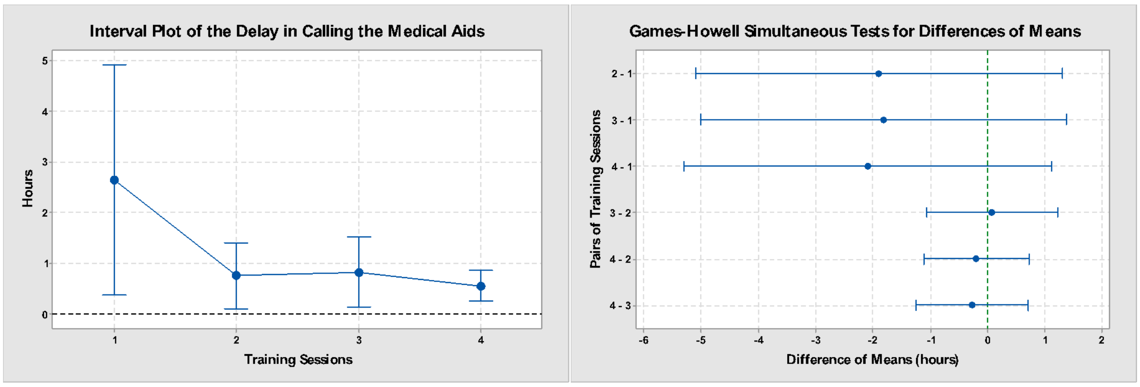


Figure 100: KPI-EM26 - Interval Plot and Games-Howell Tests

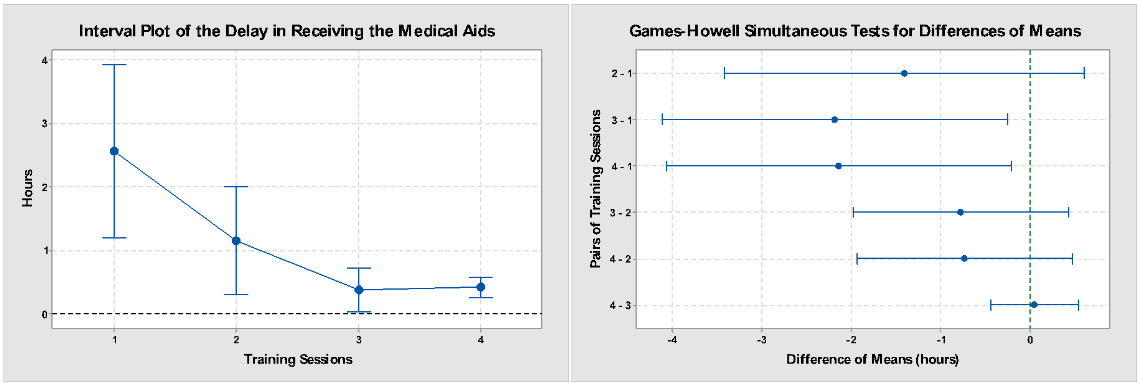


Figure 101: KPI-EM27 - Interval Plot and Games-Howell Tests

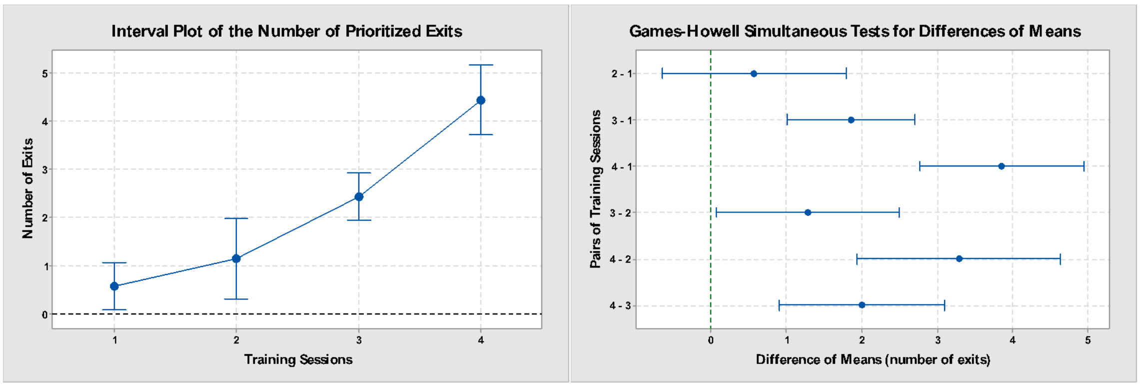


Figure 102: KPI-EM28 - Interval Plot and Games-Howell Tests

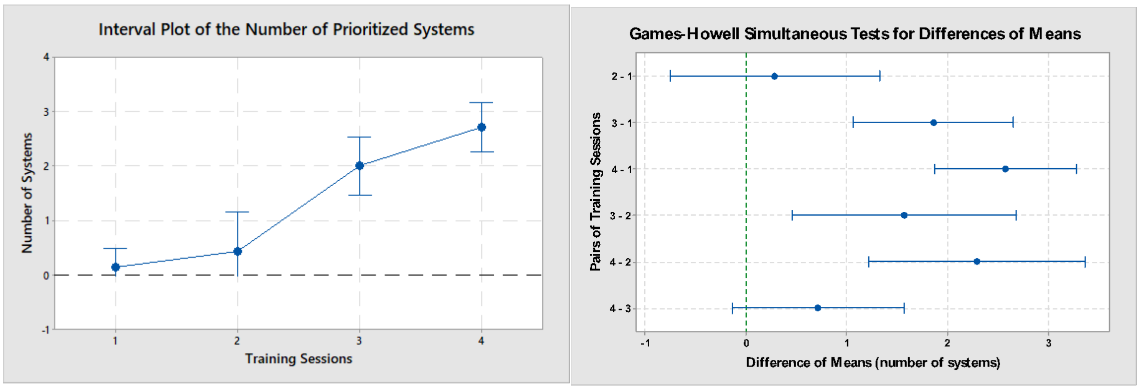


Figure 103: KPI-EM29 - Interval Plot and Games-Howell Tests

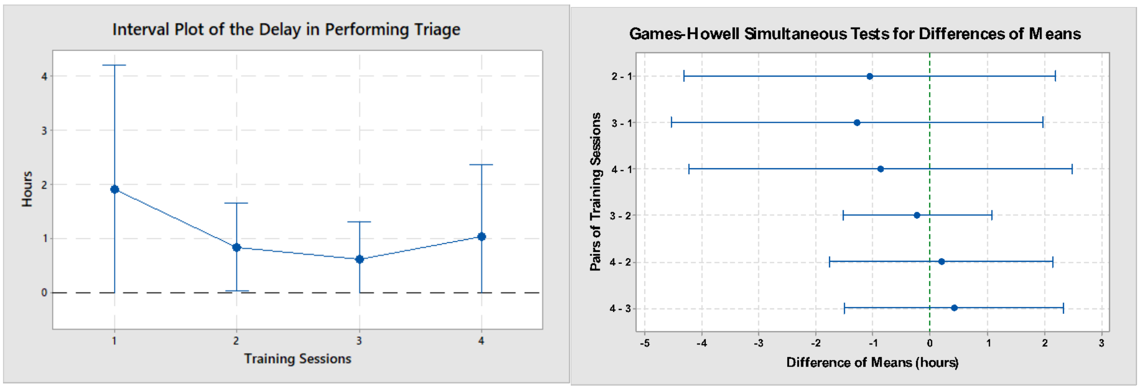


Figure 104: KPI-EM30 - Interval Plot and Games-Howell Tests

6.3 Emergency manager: psychological stress KPI results

The psychological stress results calculated in terms of heart rate for the emergency managers are well depicted in Figure 105 and Figure 106, which includes the evolution (in terms of mean value and 95% CI) of the heart rate recorded every five seconds throughout the whole duration of the training. The figures include not only the heart rate measurements in the case of the 4 replications, but also the heart rate at rest in order to have a comparison base with the data registered in the sessions. General descriptive statistics (mean, standard deviation and 95% CI) are also reported in Table 10 together with the grouping information that report about the statistical difference of the means: means that do not share a letter are significantly different.

Table 10: KPI-EM31 – Descriptive statistics and difference of the means

Replication	Mean	StDev	95% CI	Grouping
At rest	67.474	2.899	(67.3358; 67.6126)	A
R1	83.350	14.303	(82.667; 84.033)	B
R2	73.221	9.920	(72.747; 73.694)	C
R3	75.965	12.560	(75.365; 76.565)	D
R4	70.325	9.848	(69.855; 70.795)	E

A first analysis of the emergency managers' heart rate at rest shows that the heart rate undergoes a very limited variability (standard deviation = 2.90 bpm) around the mean value (it is steadily around 67.5 bpm) and the overall CI presents a very small width (67.33 bpm; 67.61 bpm) as expected – no source of stress are indeed present. Moving now to the emergency managers' heart rate during the replications, there exist many considerations to be highlighted. In R1, the emergency managers have a higher heart rate (mean = 83.35) and present a high variability (standard deviation = 14.3). This proves that the first time the emergency managers face the virtual disaster, a sense of immersion in the game is perceived. As consequence, we can assume that there is a reaction to the sequence of events generated during the training. The increased heart rate induced by the R1 is mostly due to the fact that the emergency managers are overwhelmed by the fast chain of events and by the inability to cope efficiently with the emergency because of a limited knowledge of the emergency procedures to be activated. In the R2, a greater comfort with the situation is observed in the emergency managers. The heart rate mean value is far below the previous mean value (the new mean is 73.22 bpm) and the variability is less accentuated (standard deviation = 9.92 bpm). Here, the emergency managers have a better understanding of what is happening, which are the available resources and how to exploit them efficiently (as well as he/she is more used to the disaster scenario represented in the virtual environments). The R3 provokes in the emergency managers a little bit of more stress: the heart rate mean value is 75.96 bpm and the variability increases as well (standard deviation = 12.56). This is the evidence that what we were expecting was correct: replacing the partner leads to a greater stress. After 4 replications, the emergency managers' heart rate goes down again to a mean value equal to 70.32 bpm and a variability which is reduced to 9.85 bpm in terms of standard deviation. What is relevant to underline is that, the emergency managers' heart rate in a replication is statistically different from the heart rate in every other replication (see the GH-test in Figure 106) as the p-value is in every case far below 0.05. Therefore, each additional replication leads to a significant improvement of the emergency managers' comfort when dealing with a stress-generating course of event, with undoubtful benefits on the learning strategy.

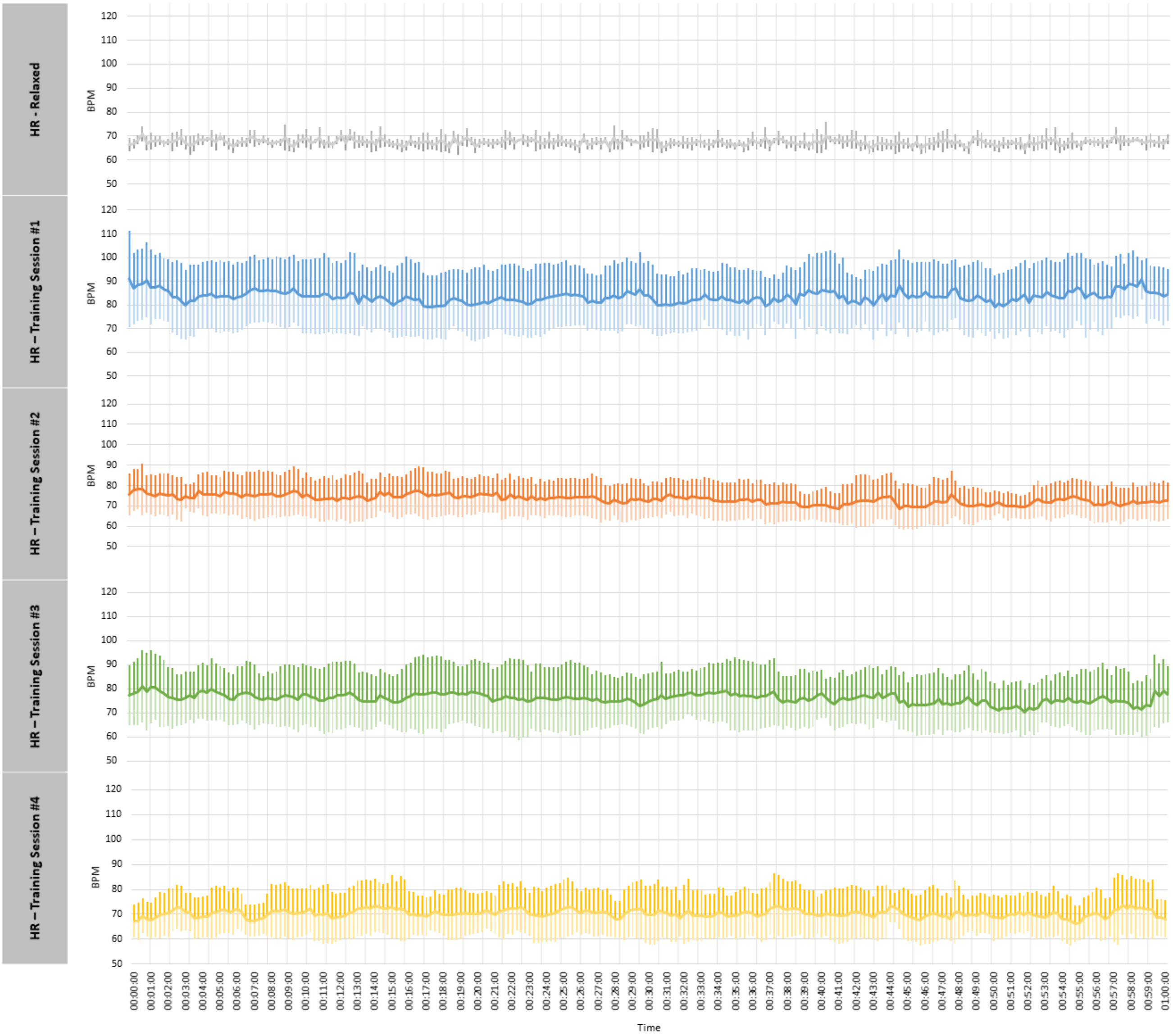


Figure 105: KPI-EM31 – mean and confidence intervals every 5 seconds

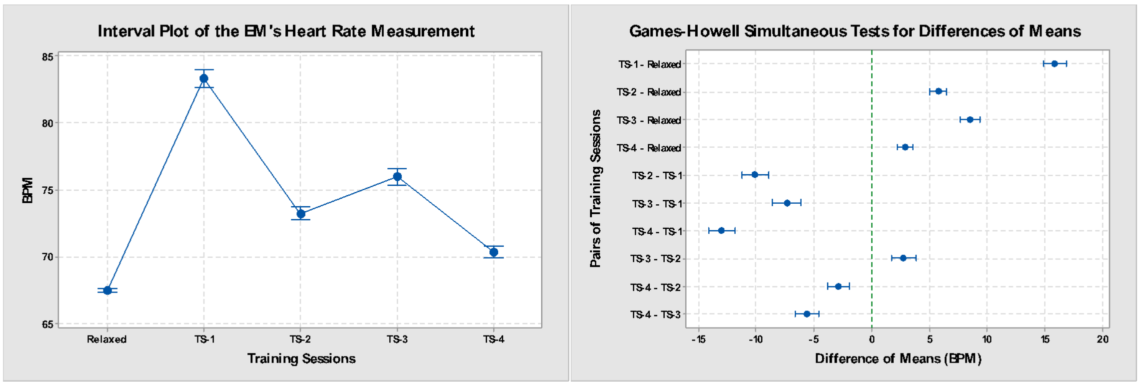


Figure 106: KPI-EM31 – Interval Plot and Games-Howell Tests

6.4 Emergency response team member: mission fulfillment KPI results

In addition to the results for the emergency managers, the system also provides a comprehensive set of KPIs results for the emergency response team members. As the emergency response team members are expected to execute the task the emergency managers have assigned to him/her, the mission fulfillment KPIs results refer to improvements in the time needed to perform successfully specific tasks. A set of 9 crucial tasks is here considered for discussion and evaluation.

In particular, the total time to perform the 9 tasks provides a quick overview of the benefits achieved after 4 replications. Indeed, if we consider the mean value, it decreases from 12.46 min, 8.97 min, 8.33 min to 7.47 min. The improvement is also clear in terms of variability: the trainees learned to execute all the tasks with a duration comprised in the 95% CI (6,635; 8,298) of R4, far different from the CI (9,85; 15,07) of the R1. The improvement is also statistically justified; the difference of the means between R1 and R3 (p-value = 0.030) and R1 and R4 (p-value = 0.011) are significant according to the GH-test, which is illustrated in Figure 107, thus leading to undoubtful benefits to the overall disaster and emergency management. To examine this KPI in detail and understand why we obtained such improvement, a further analysis can be punctually conducted on each task and related KPI. The time to perform the task #1 (see Figure 108) experiences a sharp improvement along the replications; the ETM has indeed improved the movement speed, reduced the wrong choices and cut to the chase immediately to send the evacuation order as soon as possible. A similar improvement is also showed in Figure 109, the time to perform the task #2 where the mean nosedives from 2.45 min (in the R1) down to 1.23 min (in the R4), also statistically confirmed by the difference of the means. With reference to the task #3, the trainees performing the role of emergency response team members were able to find quickly the way to count and check, on the average, the people in the safe zone. This is reflected in the results reported in Figure 110 (a steady trend around 40-45 seconds).

Statistically significant improvements are also obtained in the case of the time to perform:

- task #4, where the mean decreases from 1.79 min to 1.28 min (p-value = 0.009);
- task #5, whose duration goes down from 1.35 min to 0.65 min on the average (p-value = 0.017);
- task #9, where the decrease of the mean is significant after 3 replications – between R1 and R3 (from 1.58 min to 0.8 min, with p-value = 0.047) and is more consolidated in R4 (from 1.58 min to 0.78 min, with p-value = 0.035);
- and task #10 (where the only significant difference is between the 1st and 4th mean value, 1.17 min and 0.73 min, with a p-value = 0.030).

Other replication would have no benefits, according to the results, on the time to perform task #6 and task #7. They indeed exhibit a steady trend and it cannot be concluded that at least two means are statistically different (see Figure 113 and Figure 114). The trainees have commented on this fact highlighting that they used to execute the task #6 (calling the police authorities) after task #5 and task #4 (calling the firefighters and the medical aids). Therefore, they have already acquired some knowledge and capability to get in touch with the external aids quickly after having repeated – in the same replication – the call three times. Task #7, ultimately, is a ‘very easy task to be executed in the control room’, therefore it is performed rapidly since the 1st training session.

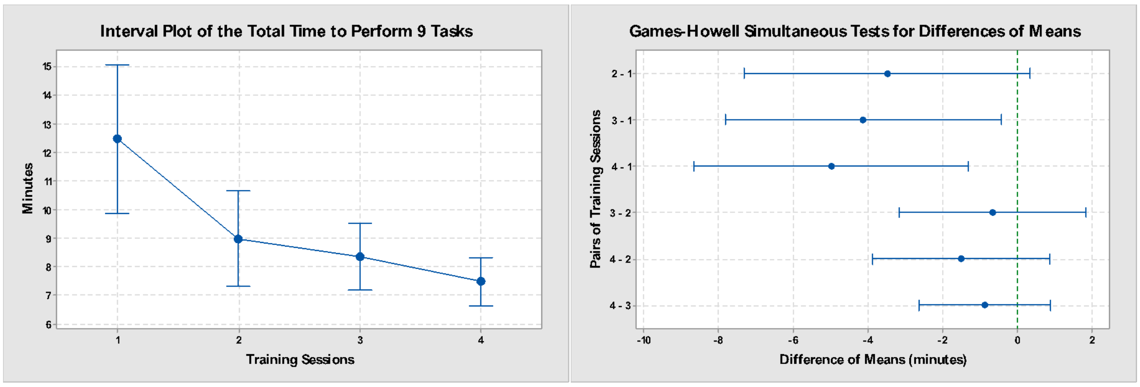


Figure 107: KPI-ETM0 - Interval Plot and Games-Howell Tests

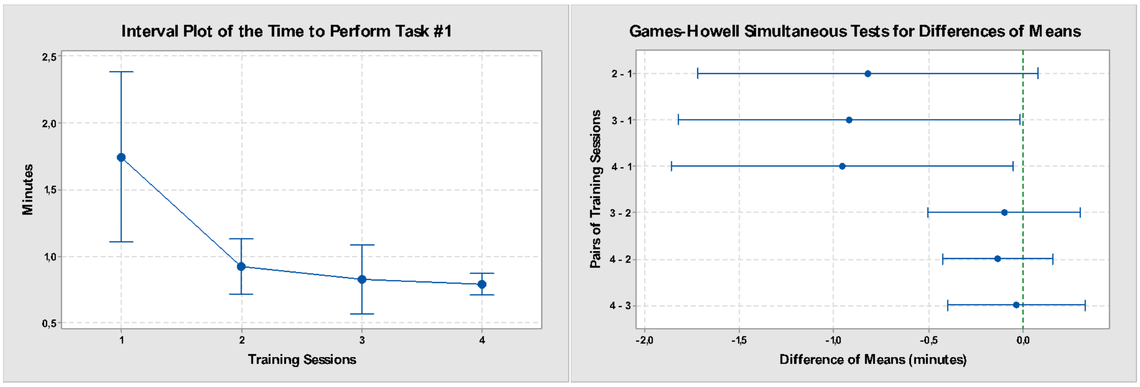


Figure 108: KPI-ETM1 - Interval Plot and Games-Howell Tests

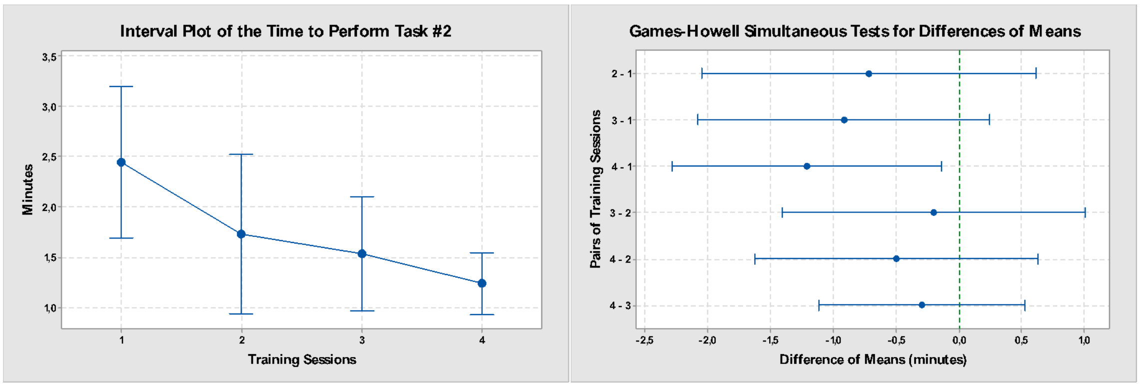


Figure 109: KPI-ETM2 - Interval Plot and Games-Howell Tests

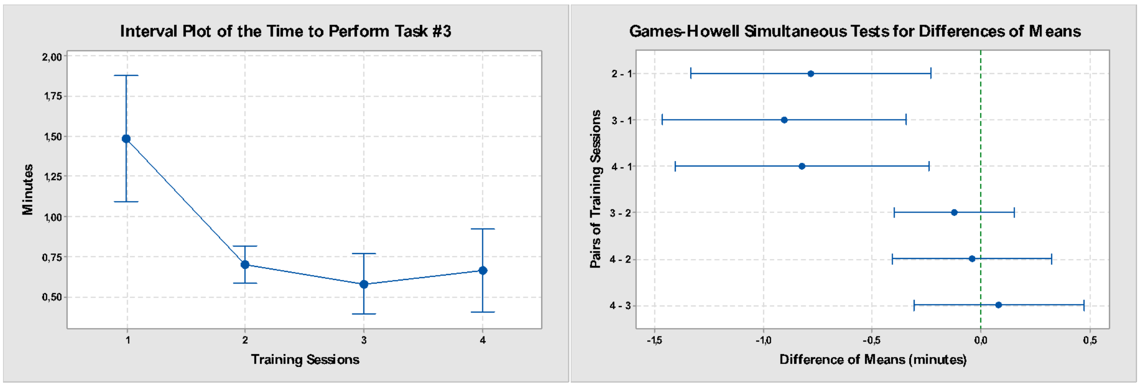


Figure 110: KPI-ETM3 - Interval Plot and Games-Howell Tests

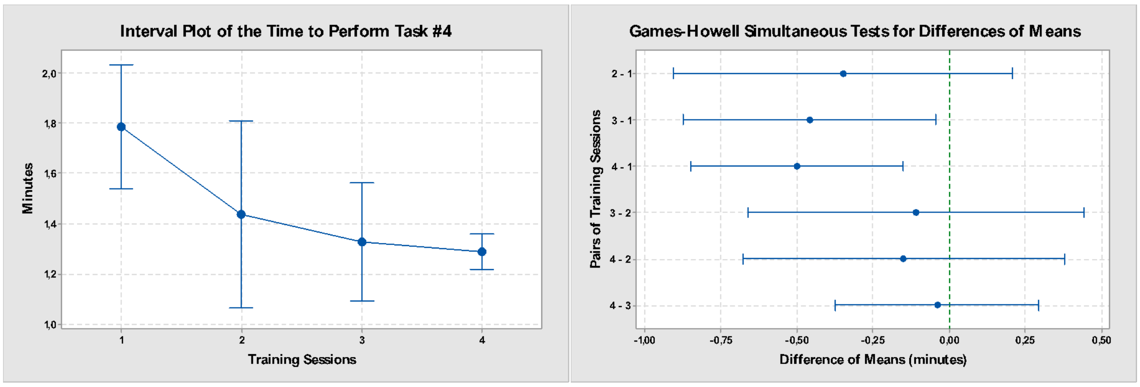


Figure 111: KPI-ETM4 - Interval Plot and Games-Howell Tests

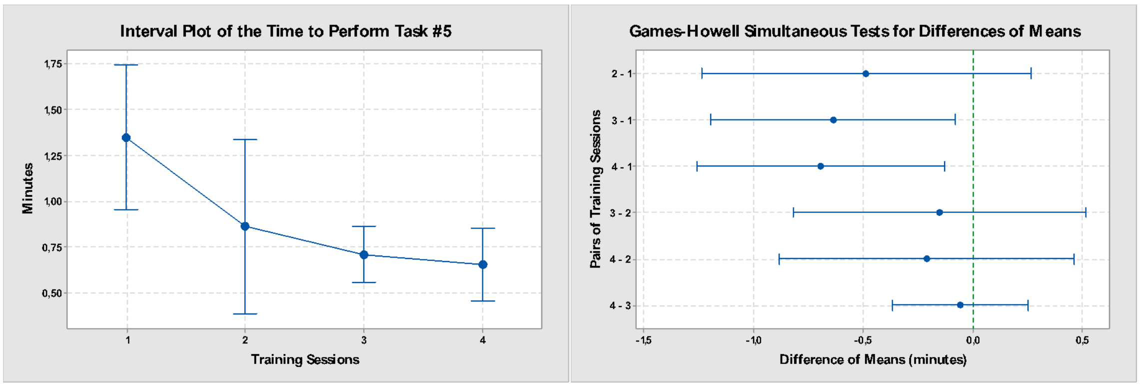


Figure 112: KPI-ETM5 - Interval Plot and Games-Howell Tests

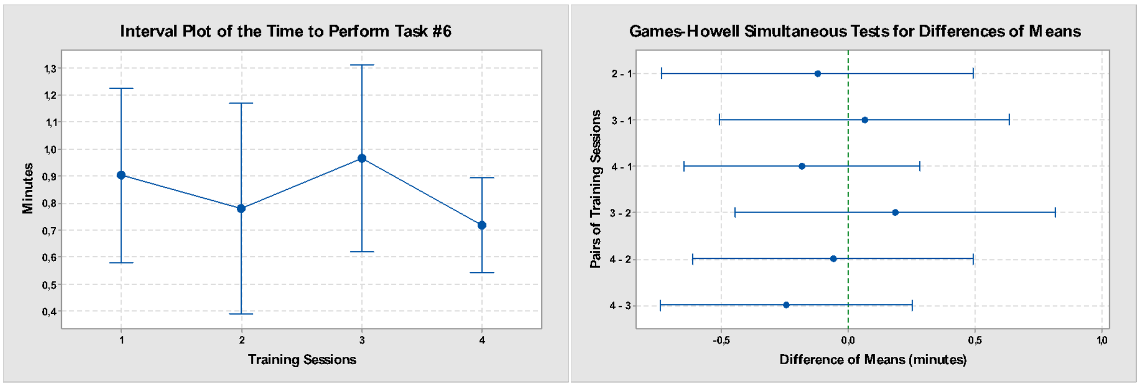


Figure 113: KPI-ETM6 - Interval Plot and Games-Howell Tests

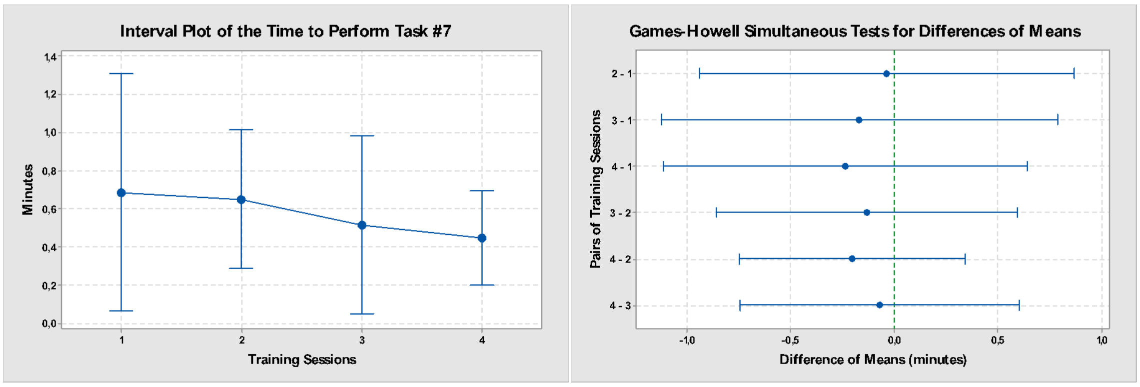


Figure 114: KPI-ETM7 - Interval Plot and Games-Howell Tests

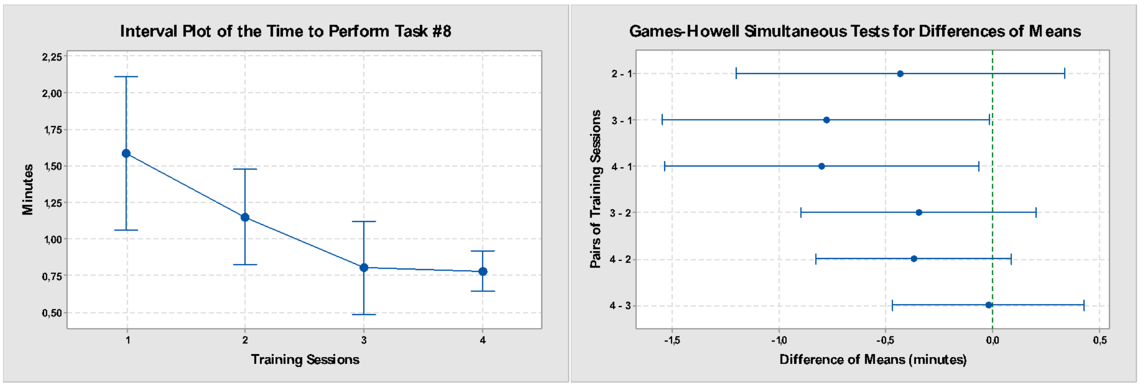


Figure 115: KPI-ETM8 - Interval Plot and Games-Howell Tests

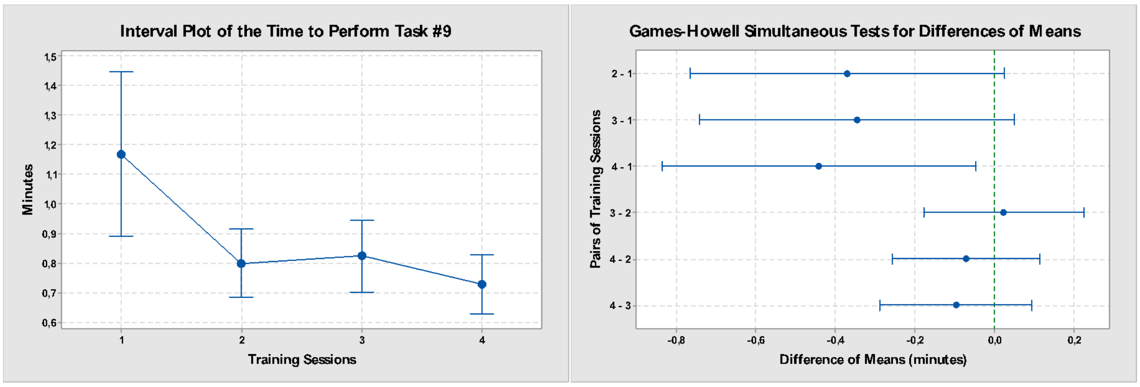


Figure 116: KPI-ETM9 - Interval Plot and Games-Howell Tests

6.5 Emergency team member: psychological stress KPI results

The results of the emergency response team members' psychological stress concludes this section. These results are even more interesting as the emergency response team members are not watching the evolution of the disaster scenario on a screen, but he/she is totally immersed into it thanks to the use of the head mounted display and of personalized motion controllers and audio devices. The proposed technological architecture heightens the stress the emergency response team members would experience when going around in the virtual disaster scenario with the ultimate aim to mitigate from time to time the emotional involvement and achieve significant benefits. Psychological stress data are depicted in Figure 117 and Figure 118, which includes the evolution (in terms of mean value and 95% CI) of the heart rate recorded every five seconds throughout the whole duration of the training. The figures include not only the heart rate measurements along the 4 replications, but also the heart rate at rest. General descriptive statistics (mean, standard deviation and 95% CI) are also reported in Table 11 together with the grouping information that report about the statistical difference of the means.

Table 11: KPI-ETM10 – Descriptive statistics and difference of the means

TS	Mean	StDev	95% CI	Grouping
At rest	67.474	2.899	(67.336; 67.613)	A
R1	85.972	12.318	(85,384; 86,560)	B
R2	85.609	13.746	(84,953; 86,265)	B
R3	87.801	13.843	(87,139; 88,462)	C
R4	87.289	15.141	(86,566; 88,012)	C

Unlike the case of the emergency manager, the usage of immersive virtual reality tools and devices keeps the heart rate very high (see the mean column in Table 11) due to the level of involvement in the virtual environment. The mean values does not undergo any substantial variation (85.97 bpm, 85.61 bpm, 87.80 bpm, 87.29 bpm) with a very little increase between R2 and R3. If we focus on the variability represented by the standard deviation, it always remains very high. This is basically a strong evidence of the fact that the emergency response team members' heart rate is deeply affected by the sense of immersion perceived, by the feeling of reality of the developed training environment, by the need to move and make all natural movements (yet limited because of sensors) and the sequence of overwhelming events. We can therefore conclude that the ETM's behavior in the virtual environment will be very similar to the one the emergency response team members would have in the real world. As showed in the GH-test of Figure 118, there are no significant differences between the pairs of means. The greater difference is registered between R2 and R3 probably because the new partner (the EM) generates additional stress compared to the previous one. The emergency response team members indeed commented on this by saying that 'they have no idea about how the new emergency manager would have led the team, what he would ask for and in which order, how the emergency manager's way of cooperation and communication would have been, …' and so on. Hence, we can conclude that the 4 replications are not sufficient to observe significant improvement in the capability of the emergency response team members to manage the psychological stress, especially because there was the replacement of the partner. Additional replications would be probably needed to achieve relevant mitigation of the psychological stress and anxiety. Further studies and research will focus on this aspect.

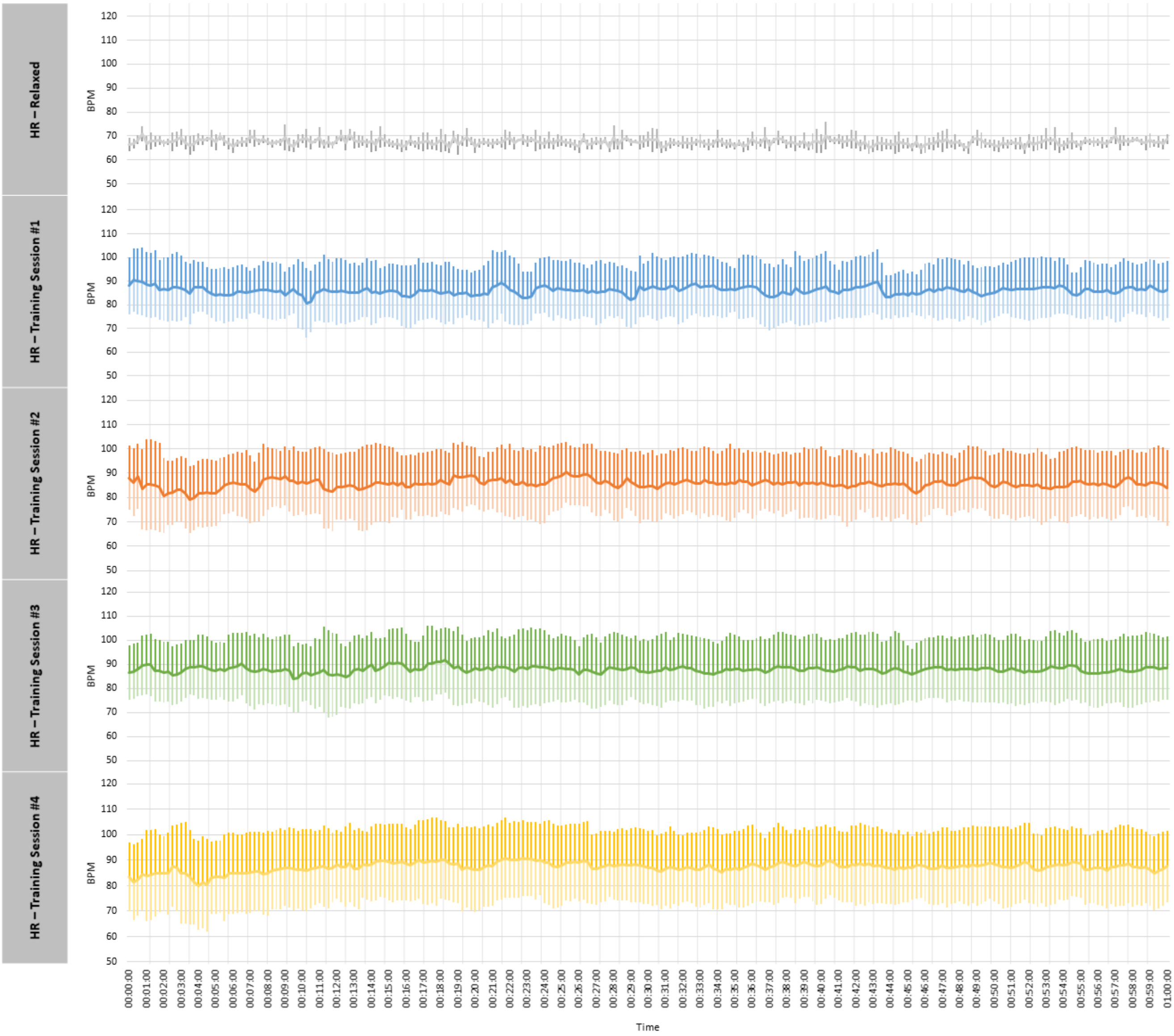


Figure 117: KPI-ETM10 – mean and confidence intervals every 5 seconds

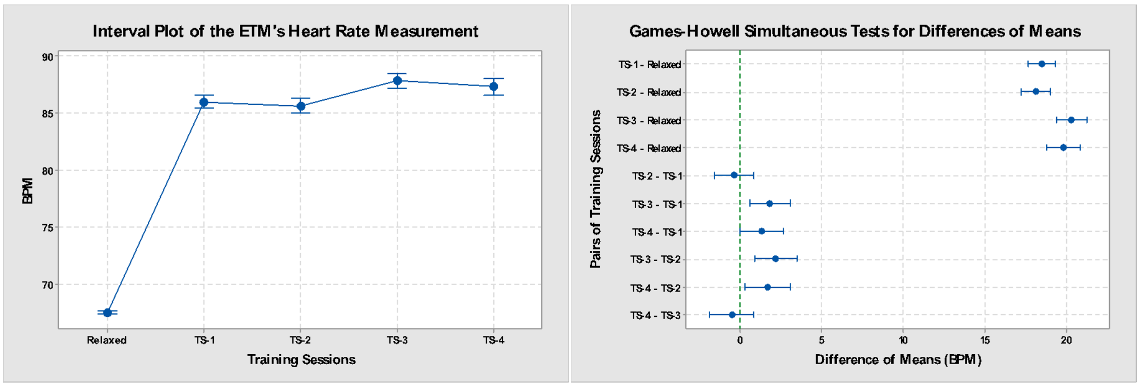


Figure 118: KPI-ETM10 – Interval Plot and Games-Howell Tests

6.6 Cross-sectional correlation analysis of workload, stress and KPIs

In order to meet the last point of the Study Aim #2.2, result data from the first of the four training sessions conducted by the operators playing the role of emergency manager were cross-sectionally analyzed. A sub-set of KPIs has been considered relevant by the subject matter experts and by the stakeholders involved in the project to be linked to the data regarding the stress and perceived workload levels. They include (and have been identified as follows):

- KPI-EM0: Training Completion Percentage;
- KPI-EM1: Total real training time (h);
- KPI-EM3: Final burning area (m^2);
- KPI-EM21: Delay in giving the evacuation order (min);
- KPI-EM6: Number of rescued people from the plant;
- KPI-EM7: Rescue operations duration (min);
- KPI-EM25: Delay in receiving the firefighters (min);
- KPI-EM27: Delay in receiving the medical aids (min);
- KPI-EM12: Number of unblocked exits;
- KPI-EM15: Number of disconnected systems.

This section presents the results of the 2nd order polynomial regression analysis. Table 12 displays the R^2 and p-value for the association between:

- the average heart rate and the j-th (j= 1, …, 12) workload contributing factor;
- the average heart rate and the OWJ.

Only in the case of the association between the average heart rate and F4 the correlation is not strong enough (the p-value is on the edge of the significance level though). In the same table, the R^2 and p-value are reported for the association between:

- the heart rate standard deviation and the j-th (j= 1, …, 12) workload contributing factor;
- the R^2 and p-value for the association between the heart rate standard deviation and the OWJ.

Even in this case, the correlation is very strong in several cases, except for F2, F5 and F6 that present a high p-value. These data are illustrated in Figure 119 where the heart rate mean value (blue dots) and standard deviation (orange dots) are given as function of the OWJ. What immediately emerges from the visual analysis of the results is that as the perceived workload increases, the average heart rate and the heart rate standard deviation increase almost proportionally (despite a 2nd order polynomial regression curve was used). Since the OWJ may have a direct correlation with the KPIs of the training session that represent the potential outcomes of an emergency response scenario, this correlation has been investigated in Table 13, which includes the R^2 and p-value for the association between:

- the i-th (i = 1, …, 10) KPI and the j-th (j= 1, …, 12) workload contributing factor;
- the i-th (i = 1, …, 10) KPI and the OWJ.

Based on the observed results, the OWJ presents a strong correlation with KPI-EM0, KPI-EM3, KPI-EM21, KPI-EM6, KPI-EM7 and KPI-EM15. Despite the p-value is higher than the significance level for the remaining KPIs, a deeper analysis to each individual workload contributing factor reveals that strong correlations do exist even between the KPIs and the single factors (but not with the OWJ). A graphical representation (scatter plot and 2nd order polynomial regression curve whose R^2 value is given in Table 13) is illustrated in the graphs from Figure 120 to Figure 129.

Table 12: Correlation between Heart Rate Mean/ Heart Rate Standard Deviation and OWJ: Goodness-of-Fit of a second order polynomial regression

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	OWJ
HR Mean	R^2	.278	.198	.265	.128	.288	.217	.371	.311	.319	.468	.100	.349	.359
	p	**.004***	**.018***	**.005***	.062	**.003***	**.012***	**.001***	**.002***	**.002***	**.000***	.101	**.001***	**.001***
HR St. Dev.	R^2	.417	.101	.710	.391	.118	.012	.522	.594	.589	.653	.475	**.237**	**.431**
	p	**.000***	.099	**.000***	**.000***	.074	.573	**.000***	**.000***	**.000***	**.000***	**.000***	**.009***	**.000***

Table 13: Correlation between KPIs and OWJ: Goodness-of-Fit of a second order polynomial regression

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	OWJ
KPI-EM0	R^2	.471	.141	.185	.045	.321	.122	.080	.256	.151	.411	.263	.196	.237
	p	**.000***	**.049***	**.022***	.276	**.002***	.068	.146	**.006***	**.041***	**.000***	**.005***	**.018***	**.009***
KPI-EM1	R^2	.107	.019	.128	.022	.114	.013	.116	.098	.091	.090	.133	.045	.016
	p	.090	.483	.061	.452	.079	.560	.077	.105	.118	.121	.056	.277	.526
KPI-EM3	R^2	.382	.092	.188	.007	.648	.203	.105	.223	.231	.545	.155	.247	.407
	p	**.000***	.118	**.021***	.674	**.000***	**.016***	.093	**.011***	**.010***	**.000***	**.038***	**.007***	**.000***
KPI-EM21	R^2	.185	.038	.063	.037	.335	.214	.084	.075	.156	.325	.116	.637	.302
	p	**.022***	.322	.199	.327	**.001***	**.013***	.134	.158	**.037***	**.002***	.076	**.000***	**.002***
KPI-EM6	R^2	.265	.031	.174	.118	.157	.115	.078	.094	.136	.231	.288	.306	.150
	p	**.005***	.370	**.027***	.073	**.037***	.078	.149	.113	.054	**.010***	**.003***	**.002***	**.042***
KPI-EM7	R^2	.252	.146	.144	.030	.116	.015	.166	.209	.156	.137	.062	.140	.218
	p	**.006***	**.045***	**.046***	.380	.076	.539	**.031***	**.014***	**.038***	.053	.201	**.050***	**.012***
KPI-EM25	R^2	.001	.023	.098	.536	.067	.096	.039	.012	.036	.144	.019	.014	.086
	p	.903	.445	.105	**.000***	.183	.108	.313	.585	.334	**.046***	.489	.556	.130
KPI-EM27	R^2	.169	.275	.126	.138	.130	.191	.082	.059	.067	.153	.207	.141	.096
	p	**.030***	**.004***	.063	.051	.059	**.020***	.140	.212	.185	**.039***	**.015***	**.049***	.109
KPI-EM12	R^2	.171	.045	.065	.134	.158	.127	.157	.123	.165	.253	.107	.345	.123
	p	**.029***	.277	.190	.055	**.036***	.063	**.037***	.067	**.032***	**.006***	.090	**.001***	.068
KPI-EM15	R^2	.173	.064	.177	.205	.194	.005	.161	.286	.216	.185	.163	.178	.177
	p	**.028***	.196	**.026***	**.015***	**.019***	.723	**.034***	**.003***	**.013***	**.023***	**.033***	**.025***	**.026***

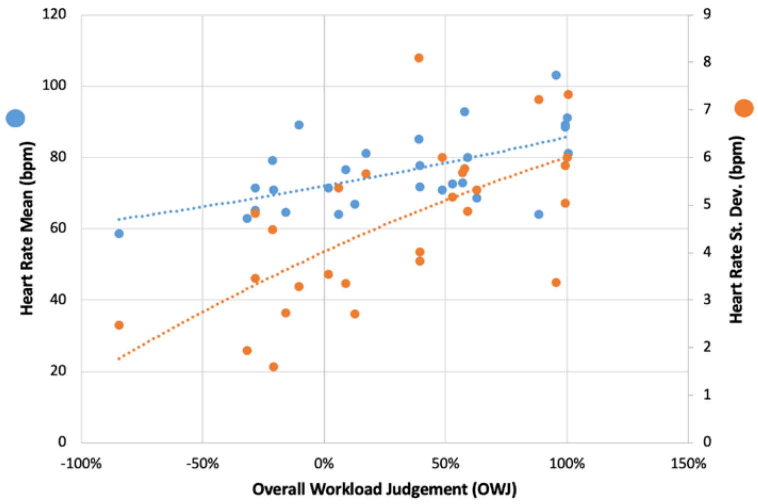


Figure 119: Correlation between the heart rate mean and the heart rate standard deviation with the OWJ

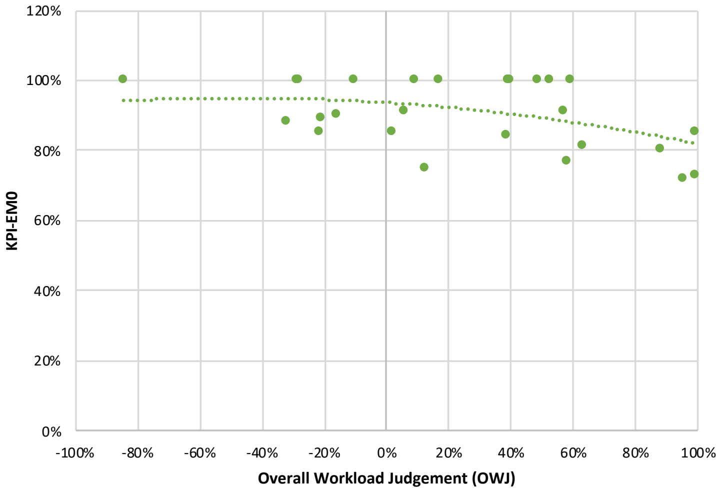


Figure 120: Correlation between KPI-EM0 with the OWJ

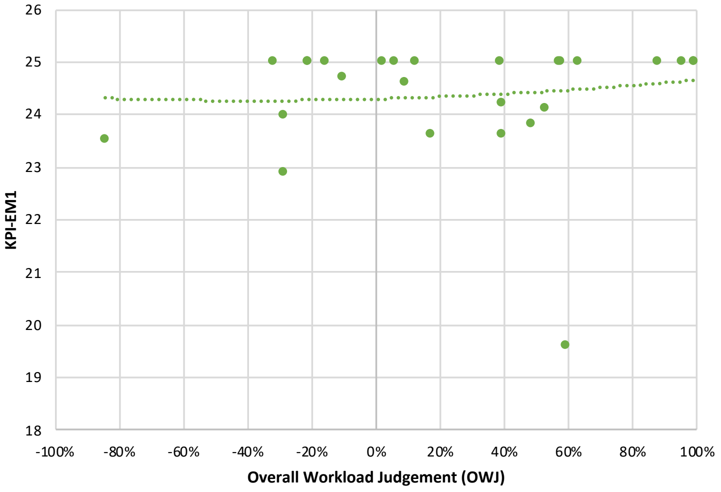


Figure 121: Correlation between KPI-EM1 with the OWJ

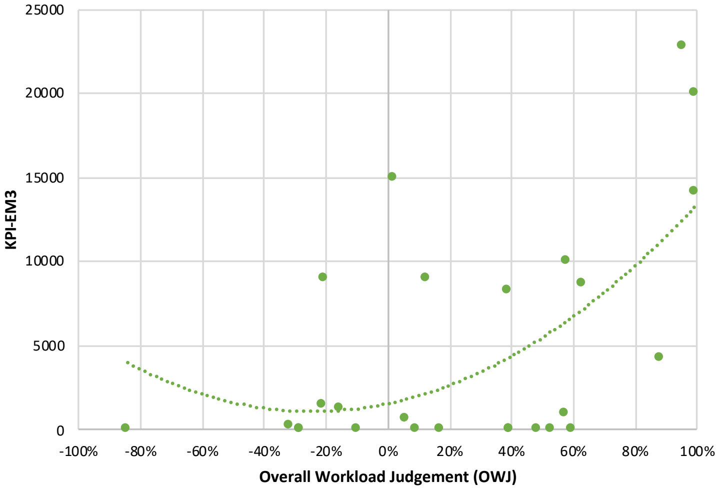


Figure 122: Correlation between KPI-EM3 with the OWJ

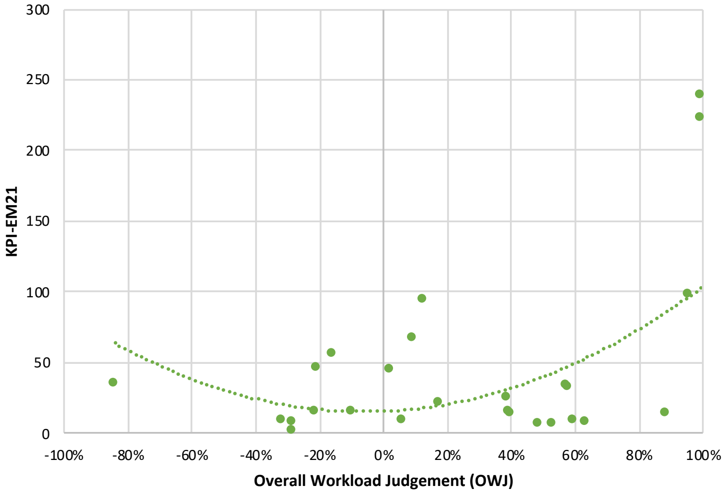


Figure 123: Correlation between KPI-EM21 with the OWJ

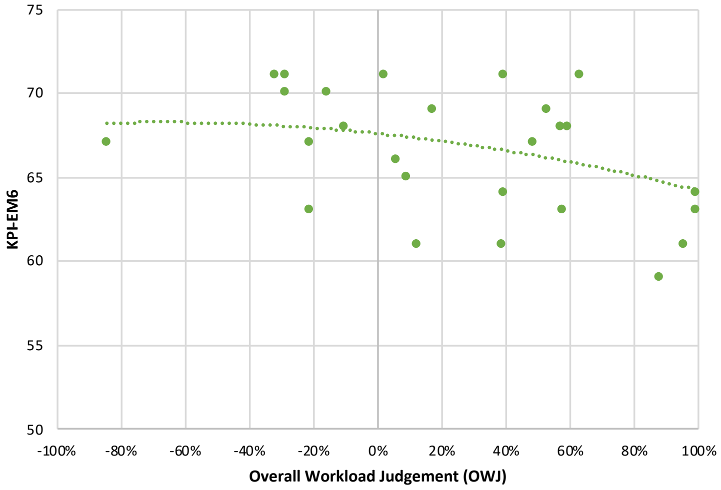


Figure 124: Correlation between KPI-EM6 with the OWJ

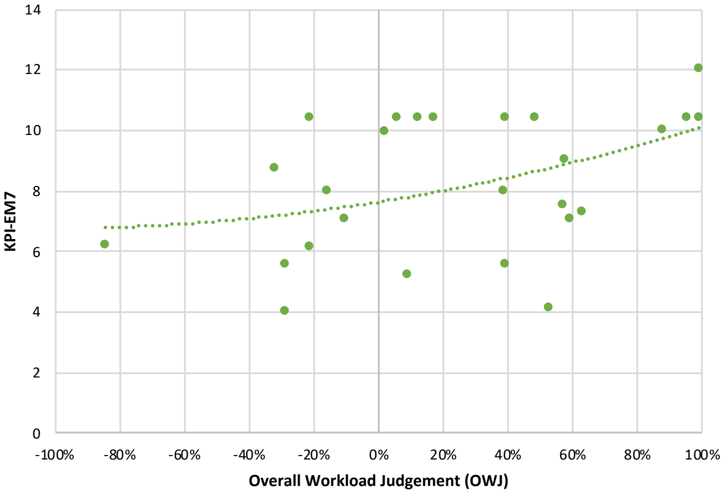


Figure 125: Correlation between KPI-EM7 with the OWJ

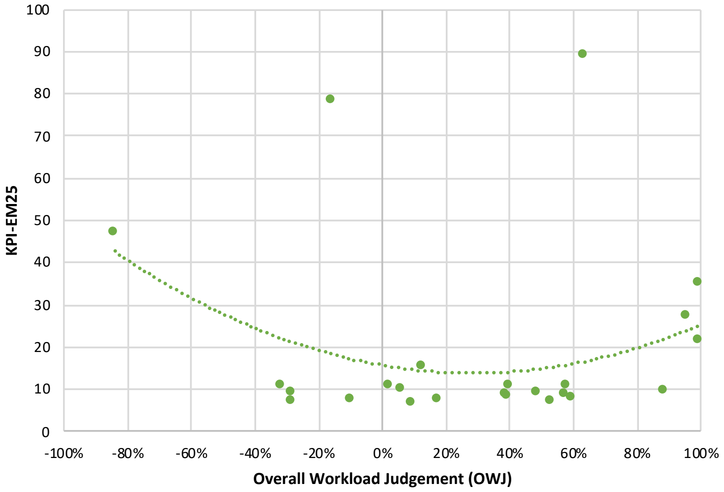


Figure 126: Correlation between KPI-EM25 with the OWJ

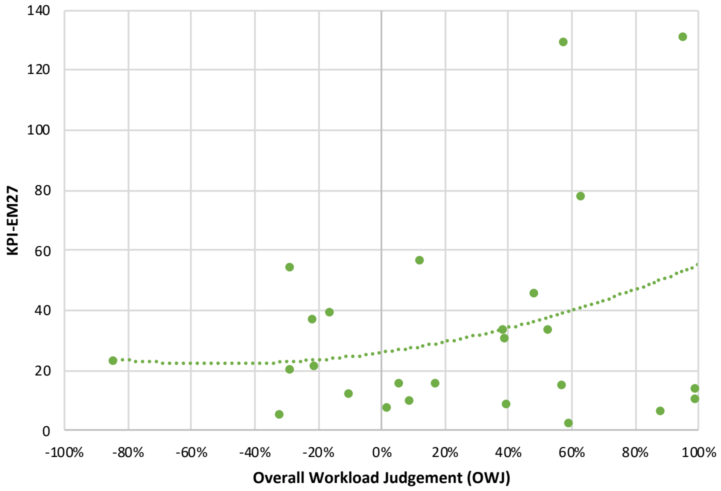


Figure 127: Correlation between KPI-EM27 with the OWJ

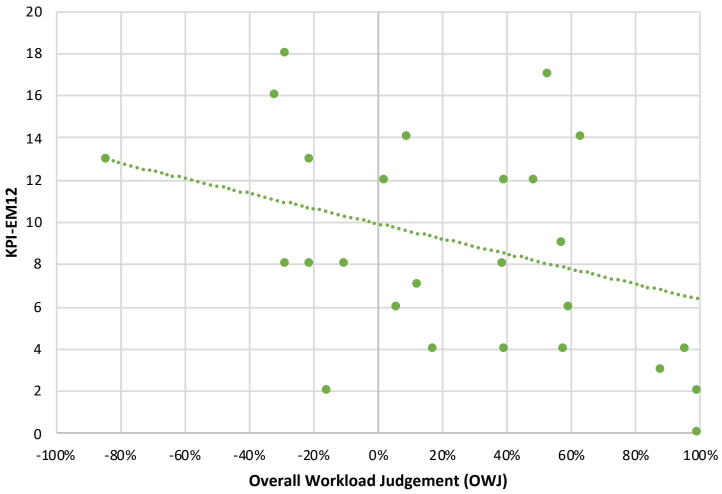


Figure 128: Correlation between KPI-EM12 with the OWJ

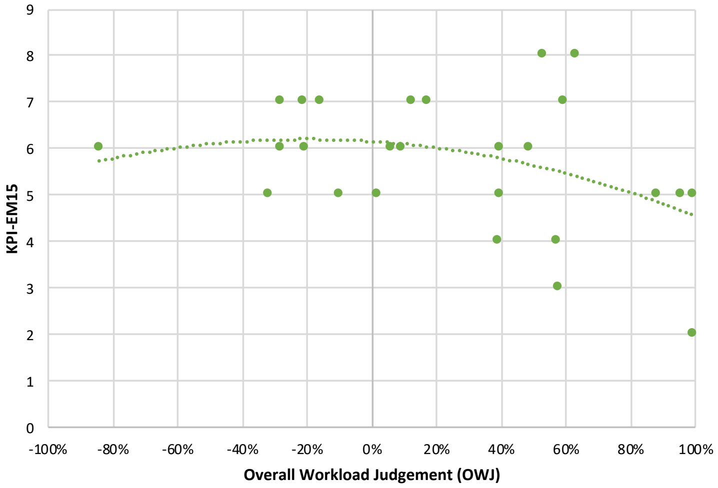


Figure 129: Correlation between KPI-EM15 with the OWJ

In this analysis, as showed in Figure 57, the association between the perceived workload and the monitored KPIs is considered mediated by the heart rate measurement that is a predictor of the stress/anxiety due to the emergency scenario. Hence, the association between the heart rate (mean and standard deviation) and the KPIs has been investigated too. Table 14 displays the R^2 and p-value for the association between:

- the heart rate mean value and the i-th (i= 1, …, 10) KPI;
- the heart rate standard deviation and the i-th (i= 1, …, 10) KPI.

A 2nd order polynomial regression curve has been adopted in this case too to highlight the latent Yerkes-Dodson effect in the available data. Results confirm that a significant correlation can be observed for:

- the heart rate mean with KPI-EM0, KPI-EM3, KPI-EM21, KPI-EM6, KPI-EM27 and KPI-EM15;
- the heart rate standard deviation with KPI-EM6, KPI-EM25 and KPI-EM15.

These data are illustrated in the group of pictures from Figure 130 to Figure 139. Herein, the pairs of data related to the heart rate mean value are in blue whereas those related to the heart rate standard deviation are given in orange. The strength of the correlation of the data by a second order polynomial regression curves depicted in the figures is given by the R^2 values collected in Table 14.

Table 14: Correlation between KPIs and Heart Rate Mean/ Heart Rate Standard Deviation: Goodness-of-Fit of a second order polynomial regression

		HR Mean	**HR St. Dev.**
KPI-EM0	**R^2**	.243	.089
	p	**.008***	.123
KPI-EM1	**R^2**	.040	.086
	p	.306	.130
KPI-EM3	**R^2**	.377	.047
	p	**.001***	.270
KPI-EM21	**R^2**	.204	.007
	p	**.016***	.666
KPI-EM6	**R^2**	.187	.144
	p	**.021***	**.046***
KPI-EM7	**R^2**	.131	.103
	p	.059	.096
KPI-EM25	**R^2**	.016	.263
	p	.524	**.005***
KPI-EM27	**R^2**	.414	.033
	p	**.000***	.356
KPI-EM12	**R^2**	.130	.079
	p	.059	.147
KPI-EM15	**R^2**	.212	.156
	p	**.014***	**.038***

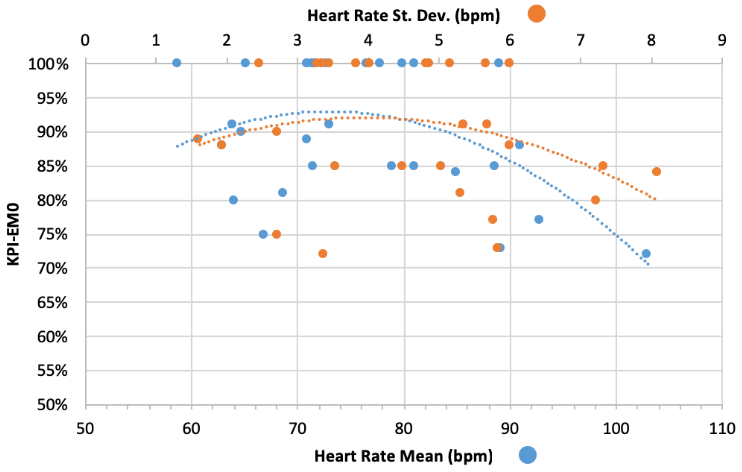


Figure 130: Correlation between KPI-EM0 and Heart Rate Mean/ Heart Rate Standard Deviation

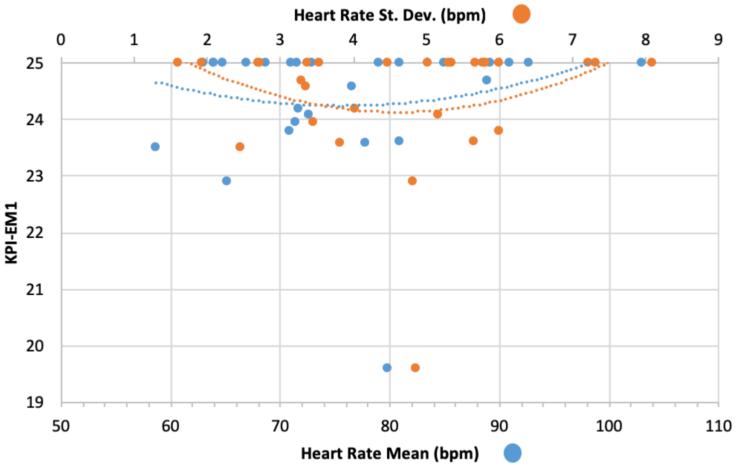


Figure 131: Correlation between KPI-EM1 and Heart Rate Mean/ Heart Rate Standard Deviation

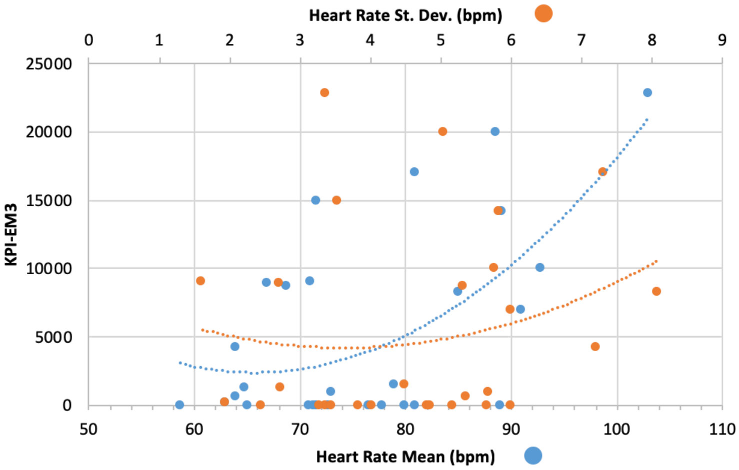


Figure 132: Correlation between KPI-EM3 and Heart Rate Mean/ Heart Rate Standard Deviation

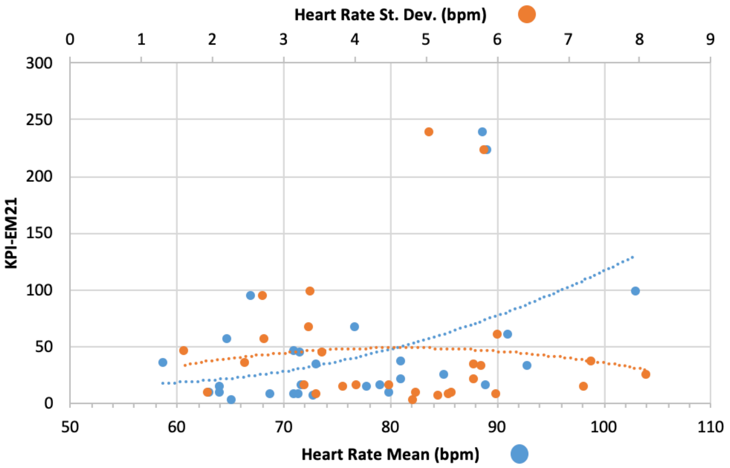


Figure 133: Correlation between KPI-EM21 and Heart Rate Mean/ Heart Rate Standard Deviation

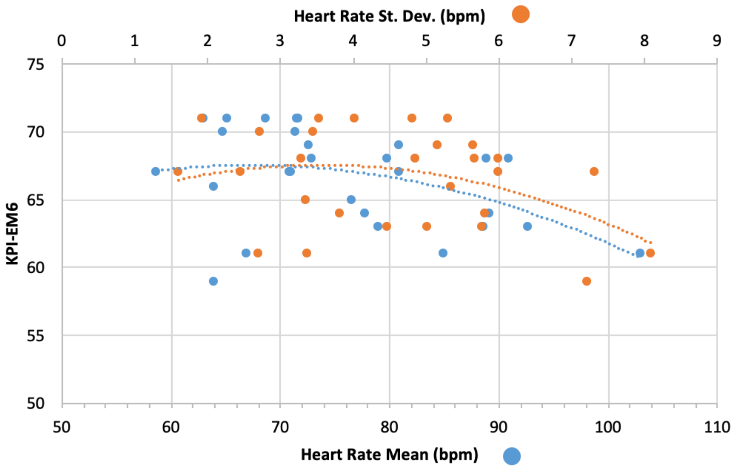


Figure 134: Correlation between KPI-EM6 and Heart Rate Mean/ Heart Rate Standard Deviation

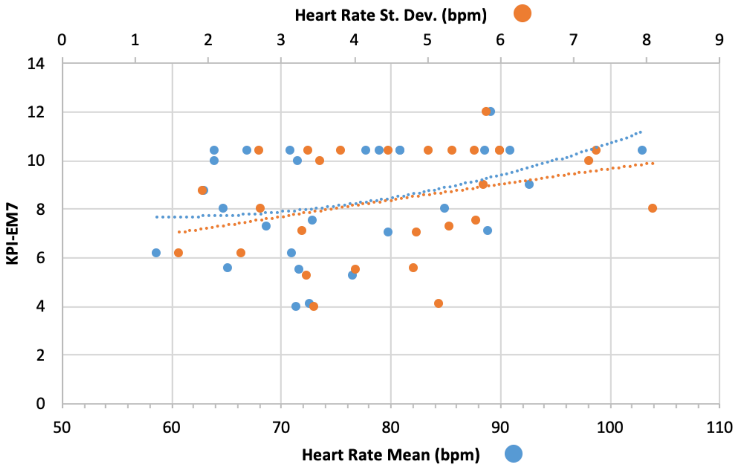


Figure 135: Correlation between KPI-EM7 and Heart Rate Mean/ Heart Rate Standard Deviation

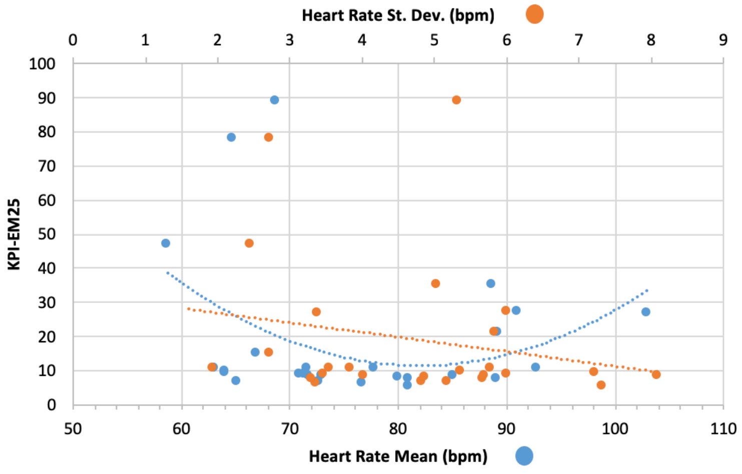


Figure 136: Correlation between KPI-EM25 and Heart Rate Mean/ Heart Rate Standard Deviation

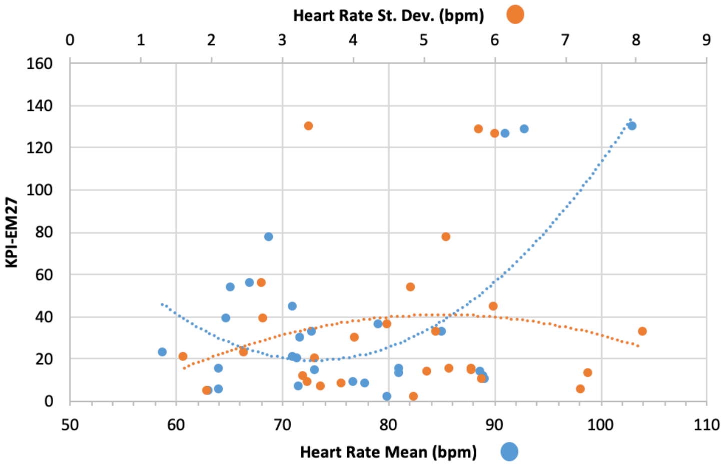


Figure 137: Correlation between KPI-EM27 and Heart Rate Mean/ Heart Rate Standard Deviation

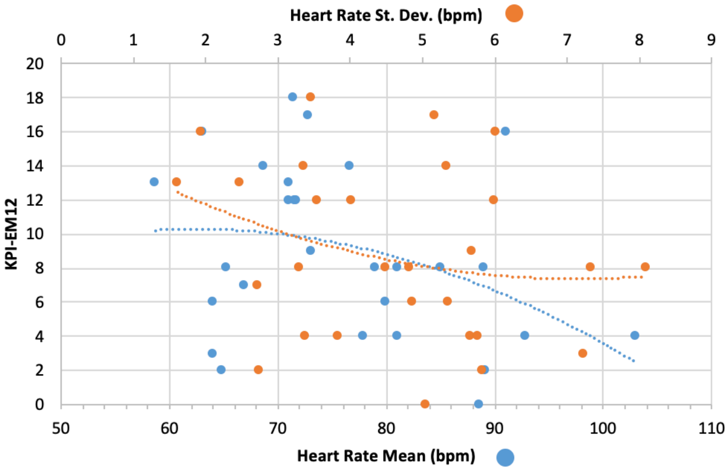


Figure 138: Correlation between KPI-EM12 and Heart Rate Mean/ Heart Rate Standard Deviation

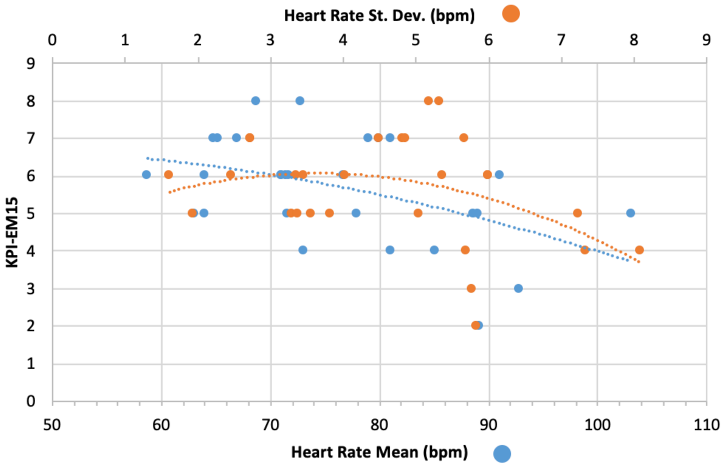


Figure 139: Correlation between KPI-EM15 and Heart Rate Mean/ Heart Rate Standard Deviation

The hypothesis of our study – there exist a correlation between heart rate descriptors and perceived workload in the event of an industrial emergency – has found a confirmation in the findings reported in Table 12. Our results are aligned with those of González-Muñoz and Gutiérrez-Martínez (2007), which argue that mental demand, temporal demand, and frustration when faced with a given task may be considered risk factors for job stress. The workload assessment methodology used in this research study enriches the results of previous studies and provides a deeper investigation of the factors influencing the stress/anxiety in an emergency scenario. Workload has been proved to be correlated to the heart rate (and therefore to stress). As showed in Figure 140, which displays the average heart rate of all the study subjects over the session, a high heart rate is observed at the beginning of the virtual emergency session, which decreases as the emergency scenario evolves. In some cases, the emergency has not been managed properly therefore some players tried to respond to the divergent chain of events with scarce success and with an increased heart rate in the last minutes of the session. It has been found that people who succeeded in the session used to have a constant high heart rate from the beginning to the end of the training session (which implies a little standard deviation) and reported a balanced OWJ (between -10% and 10%). We argue that these persons are those who fit the most the role of emergency operators in an industrial plant. The players who didn't succeed reported instead a higher perceived workload and their heart rate presents a gradual decrease until the last part of the training session in which the players got worried about the outcomes of their emergency response and tried some actions to get the situation behind the wheel again. As clearly displayed in Figure 57, the Yerkes-Dodson Law does not properly apply in this case: indeed, the U-shaped relationship is between stress and human performance (i.e. the KPIs) and not between human factors (perceived workload and stress). The 2nd order polynomial regression curves used to predict the heart rate mean and standard deviation as function of the perceived workload (i.e. the OWJ) are indeed most likely lines rather than curves.

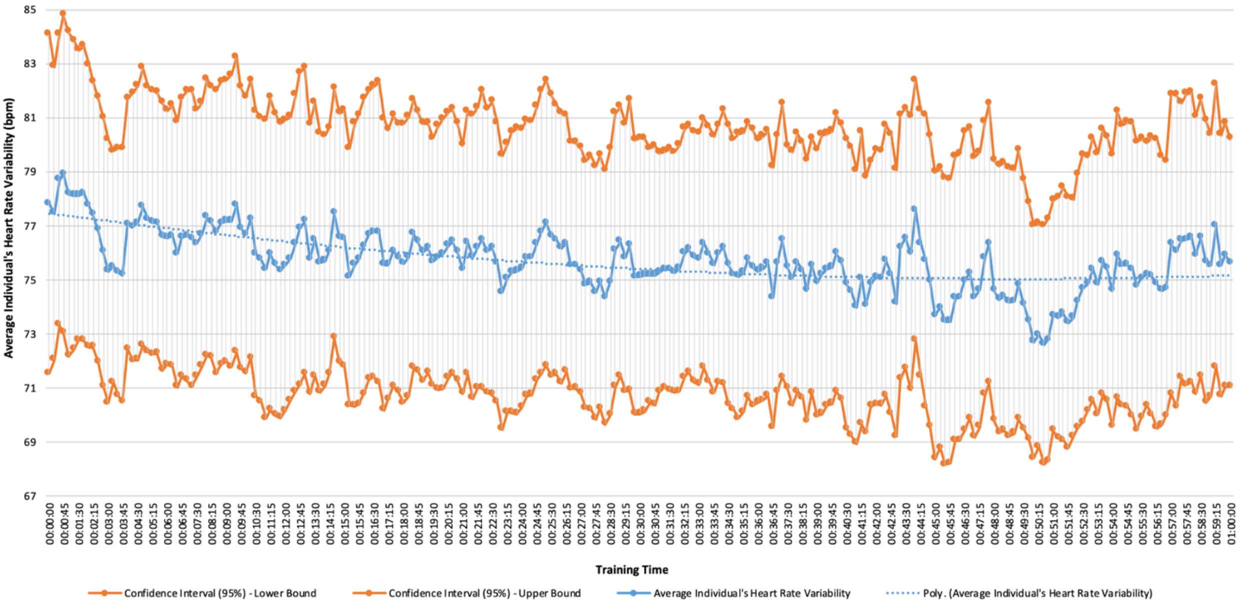


Figure 140: Heart rate variability for an average study subject

This does not apply when the considered output is a KPI, a training performance outcome. The relationship between KPI-EM0 (the training completion percentage) and the OWJ is represented by an inverted U-shaped curve (see Figure 120). The curve has its apex when the OWJ is less than 0% (when the player feels underloaded) and starts dropping as the OWJ increases. The correlation is statistically significant as confirmed by the p-value = .009 in Table 13, therefore we can conclude that the training completion percentage decreases as the perceived workload increases.

The relationship, and therefore, the association is not significant between the OWJ and the KPI-EM1 (training time). The reason for this result is the definition of training time itself and its upper bound. The training session ends (and it is stopped) after 25 (simulated) hours from the beginning of the session (the speed of the serious game can be increased or decreased at the player's convenience). Only in 11 observations, the operators succeeded (i.e. a training time less than 25 has been collected), which means that observed training time values are distributed in a 1.5 hours range.

A significant U-shaped relationship has been found for the KPI-EM3, KPI-EM21, KPI-EM6 and KPI-EM7. In the analysis of Figure 122, it is showed how the lowest level of the burning area is achieved when the perceived workload is around 0% (balanced workload). Indeed, if the operators are too overloaded, they forget to execute properly the procedure and support the external aids. In the case the operators felt underloaded, they underestimated the danger and forgot to execute simple actions, e.g. launch the alarm. It is also arguable that in this case, the operators did not feel enough immersed in the serious game, therefore their performance (and connected training outcomes) is also scarce. The perceived workload may be then considered as a predictor of the operators' real feeling of being immersed. A similar behavior is showed in Figure 123 by the relationship between the OWJ and the KPI-EM21. Other two KPIs which show a strong correlation with the OWJ are those related to the evacuees and the time needed to save people in the plant. The number of people saved decreases as the OWJ increases; however, it does not decrease also when the player feels underloaded. Actions to save people are the first ones that are put into practice by the players even when they feel underloaded or the player do not feel enough immersed. Similarly, but with an inverted shape, the relationship between the OWJ and the KPI-EM7 shows how the time needed to save people increases as the OWJ increases.

KPI-EM25, KPI-EM27 and KPI-EM12 do not result to be correlated to the perceived workload. This result may require additional investigation with much more experiments in order to confirm that there is no correlation or prove the opposite.

Finally, KPI-EM15 appears to be correlated to the perceived workload. The number of systems disconnected is high in case of a low or balanced workload. As the workload begins to increase and be overbalanced, the number of systems disconnected during the sessions diminishes, thus showing that when the players feel overloaded, they forget to shut off the critical systems and focus on other aspects of the disaster, with the risk of potential harmful consequences.

A general look at the behavior of these relationships reveal that the higher value of the KPIs is achieved when the workload is balanced because excessive demand or reduced workload may cause delays in the first case and low vigilance in the second case. Workload appears then to be a relevant component of a human factors' analysis in industrial emergency response scenarios and must be considered in the context of an Industrial Occupational Health & Safety 4.0.

Similar results are achieved when we correlate the training KPIs with the stress level measured with the heart rate mean and standard deviation over a training session. The first figure on this regard, Figure 130, provides material for interesting insights. The second order polynomial regression curve used to correlate the pairs of data have their peak for low heart rate mean values and standard deviation values and start decreasing consistently after 80 bpm (in the case of the heart rate mean) and 5 bpm (in the case of the heart rate standard deviation). On one side, the results are consistent with the literature as higher heart rate is associated to higher stress and therefore lower expected performance. This is in fact confirmed by the findings of this study. On the other side, this study shows an interesting point to discuss. According to medical literature, lowered heart rate variability is usually associated to higher stress levels, therefore a high performance would be expected for high values of the heart rate standard deviation. However, the relationship between KPI-EM0 and the heart rate standard deviation is pretty similar to the one with the heart rate mean (the higher the standard deviation, the lower the performance), which is the contrary of what was expected. This phenomenon can be explained with the actual training outcomes of those players who did not succeed in the serious game. They reported not only a higher perceived workload but their heart rate presents a gradual decrease until the last part of the training session in which the players got very worried about the outcomes of their emergency response and their capability to handle it. This implies a greater variability (i.e. standard deviation) if compared to those players who always kept a very high concentration throughout the session, who felt immersed in the virtual environment and whose heart rate was usually steady and high. The reduction of the heart rate can be interpreted then as a lower concentration level and lower immersion in the simulated scenario, rather than a purely physiological description of the stress level which impacts on performance. On this aspect, further investigation is needed because, as shown in Table 14, the p-value associated to the correlation between KPI-EM0 and the heart rate mean is significant, whereas the one with the heart rate standard deviation is not. As reported in the same table and as occurred between the KPI-EM1 and the OWJ, a significant relationship between KPI-EM1 and the heart rate mean and standard deviation has not been found. Even in this case, the definition of the KPI as upper-bounded does not allow to appreciate a significant correlation.

A significant relationship has been found between the heart rate mean and KPI-EM3 and KPI-EM21. When a high heart rate has been recorded, players failed in extinguishing the fire and they did not succeed in the virtual scenario. The final burning area increases then as stress level increases. Similarly, when they are too stressed, the players used to forget to launch the evacuation alarm, they used to take too much time to make a decision, they confusedly focus on other tasks such as cooperating with the firefighters or going in the plant to find injured people. No significant relationship has been found for the standard deviation with these two KPIs.

The KPI-EM6 shows the same behavior of KPI-EM0 (see Figure 134). The KPI worsens as the heart rate mean and standard deviation increase. The number of people (employees and visitors of the virtual industrial site) in the plant is 71, therefore it can be noticed from the graph that in several cases the players execute all the necessary actions to save them. As the stress level increases and the concentration level decreases, a lower performance related to this KPI is observed. Stress appears to be therefore an important factor to consider when the people lives are at risk and precise emergency protocols must be followed. Despite even the time to save people increases with the heart rate mean and standard deviation (Figure 135), this correlation is not statistically significant. It is however connected to the previous KPI (the number of people saved is a consequence of the time to save people and vice versa).

KPI-EM25 and KPI-EM27 are two relevant KPIs defined to include in our analysis the impact of some minor activities, usually neglected by the operators, that have a large impact on the next activities and on the outcomes of the emergency response. The operations of the firefighters and medical aids is indeed usually delayed if the emergency manager does not meet them and explains them the scenario ongoing.

The results show that KPI-EM25 has a significant correlation with the heart rate standard deviation, while KPI-EM27 has a correlation with the heart rate mean rate. The correlation appears to be significant but a look at the data in the graph does not show a clear relationship between the sets of data. Even if we remove the two outliers, the correlation still remains not significant (p-value =0,068). The same applies to KPI-EM27: if the three outliers are removed the p-value is still higher than the significance level (p-value = 0,087). KPI-EM12 presents a dispersed cloud of data points which does not permit to identify a clear trend. The regression curve always shows a decrease in the performance as the heart rate mean and standard deviation increases but no statistical significance can be obtained from these data. Finally, the correlation between the heart rate mean and standard deviation is again significant in both cases for KPI-EM15, which appears to be then particularly affected by human factors.

7 Final remarks

Research contributions to Industry 4.0 mainly include theoretical insights and conceptualization efforts to explore the many facets related to the Industry 4.0 paradigm. Success factors for the profitable introduction of the hyper-connected smart factory are investigated in Park (2016). The state of the art analysis shows that industry 4.0 is still an open research field were much has been done but there is still more to do to accomplish its vision. Indeed, there has been a great deal of efforts toward smart factory concepts and engineering. However, such efforts are mostly related to automation systems, plant solutions, communication infrastructures, systems connectivity and interoperability, data flows management, etc. (Saucedo-Martínez et al., 2017). Human factors are instead extensively considered in Kõrbe Kaare and Otto (2015) where a human centric employee performance measurement system is proposed. Moreover, as the inner complexity of industrial systems grows, proper workforce qualification strategies are required. To this end, a holistic competence model can be found in Hecklau et al. (2016). While technology drives for greater automation in transportation and industry, human factors are still essential in several sectors and domains, especially in the industrial emergency management, despite they are frequently cause of individual biases and errors. For this reason, the need for effective industrial emergency preparedness and response training methodologies and systems is becoming more and more urgent.

This thesis aims at filling the gap in the current industrial emergency training practice and literature by proposing (designing – developing – implementing – testing) an innovative multiplayer industrial emergency preparedness and response training system, in the context of the DIEM-SSP (Disasters and Emergencies Management for Safety and Security in industrial Plants) PRIN research project (CUP: B88C13002040001), sponsored by the Italian Ministry of University and Research (MIUR).

The problem related to the industrial risk management and industrial disaster and emergency preparedness has been extensively investigated in terms of legislation, organizational procedures and best practices. Analytical modeling effort has been devoted to recreate a comprehensive solution capable to embed all these aspects and extensive body of knowledge and to acquire it in an intuitive manner.

The system leverages on Industry 4.0 enabling technologies – namely Simulation, Virtual Reality & Serious Games – and on a cooperative, experiential and differentiated training strategy, is capable to enhance in a statistically significant way technical (i.e. procedural) and non-technical (e.g. leadership, decision-making, team-working, stress management) skills of the emergency response staff. Realism and experiential learning (as required by the training strategy) are first ensured by the capability to include a 'serious game' logic (thanks to a discrete-event modeling approach used in the development of the system) able to take into account emergency procedures and protocols (usually executed in case of disasters in an industrial plant). The feeling to experience a real-world emergency and to act (and react) as the operators usually do during a real emergency is also provided by:

- a flexible and configurable model of the dynamic evolution of the fire affecting the industrial facilities based on stochastic cellular automata and particle systems;
- how the 'external' factors (e.g. police, ambulances, firefighters, etc.) may influence the evolution of the accident due to their behavior and mutual interaction based on an integrated multi-agent and discrete-event model;

- how the 'internal' factors (e.g. emergency manager, emergency response team members, employees, visitors) may influence the evolution of the accident due to their behavior and mutual interaction according to an integrated multi-agent social force model.

The system has found expression in a system-of-systems architecture based on the IEEE 1516 HLA standard for distributed simulation that allowed coupling the benefits of the fast-time and virtual simulation. Multiple interfaces and virtual reality devices (such as head mounted displays) totally involve the emergency manager and immerse the emergency team members in a realistic virtual training environment.

Large experimentations have been carried out on a real case study. Experimental results have demonstrated that meaningful benefits on the rate of retention and the hands-on applicability of theoretical concepts related to the correct emergency protocols can be achieved with the proposed system. This includes not only the technical and procedural competencies but also (and above all) the non-technical skills (e.g. leadership, decision-making, team-working, stress management). The system has been indeed designed and developed with the aim to address the training needs of all the key roles that are part of an industrial emergency response scenario including the emergency managers and emergency team members. Such results give evidence that the proposed solution can have not negligible effect in terms of emergency preparedness for Industries. Furthermore, the magnitude of the psychological pressure is analyzed in terms of average heart rate for emergency managers (that cover a strategic role in emergency management) and emergency team members (that are mostly field operators). Here, research results show that emergency managers are able to improve their capability to manage stress and it reinforces the conclusion that the proposed solution has real impacts on emergencies preparedness and management. On the other side, the emergency team members that are directly involved in the disaster-generated chain of physical events keep very high heart rates even after repeated training. While this aspect highlights an area that requires further investigation, in the near future it simultaneously gives evidence of the training systems capabilities in terms of users' involvement and engagement. This study is the first in-depth investigation of the comprehensive learning outcome (intended as a combination of technical/procedural performance as well as of the magnitude of the psychological pressure evoked by the 'collaborative', 'stress-generating' and 'decision-centered' aspects of an industrial emergency response), thus confirming the real and value-adding potential of the proposed system.

This study is also intended to fill the gap in current literature which lacks of an approach to understand the effects and correlation of human factors with the outcomes of an event that is hard to reproduce realistically in the real world. A "snapshot" of the study subjects' behavior is provided to explore whether and to which extent stress and the perceived workload are correlated to the capability of the emergency manager to coordinate and monitor the execution of all the actions intended to deal with an industrial accident and its effects. The findings of a cross-sectional regression of data show how a balanced workload and the ability to control emotivity are a precondition for an optimal industrial emergency response. This study pushes for an increased attention on human factors in the Occupational Health and Safety 4.0 and investigates an approach to analyze their effects with the ultimate aim to include them in the design of industrial safety protocols and regulations and assessment of risks and hazards. Safety competency research and assessment in major hazards industries can receive a profound boost with this approach. Despite competencies can be developed to prepare emergency operators to manage their emotivity after repeated training sessions, an improved workload balance and assignment of duties to the emergency operators can be achieved with the presented approach, with significant results of the operators' capability to manage unpredictable emergency scenarios. The industrial Safety 4.0 Operator is the one that will leverage on the Industry 4.0 key enabling technologies to master procedures, safety regulations and learn how to respond in the optimal way to any kind of emergency scenario. However, to do that, technologies and tools are not enough. Emergencies and accidents bring human factors into play, which are correlated among them and with the outcomes of an emergency scenario as demonstrated in this study. The analysis and management of human factors become then an emergent challenge in the context of the industrial Safety 4.0. Emergency preparedness and response protocols can be considered excellent only when they are designed to include the impacts of human factors (assessed with an approach like the one proposed in this study) and with the mind-set that operators need to acquire knowledge and practice the emergency scenario – in the perspective of a continuing professional development – so that operators are confident in what they are doing and are able to master their emotivity. Emergency protocol designers, employers and security officers must consider this aspect when protocols and procedures are defined.

The overall system may have some limitations due to the high modeling and development costs and the approach may appear too expensive in terms of efforts but it is indispensable in major hazards industrial sites such as nuclear power plant. Current and future research should spend time in optimizing industrial plants' staff training in the light of a renovated perspective on the crucial role of human factors. There is certainly a recognized need for further research about the reliability of human factor measurements and their correlation with several aspects of industrial safety. However, the economic savings coming from the correct disaster management (in case of an unlikely event) strongly repay the modeling effort. Furthermore, such solution can be easily integrated with external tools thanks to high reusability and configurability of the system architecture.

As final insights, by leveraging on the proposed groundbreaking training system, practitioners, professional associations, staff training agencies and, above all, industries will be able to:

- exercise and practice decision-making and other 'non-technical' skills such as communication, situation awareness, stress management, and teamwork;
- boost expertise in situation assessment and judgement;
- assist the emergency team candidates or members to develop a shared understanding and to build up a repertoire of patterns which can be quickly recognized and acted upon during real-world emergency situations;
- minimize the emergency team candidates' or members' psychological pressure and stress;
- increase the emergency team candidates' or members' comfortability in their roles thanks to experiential learning associated with new technologies;
- deliver shorter and more effective training sessions, thus enabling companies to switch their employees from their daily tasks to training with lower frequency and therefore benefiting of an increased business continuity;
- deliver geographically dispersed training sessions with people participating to the sessions coming from distant facilities, thus avoiding duplication of efforts, costs and time.

Aside from training outcomes, it is interesting to note that the proposed approach impacts not only on emergency response team performance. It can have direct impacts on risk management practices in industries. As a matter of facts, results of training sessions can provide considerable data and feedbacks that:

- can support emergency response systems design and implementation,
- in a reverse engineering perspective, can highlight the need for actual emergency procedures (re)design process;
- enable greater flexibility and faster responses to comply with changes in the national and international security norms.

Moreover, being conceived upon Industry 4.0 technologies and principles the proposed training system enables interoperability with other already available Industry 4.0 solutions. For instance, if an industry has a Digital Twin for remote monitoring and control, the training system can provide information on people that are currently involved in training activities, the expected training duration, etc. Vice versa, whenever a disaster occurs, data collected by Internet-of-Things devices and available through the Digital Twin can feed into the training system to enable new training scenarios.

8 Related research

This last chapter offers an overview of a selection of other relevant research studies (among others) conducted in the context of the doctoral activities and that are linked to the main research stream above illustrated. These research efforts, described synthetically in the following, have been published on international journals and on the proceedings of industrial systems engineering workshops. They include studies in the field of the:

- **Industrial disaster response**
    - Longo F., Nicoletti L., Padovano A. (2018). Workplace safety and emergency procedures (re)design: a human workload assessment through virtual reality. In: *Proceedings of the Summer School Francesco Turco*. Palermo, Italy, 12-14-September-2018.
- **Human factors analysis in industry**
    - Longo F., Nicoletti L., Padovano A. (2019). Modeling workers' behavior: a human factors taxonomy and a fuzzy analysis in the case of industrial accidents. *International Journal of Industrial Ergonomics*, Vol. 69, pp. 29-47. DOI: 10.1016/j.ergon.2018.09.002.
- **Smart Operators in industry**
    - Longo F., Nicoletti L., Padovano A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers & Industrial Engineering*, Vol. 113, pp. 144-159. DOI: 10.1016/j.cie.2017.09.016.

Title

Workplace safety and emergency procedure (re)design:
a human workload assessment by virtual reality

Research Area

Using virtual reality for human workload assessment in case of industrial accident response

Keywords

Industrial Emergency, Safety & Security, Virtual Reality, Human Workload, NASA-TLX

Abstract

Be prepared to the unknown is the mantra of modern high-risk industries, which are concerned about the effectiveness of their workplace safety & emergency procedures and the performance of their operators in safety-critical tasks. Virtual Reality (VR) applications and Serious Games (SG) provide a quasi-real testing environment that allows industries to detect whether operators are able to perform tasks without performance degradation due to an unbalanced workload. The present study proposes an eXpanded NASA Task Load indeX (X-NASA-TLX) and an Overall Workload Judgement (OWJ) to assess quantitatively the operators' workload during a synthetic emergency scenario. The case study is represented by a fire caused by a faulty gas line in a steel mill during which the operators are required to comply meticulously with the emergency procedure. The emergency scenario is experienced by using a head mounted display, motion controllers and audio equipment to convey a high sense of immersion. This study shows that VR and SG coupled with the X-NASA-TLX results can be considered as a reasonable means for investigating workload-balancing problems. Insights based on the OWJ are reported, thus demonstrating the potential of this approach to support the workplace safety and emergency procedures analysis and (re)design.

Background

Workload assessment studies are commonly used to demonstrate whether or not workers are able to perform tasks without unacceptable performance degradation (Di Domenico & Nussbaum, 2008): excess workload usually results in reduced task performance and more errors, while conversely underload leads to boredom and reduced situation awareness and alertness (Jung & Jung, 2001). Workload issues may be even more relevant for risk prevention because the demands imposed by a safety-critical situation for human resources vary according to the operators' experience, training level, skills, psychological state when the task is performed and the cooperation patterns with the other team members (Coelho et al., 2015). One of the most frequently cited workload measures in literature is the NASA Task Load Index, NASA-TLX (Hart and Staveland, 1988; Hart, 2006). However, it cannot be blindly applied in situations that have never been experienced by the test subjects in the real world because a good safety performance consists of making rare emergencies.

Problem statement

The NASA-TLX is a generic index that should be enriched in accordance to the peculiar aspects of the application domain and cannot be applied in situations that have never been experienced by the subjects.

Study aims

To extend the NASA-TLX and define a workload assessment methodology in safety & emergency protocol analysis and (re)design studies

Methods

The eXpanded NASA Task Load Index (X-NASA TLX) has been defined to extend the traditional six dimensions of the NASA-TLX to twelve with the aim to include the peculiar aspects of the application domain (i.e. industrial emergency management) and of the way the tasks are executed (i.e. virtual reality). The workload contributing factors have also been redefined to increase proportionally the perceived workload. They include factors related to the following scales:

- the scenario's demands imposed on the subject: mental demands, physical demands, temporal demand;
- the subject's interaction with the scenario: failure, effort, frustration;
- the scenario's demands imposed on the team: coordination demand, communication demand, cooperation demand;
- the team's interaction with the scenario: ineffectiveness, lack of support, dissatisfaction.

The methodology used to assess human workload in an industrial emergency response scenario is based on three phases. Test subjects are initially asked to provide responses to pairwise comparisons to collate the degree to which each X-NASA-TLX factors generally contributes, in their opinion, to the perceived workload. In order to answer the questions 'how much does factor A influence the perceived workload compared to factor B?', the paradigm of the Fuzzy Analytic Hierarchy Process has been used. The fuzzy weights for every workload contributing factor are eventually converted back to crisp numbers by calculating their Centre of Gravity (CoG). In addition to the weights, subjects were asked to give a subjective workload rating to a certain factor in a specific scenario. The case study is represented by a fire caused by a faulty gas line in a steel mill during which the operators are required to comply meticulously with the emergency procedure.

Figure A.1: Emergency scenario

The emergency scenario is experienced by using a head mounted display, motion controllers and audio equipment to convey a high sense of immersion. After having collected all the ratings for the workload contributing factor by every test subject, the CoG of the fuzzy weights and the group mean rating for every factor have been used to obtain a graphical representation of the perceived contribution of the 12 factors on the workload. The weights will be shown as the dependent measure on the x-axis and the workload ratings are shown as the independent measures on the y-axis. The contribution of the factor to the perceived workload is then represented by the area of the rectangle obtained as the product of the weight and the rating. It is worth noticing that the rectangles may be drawn both above and below the x-axis depending on the value of the rating – positive (if the factor increases the perceived workload) or negative (if the factor decreases the perceived workload). However, a synthetic indication of the perceived workload is not yet calculated. To do so, we introduce the Overall Workload Judgement (OWJ). This index is calculated as the algebraic sum of all the contributions of the factors (the weighted sum of all the group mean ratings). The OWJ will range from -100% and +100%: nine intervals were defined to support experts, practitioners and professionals in (re)designing workplace safety measures and emergency procedures.

Overall Workload Judgement	Interval
Absolutely Overloaded	(+75%; +100%]
Strongly Overloaded	(+50%; +75%]
Fairly Overloaded	(+30%; +50%]
Weakly Overloaded	(+10%; +30%]
Balanced Workload	[-10%; +10%]
Weakly Underloaded	[-30%; -10%)
Fairly Underloaded	[-50%; -30%)
Strongly Underloaded	[-75%; -50%)
Absolutely Underloaded	[-100%; -75%)

Table A.1: Overall workload judgement: interval definition

Results

The proposed fire emergency has been managed successfully by most of the test subjects (73 subjects out of 80) – meaning that the fire has been extinguished and the emergency procedure has been respected properly. This does not necessarily mean that in the remaining 7 cases the fire was not controlled, but that it has been managed without following the correct protocol. For example, the player did not launch the alarm, at least one personal protective equipment has not been used, delays in connecting the hose to the fire system and to the nozzle, the player forgot to cool the surrounding objects, the player left the room of the fire too early). Only in 3 cases, this improper behavior jeopardized the scenario and resulted in a breakdown with an uncontrolled fire. This does not necessarily mean that a specific combination of human errors will result into a breakdown but that they are likely to escalate into secondary effects and then a breakdown. Therefore, in the proposed case study, the risk that the emergency results in an uncontrolled disaster is 3.75% (3/80).

In terms of the degree to which each scale contributed to the perceived workload, the scenario's demands on the subjects recorded the highest influence on the perceived workload, followed by the subject's interaction with the scenario. A closer look at the results of the pair-wise comparisons of the single factors highlights the pivotal role of the Temporal Demand, which is the most influential workload contributing factor by far. The podium is then completed by the Physical Demand imposed by the scenario and the Failure perceived by the operator during the emergency operations. The modest weight of the Mental Demand imposed by the scenario on the subject represents an interesting element of appraisal. It corroborates that fact that the critical and mental processing activities in an emergency scenario are less crucial than the teamwork demand in the determination of the operators' workload. This result has been justified by the fact that an emergency management often degenerates into a mere execution of a predefined plan and sequence of well-accurate tasks that leave little room for subjective assessments.

If we now move the focus to the weighted scores that consider also the relative importance of each factor, our final considerations slightly deviate from those just described. Figure A.1 shows the weighted scores and illustrates in a synoptic view the weights and the scores of every workload contributing factor. In this final configuration, the temporal demand, the physical demand and the cooperation demand keep their high contribution to the perceived workload due to their higher weight compared to the other ones. On the opposite side, the very low sense of failure and the good support by the team members lower significantly the perceived workload level. The contributions of the other factors are instead mitigated when weighting the scores: their contributions (indicated in Figure A.1 by a yellow dash) lie in the range (-3,3%; +3,3%).

Factor		Contribution	
F1	Mental Demand	-2,69%	▬
F2	Physical Demand	7,54%	▲
F3	Temporal Demand	10,98%	▲
F4	Failure	-4,00%	▼
F5	Effort	-0,28%	▬
F6	Frustration	-2,59%	▬
F7	Coordination Demand	1,85%	▬
F8	Communication Demand	-0,69%	▬
F9	Cooperation Demand	4,54%	▲
F10	Ineffectiveness	-1,71%	▬
F11	Lack of Support	-5,02%	▼
F12	Dissatisfaction	-1,45%	▬

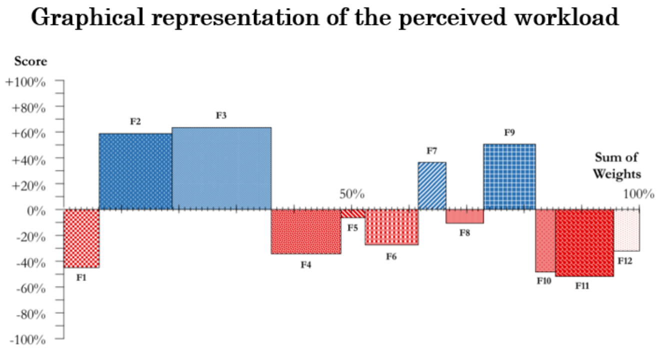


Figure A.1: Results and graphical representation of the perceived workload

This analysis can be concluded with the calculation of the Overall Workload Judgement as an algebraic sum of weighted scores. In the proposed case study, the OWJ is equal to 6,48%, meaning that the operator feels marginally overloaded. However, according to the intervals defined in Table A.1, we can conclude that the proposed emergency procedure in the case of a fire in the recreated steel mill guarantees a properly balanced workload. This does not mean that the emergency will be certainly work out successfully but a combined assessment of the results of the testing sessions and of the perceived workload provides interesting insights to assess/re-design (if needed) the emergency procedures.

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Title

Modeling workers' behavior: a human factors taxonomy and
a fuzzy analysis in the case of industrial accidents

Research Area

Investigating the relevance of human factors in the case of industrial accident response scenarios

Keywords

Industrial Accidents, Safety Management, Human Behavior Modelling, Human Factors, Fuzzy Analytical Hierarchy Process

Abstract

While 'Industry 4.0' drives for greater automation, human factors are still essential in certain domains, especially in industrial disaster management. Despite human factors are frequently cause of individual biases and errors, a systematic quantitative analysis of the correlation between them and the workers' response performance in case of an industrial disaster has never been conducted. The aim of the present study is twofold: to design an original human factors taxonomy, which encompasses all the industrial worker's cognitive capabilities, physical skills, and psychological attitudes; to establish a correlation between each factor and the workers' response performance in case of an industrial emergency.

A Fuzzy Analytic Hierarchy Process (FAHP) analysis has been conducted in collaboration with 44 subject matter experts by using an ad-hoc developed tool to investigate, in particular, two types of workers, the role of emergency manager and the emergency team member. Results reveal that the factors have not the same weight in determining the human response performance: cognitive and psychological aspects have a substantial influence on the emergency manager's response performance, while the emergency team member's response performance is more influenced by psychological and physical aspects.

Background

Industries shifting towards the Industry 4.0 paradigm are totally committed to developing models that can predict reliably operators' performance from different perspectives (Bommer & Fendley, 2016). Over the last decades, descriptive personality dimensions-based classifications, such as the 'Five Factor Model' by Costa and McCrae (1992), acquired a large consensus even in the industrial domain. In parallel with these works, artificial intelligence and software engineering science have widely attempted to integrate psychological notions into rational personality-gifted computer-based agents in several domains, e.g. the BDI architecture by Bratman (1987), the OCEAN model (Oren & Ghasem-Aghaee, 2003) or the ACT-R (Park et al., 2017). What emerges is that most of the theoretical behavioral models for rational personality-gifted computer-based agents focus only on a limited number of personality aspects (e.g. neuroticism, extraversion, psychoticism) and do not have an all-encompassing perspective on human personality (Elkosantini, 2015). In the industrial sector, the last years were marked by a growing interest in modelling human error and performance (Ergai et al., 2016), but a lack of attention on psychological and physical traits, and in general on personality aspects, has been observed (Ejeta et al., 2015). Such analysis should be attentively conducted especially in critical and challenging industrial operations, such as an industrial emergency response. Indeed, an industrial emergency response team usually shows individual cognitive biases and teamwork errors during an emergency due to everyone's own personality (Petrillo et al., 2017).

Problem statement

A complete taxonomy of human factors affecting the performance of an industrial worker is missing in the literature. It would be useful to investigate how much cognitive capabilities, physical skills, and psychological attitude affect workers' response performance in case of an industrial emergency response.

Study aims

The present study is intended to address two main aims:

1. To design an original human factors taxonomy which encompasses all the relevant cognitive capabilities, physical skills and psychological attitudes of a generic industrial worker;
2. To investigate which factors affect more than others the performance of the emergency manager and of an emergency team member in the case of an industrial emergency response.

Methods

An original human factors taxonomy for a generic industrial worker – everyone who carries out a manual and/or intellectual labor in an industrial context – has been conceived and structured on three hierarchical levels: spheres (S), traits (T), and facets (F). The 3 spheres (S) contain 11 traits (T), which, in turn, include 50 facets (F), presented as positive 'abilities' of an industrial worker (the more the better). Spheres, traits, and facets are generally referred to as 'factors' and can be grouped into 'clusters' if they have the same 'father' node in the hierarchical structure. The overall structure of the proposed taxonomy is depicted in Figure B.1, where the 15 clusters (represented by the yellow boxes) are identified by the prefix C. The taxonomy is composed of:

- the cognitive sphere (S1), which includes attention, communication, knowledge, memory, and reasoning;
- the physical sphere (S2), which includes health, perception and motion;
- the psychological sphere (S3), which includes emotions, relationships and self-management.

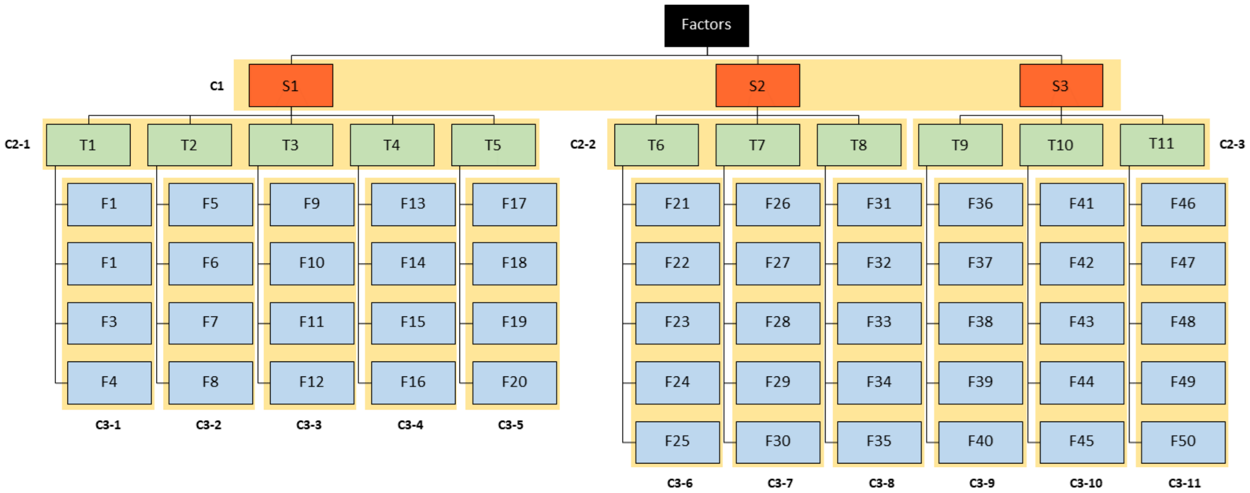

Figure B.1: The structure of the human factors taxonomy for the industrial worker

In order to understand which factors are the most relevant in the event of an industrial emergency response scenario, the Fuzzy Analytic Hierarchy Process has been used to collect subjective judgments from 44 field experts. Once the pairwise comparisons have been collected, the judgements have been synthetized into a single group pairwise comparison matrix for each cluster calculate by using the geometric mean. These fuzzy weights, derived as in Ramík and Perzina (2014), will be referred to as cluster-dependent as the sum of the weights of the factors belonging to the same cluster is 1. After a consistency check, the Center of Gravity method has been used to defuzzify the weights. Since a comparison among factors belonging to different clusters is needed in order to develop a global ranking of the factors, a cluster-independent crisp weight has been calculated as the product of the crisp weights of the subset of factors linked with each other by a parent-child relationship (the sum of the weights of all the factors is 1). This procedure has been applied to evaluate the most relevant human factors respectively for the emergency manager – the one designated to manage and coordinate a number of people towards the resolution of the emergency – and for the emergency team member – the one with more technical competencies and acting directly on the field under the direction of the emergency manager.

Results

The cluster-dependent weights of the factors show that for the emergency manager the 'cognitive sphere' is definitely the most important one, followed by the 'psychological sphere', thus proving that the physical capabilities are not essential for those who are designated to manage the emergency. The three personality spheres have instead more or less the same degree of importance in the case of the emergency team member. Some relevant insights at a lower level of detail will be provided.

Within the cognitive sphere, 'reasoning' is clearly the predominant trait for the emergency manager. Next up, 'knowledge' and 'communication' are also important. On the other side, 'knowledge' and 'attention' are the key cognitive traits for the emergency team member. The ranking of the psychological traits is the same for both the professional figures. In particular, the 'self-management' is the most influential trait, followed by the 'relationship' trait. With reference to the 'attention' trait, the 'divided attention' has a considerable relevance on the emergency manager response performance, while in the case of the emergency team member, the 'focused attention' is in the first place. This is justifiable because while an emergency manager needs to keep the focus on different aspects of the emergency, assign priorities and manage several things at a time, the emergency team member should be able to avoid distractions, to focus on one single task and to accomplish it effectively and efficiently.

Turning to the third cluster of facets, we can conclude that the Emergency Manager response performance is deeply influenced by the 'situational knowledge' and the 'procedural knowledge'. Different is instead the case of the Emergency Team Member, where the 'technical knowledge' prevails very few percentage points over the 'procedural knowledge'. These results for the 'memory' trait are confirmed also by the results for the 'knowledge' trait.

Within the psychological sphere, as far as the 'emotions' trait is concerned, 'conscientiousness' is the most relevant facet for the Emergency Manager. Composure is highly important too because the Emergency Manager should be extremely calm and cold-headed when facing the emergency and not being overwhelmed by events. In the case of the Emergency Team Member, 'composure' is the prevailing facet. The 'relationship' trait shows that 'leadership' has the greatest influence on the Emergency Manager performance as expected, together with 'initiative' and 'teamwork'. Lower importance characterizes the 'trust' and 'empathy' facets. On the contrary, for the Emergency Team

Member, 'teamwork' is crucial together with 'initiative'. Last but not least, the 'self-management' reveals the same ranking of its facets for both the Emergency Manager and the Emergency Team Member. In particular, 'self-control' is the most important facet by far, followed by 'self-organization'. Once the cluster-independent crisp weights and a ranking of the human personality spheres, traits and facets have been calculated, a Pareto analysis with a 60:30:10 split principle allows to infer some valuable general insights on the results and on which are the sets of most and less important human personality factors in case of industrial emergency management. The analysis shows that 'reasoning', 'self-management', 'knowledge' and 'relationships' are the most important traits for the emergency manager, while 'Perception', 'Motion' and 'Attention' is instead composed of those traits with a very low influence on the emergency manager performance. In the case of the emergency team member, 'self-management' goes up to the first position due to the fact that this professional figure is usually involved into field operations. The first class of traits also includes 'health', 'motion', 'knowledge', 'emotions'. 'Attention', 'reasoning' and 'communication' have instead the lowest effect on the emergency team member response performance. This study represents a meticulous guide for the company recruiters, associations, and practitioners as well as for the development of competency-based job descriptions in the field of industrial safety & security. A similar approach can be used in other industrial domains as the proposed human factors taxonomy provides a generic all-encompassing list of cognitive capabilities, physical skills and psychological attitude that affect every industrial worker's response performance.

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Title

Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context

Research Area

Investigating the learning curve of smart operators in the field of the modern Industry 4.0

Keywords

Smart factory, Industry 4.0, Augmented reality, Smart operators, Intelligent vocal assistance

Abstract

As the Industry 4.0 takes shape, human operators experience an increased complexity of their daily tasks: they are required to be highly flexible and to demonstrate adaptive capabilities in a very dynamic working environment. It calls for tools and approaches that could be easily embedded into everyday practices and able to combine complex methodologies with high usability requirements. In this perspective, the proposed research work is focused on the design and development of a practical solution, called Sophos-MS, able to integrate augmented reality contents and intelligent tutoring systems with cutting-edge fruition technologies for operators' support in complex man-machine interactions. After establishing a reference methodological framework for the smart operator concept within the Industry 4.0 paradigm, the proposed solution is presented, along with its functional and non-function requirements. Such requirements are fulfilled through a structured design strategy whose main outcomes include a multi-layered modular solution, Sophos-MS, that relies on Augmented Reality contents and on an intelligent personal digital assistant with vocal interaction capabilities. The proposed approach has been deployed and its training potentials have been investigated with field experiments. The experimental campaign results have been firstly checked to ensure their statistical relevance and then analytically assessed in order to show that the proposed solution has a real impact on operators' learning curves and can make the difference between who uses it and who does not.

Background

Research contributions to Industry 4.0 mainly include theoretical insights and conceptualization efforts to explore the many facets related to the Industry 4.0 paradigm. Success factors for the profitable introduction of hyper-connected smart factory are investigated in Park (2016). The state of the art analysis shows that industry 4.0 is still an open research field were much has been done but there is still more to do to accomplish its vision. Indeed, there has been a great deal of efforts toward smart factory concepts and engineering. However, such efforts are mostly related to automation systems, plant solutions, communication infrastructures, systems connectivity and interoperability, data flows management, etc. (Saucedo-Martínez et al., 2017). Human factors become the gravity center of the smart manufacturing Cyber Physical Space. Human factors, in particular, are extensively considered in Kõrbe Kaare and Otto (2015) where a human centric employee performance measurement system is proposed. Moreover, as the inner complexity of manufacturing systems grows, proper workforce qualification strategies are required. To this end, a holistic competence model can be found in Hecklau et al. (2016). Human factors, indeed, are expected to benefit from the intelligence generated within the cyber context and in turn to add further intelligence: a meta-intelligence level. As a consequence, human factors are at the heart of a virtuous closed-loop chain with a valuable feedback system that makes the overall manufacturing system grow.

Problem statement

Current literature lacks of works investigating the role of operators and human resources in the new smart factory context. Research efforts are needed to align (and enhance) operators' capabilities/competencies in the perspective of a modern human-centered approach to industrialization. In this perspective, a crucial aspect is the definition of the interaction patterns that involve human resources and physical contexts as well as human resources and the cyber context.

Study aims

To propose a human-centered approach along with its implementation and deployment to align (and enhance) operators' capabilities/competencies with the new smart factory context by means of:

- a methodological framework aimed at shaping the augmented operator paradigm within the industry 4.0 vision;
- a breakthrough solution that implements the aforementioned framework and enhance the learning capabilities of the operator significantly.

Methods

In the context of this study, the augmented operator paradigm has been defined and investigated. The operator is augmented because of the capability to interact with intangible assets and digital contents in highly interactive experiences. In other words, his ability to perceive and act within the physical world is enhanced by the possibility to be immersed in a virtual reality environment where different contents levels superimpose each other. Moreover, Augmented Reality applications are suited to connect virtual and real objects since they take the current view of the real world and adds digital resources on top of it. So the augmented operator owns a superior knowledge of the working environment deriving not only from daily interactions due to operational tasks/ procedures but even with a variety of value added contents that are suited to augment his skills and abilities to perceive and act within the working environment. Levels of immersion are related to the technology used to deliver such contents (e.g. headsets, smart glasses, smartphones or tablets). Aside from already existing approaches and technologies, this research work conceptualizes, designs and provides a prototype of a new approach/component/solution to extend operators' capabilities within the smart factory paradigm. It is an intelligent personal digital assistant with vocal interaction capabilities and therefore able to answer operator's questions about tasks/procedures/equipment. It is meant to provide operators with quick and effective support allowing them to acquire the information they need through a Q&A approach as they would if they were talking with a knowledgeable expert. Intelligence is here intended as the ability to find out proper responses delivering meaningful contents upon request but not only. Within the proposed framework, intelligence is also the capability to learn and evolve over time based on the feedbacks provided by users. As a proof of concept, the developed system, called SOPHOS-MS where SOPHOS is the Latin name of wisdom while MS stands for manufacturing systems (shown in Figure C.1), aims at:

- Providing plants operators with real time feedbacks and augmented reality contents on tasks/procedures execution so as to minimize the risk of accidents and support training;
- Providing plant operators with a personal digital knowledgeable assistant to interact with in a vocal form in order to gain data and information about machines, tasks, procedures and processes;

- Supporting operators with information that is usually not available in the workplace (i.e. machine productivity, expected maintenance operations, warning on unexpected dangers, risks that are likely to occur, suggestions on how to increase productivity, etc.).

For augmented reality contents generation and delivery, specific markers have been encoded to be recognized by the camera of the device where the SOPHOS-MS is installed. Once the camera detects and recognizes a particular marker, associated contents are superimposed on it and the operator is immersed in a digital space he can fully interact with. Augmented contents include the machine's 3D virtual model, all relevant resources including text, images, videos. This wealth of resources has been the starting point for developing ad hoc custom contents related to the machine operational model as well as the safety and maintenance procedures it requires. The application gives access also to 3D AR animations explaining safety and maintenances procedures required along the period of operation. Regular and preventive maintenance operations such as functional checks, corrective adjustments, tests for wear, parts exchange and repair have been carefully considered. Each procedure is broken down into steps and each step is visually shown through an augmented 3D virtual animation and vocally explained by the personal digital assistant. Along the explanation, the system is also able to send visual and vocal messages drawing the attention on potential dangers or risks the operator may incur.

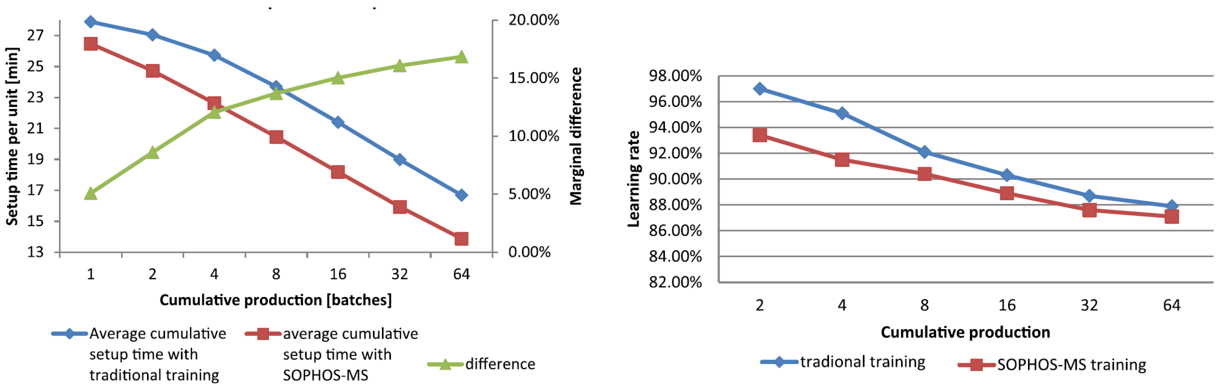
Figure C.1: The SOPHOS-MS solution

Results

The overall solution potentials, in terms of training effects and effects on labor performances, are investigated in a real application example concerning setup operations for cushion slides manufacturing. The evaluation has been based on the comparison of traditionally trained operators with operators trained by SOPHOS-MS over a two weeks time window. The solution deployment has been investigated through a particular use case concerning a CNC Milling Machine. The learning curve model that has been referred to is the Towill and Cherrington (1994).

The results highlights that a learning effect exists and in both cases (traditional and SOPHOS-MS based training) the average cumulative setup time decreases with the number of manufactured components. Furthermore, the learning effect follows a predictable pattern: when production doubles the time required for manual operation decreases on average by 8.15% in case of traditionally trained operators and by 10.18% in case of operators trained by SOPHOS-MS. This result becomes even more meaningful considering that typical learning slopes for machining operations are in the range of 90–95%. As shown in Figure C.2, operators trained by SOPHOS-MS have, on average, better performances compared to traditionally trained operators: their initial productivity level is higher at their start and they keep on outperforming traditionally trained operators all along (recalling that a learning rate of 93.40% is better than 97.00%). The average marginal difference between the two sets of operators grows asymptotically along the learning curves as operators gain experience demonstrating that SOPHOS-MS could be profitably used for initial training and make the difference between who uses it and who does not.

The Mann-Whitney U test has been applied to assess whether the average unit setup times achieved by the two groups of operators for each target production level (1, 2, 4, 8, 16, 32, 64 batches) were statistically different from each other. The results show that in all cases the two groups have different performance and such differences are not due to random effects but depend on the fact that they really belong to different populations. Aside from statistical considerations, it means that SOPHOS-MS is able to deliver a real educational advantage to people that use it for training as previously discussed when learning curves were considered for the two groups.



(a) (b)

Figure C.2: Comparison between average setup times achieved by traditional and SOPHOS-MS training (a) and learning rate comparison chart

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Acknowledgements

Undertaking this PhD has been a truly life-changing experience for me and it would not have been possible to do without the support and guidance that I received from many people.

First and foremost, I would like to express my sincere gratitude to my advisor Prof. Francesco Longo for the continuous support of my Ph.D. study and related research, for his patience, motivation, and deep expertise that I needed during these years. He has taught me, both consciously and unconsciously, how to carry out a complete and robust experimental study and to improve my problem-solving skills. Then, when I felt ready to venture into research on my own and branch out into new research areas, Prof. Longo always gave me the freedom to do whatever I wanted, at the same time continuing to contribute valuable feedback, advice, and encouragement. In addition to our academic collaboration, I greatly value the close personal rapport that Prof. Longo and I have forged over the years. I could not have imagined having a better advisor and mentor for my Ph.D. study.

Besides my advisor, I would like to thank all the fellow lab mates at the Modeling & Simulation Center – Laboratory of Enterprise Solutions (MSC-LES), the research laboratory at the University of Calabria, and at Cal-Tek S.r.l., spin-off of the same University, who have contributed immensely to my professional and personal time. The group has been a source of friendships as well as good advice and collaboration.

My sincere thank also goes to Prof. Rafael Diaz and Dr. Vera Novak, who provided me an opportunity to join their team, respectively, as Visiting Scholar at the MIT Zaragoza Logistics Center and as Sponsored Pre-Doctoral Research Fellow at the Harvard Medical School, and who gave access to the laboratory and research facilities. I thank them for their insightful comments on my work and encouragement, but also for the hard question that incented me to widen my research from various perspectives. I feel extremely privileged to have been part of their research groups in these outstanding research institutions. Among many other things, I am also thankful to all the people and friends at the SAFE Lab of the Beth Israel Deaconess Medical Center for the unforgettable memories.

I also gratefully acknowledge the reviewers and the members of my Ph.D. committee for their time and valuable feedback on my work and on the thesis.

To my friends and colleagues, thank you for listening, offering me advice, supporting me through these three years and for all the fun we have had together. Lastly, I would like to thank my family for all their love and encouragement. For my parents who raised me with a love of science and supported me in all my pursuits.

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