UNIVERSITÀ
POLITECNICA
DELLE MARCHE

Facoltà di Ingegneria

Corso di Laurea in Ingegneria Edile e Architettura

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# Comportamento umano in scenari (multi) rischio e sistemi di wayfinding negli ambienti ospedalieri: progettazione, implementazione e test di soluzioni in realtà virtuale immersiva.

# Human behavior in (multi) hazard scenarios and wayfinding systems in hospital environments: design, implementation and testing of immersive virtual reality solutions.

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But I'd like to honor friendship in this thesis. To the friendships that have been there for me, particularly during my darkest hours.
The word "friendship" is frequently spoken by many people, but only a small number of people truly understand what it means. For those who know me, the word "friend" contains a powerful meaning that I am unable to articulate.
According to Oscar Wilde "Friendship is far more tragic than love. It lasts longer". Betta who was like a mom, to the "Tub* ..." group. To Camilla, to her thousand advices and help for my last exam.
I am grateful to Luca and Daniele for being such gracious hosts and for the immortal

advice that "one must always select the lesser bad" in life. They opened their home to me without reservation every time I visited Italy.

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To conclude, I’d like to acknowledge that I’m only human and that occasionally I say foolish things when I’m not really well (physically and emotionally).

I may have disappointed a few people, and i’m sorry about that, but I firmly believe that nothing is lost and that anyone who wants to may always talk to me and work out any misunderstandings.

I'll end by thanking all of my genuine friends once more and stating that the best I can do for them is just to be their friend.

*Winds in the east,*
*mist coming in.*
*Like somethin' is brewin' and bout to begin.*
*Can't put my finger on what lies in store,*
*But I fear what's to happen all happened before.*

*(Mary Poppins)*

*Ancona, December 7th 2022*

Emanuele Gagliardi

# Abstract

Physical evacuation exercises are pre-planned activities used to prepare building occupants to handle emergency situations in accordance with their duties, emergency protocols, and the disaster scenario being evaluated.
They can specifically carry out responsibilities including locating potential hazards and safety components, carrying out individual safety procedures, choosing the best access points to a gathering place, supporting weak occupants (for employees), and containing hazard damage (for firefighters and responders).
However, since drills are "models" of emergency conditions, distortions and oversimplifications of real-world situations (such as oversimplifications of reaching safety/exiting the building, reaching a rendezvous point, and actual environmental conditions) can have an impact on the efficiency of the evacuation process.
Additionally, physical exercises demand a large investment of time and money, and weak and vulnerable groups are frequently overlooked as protagonists during rehearsals.
Because of this, immersive virtual reality (IVR) and virtual reality (VR) have been used in emergency contexts to complement physical drills, and research has shown that these technologies increase engagement and long-term memory by utilizing more interesting experiences and psychological excitation. Evacuation drills provide the advantages of minimizing resource waste and recreating a largely realistic threat. This thesis uses immersive virtual reality (IVR) to examine user behavior in a built environment during a single or multi-hazard catastrophic event, taking into account each user's role, physical and mental health, and the emergency system in operation at the time.
The development of the virtual environment first, followed by the testing, allowed for the data to be gathered and compared to identify the user's decision-making

procedures in reaction to perceived risk.

Results indicate that tests conducted with integrated emergency systems performed better than tests conducted with the conventional system (alarm only).

Users who interacted with the environment more did better in terms of the part they were playing. Knowledge of the environment and health issues is also important. The physical condition of the user acting out the action has the biggest impact on the performance of these two variables, particularly if the player has motor restrictions.

Finally, by improving the administration of the emergency system, the investigations carried out as part of this experiment may pave the way for more trustworthy outcomes in the evacuation process.

# Sommario

Le esercitazioni di evacuazione fisica sono attività pre-pianificate utilizzate per preparare gli occupanti degli edifici a gestire le situazioni di emergenza in base alle loro mansioni, ai protocolli di emergenza e allo scenario di disastro da valutare.
Le esercitazioni possono svolgere in modo specifico responsabilità quali la localizzazione di potenziali pericoli e componenti di sicurezza, l'esecuzione di procedure di sicurezza individuali, la scelta dei migliori punti di accesso a un luogo di raccolta, il sostegno agli occupanti deboli (per i dipendenti) e il contenimento dei danni causati dai pericoli (per i vigili del fuoco e i soccorritori).
Tuttavia, poiché le esercitazioni sono "modelli" delle condizioni di emergenza, le distorsioni e le eccessive semplificazioni delle situazioni reali (come le eccessive semplificazioni del raggiungimento della sicurezza/uscita dall'edificio, del raggiungimento di un punto di incontro e delle reali condizioni ambientali) possono avere un impatto sull'efficienza del processo di evacuazione.
Inoltre, le esercitazioni fisiche richiedono un grande investimento di tempo e denaro, e i gruppi deboli e vulnerabili sono spesso trascurati come protagonisti durante le prove.
Per questo motivo, la realtà virtuale immersiva (IVR) e la realtà virtuale (VR) sono state utilizzate in contesti di emergenza per integrare le esercitazioni fisiche e la ricerca ha dimostrato che queste tecnologie aumentano il coinvolgimento e la memoria a lungo termine utilizzando esperienze più interessanti e l'eccitazione psicologica. Le esercitazioni di evacuazione offrono il vantaggio di ridurre al minimo lo spreco di risorse e di ricreare una minaccia ampiamente realistica.
Questa tesi utilizza la realtà virtuale immersiva (IVR) per esaminare il comportamento degli utenti in un ambiente costruito durante un evento catastrofico singolo o multirischio, tenendo conto del ruolo di ciascun utente, della sua salute fisica e

mentale e del sistema di emergenza in funzione in quel momento.
Lo sviluppo dell'ambiente virtuale, seguito dai test, ha permesso di raccogliere e confrontare i dati per identificare le procedure decisionali dell'utente in reazione al rischio percepito. I risultati indicano che i test condotti con i sistemi di emergenza integrati hanno ottenuto risultati migliori rispetto ai test condotti con il sistema convenzionale (solo allarme). Gli utenti che hanno interagito maggiormente con l'ambiente hanno ottenuto risultati migliori in termini di ruolo svolto. Anche la conoscenza dell'ambiente e dei problemi di salute è importante. Le condizioni fisiche dell'utente che esegue l'azione hanno il maggiore impatto sulle prestazioni di queste due variabili, in particolare se il giocatore ha limitazioni motorie.
Infine, migliorando la gestione del sistema di emergenza, le indagini condotte nell'ambito di questo esperimento possono aprire la strada a risultati più affidabili nel processo di evacuazione.

# Indice

# Elenco delle figure

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# Capitolo 1

# Introduction

Over the past twenty years, we are witnessing a revolution in human interactions thanks to the spread of Virtual Reality. Among many areas that make use of this technological science, we also find evacuation drills, purely pre-planned physical activities with the purpose of training different types of occupants to deal with emergencies (disasters/hazards) and assessing safety performance in built environments (BE), a system of buildings of different size and function: individual buildings, neighborhoods or urban areas [2, 3]. Mark Zuckerberg cries out for the metaverse, the "successor to the mobile Internet," capable of bringing people together, of making them inter-arrange through state-of-the-art instrumentation [1] The technology developed to date includes Virtual Reality (VR), Immersive Virtual Reality (IVR) which enables the simulation and manipulation of digital environments by means of unconventional, highly sophisticated interfaces, and Augmented Reality (AR) which, on the other hand, enables the extension of the real-world environment through the addition of virtual objects such as video, graphics, audio or GPS data.

Drills are also widely used to assess safety performances of emergency procedures also in relation to the built environment features and the adopted risk-mitigation strategies (e.g., by evaluating response and evacuation times and the order of performed actions) [4, 5, 6, 7, 8].

Because physical evacuation drills are “models” of emergency conditions, the efficiency of the evacuation process can be affected by distortions and oversimplifications of real-world situations (e.g., oversimplifications of reaching safety/exiting the building, reaching a rendezvous point, and actual environmental conditions) [4, 7, 9, 10]. In

[1] https://europa.today.it/attualita/benvenuti-nel-futuro-metaverso-facebook-google.html

addition, drills are often conducted outside normal business hours to minimize risks to occupants and costs to business continuity (in terms of monitoring devices/human resources and loss of service provision) [6, 11]. Too often, vulnerable and fragile groups (e.g., individuals with medical or physical problems [12, 13]) are not considered/involved in the tests, even though their engagement should be a priority action in view of their specific characteristics if a dangerous condition occurs [14].
An additional limitation is inconsistent and/or biased data collection during physical emergency drills, often due to the lack of systematic and objective methods of data collection [15].
The results obtained by such studies provide a limited understanding of the drills and the ability to compare them and evaluate whether the drills constitute a valid evacuation model [15].
In addition, previous work points to limited evidence of lasting benefits, given the high contrast between test scenarios and the real world.
[4, 16, 17]. Denoted the points of limitation in physical/real-world mode evacuation testing, technologies such as Virtual Reality (VR) and Immersive Virtual Reality (IVR) were identified to address the above challenges and possibly improve planning capabilities, exercise observation, and test analysis highly consistent with semi-realistic risks [3, 9, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27].
The collected data provide an overview of the effectiveness of VR and IVR simulation systems, engagement, and long-term information retention by leveraging more attractive experiences and psychological arousal.
Virtual technology is not a tool to replace physical training, but it contributes positively to the collection of data that would be missing in a conventional test, a potential reduction in costs, and a more accurate assessment of occupant behavior.
More, IVR has been increasingly adopted and affordable, economically speaking, as a training and assessment tool given its sustainability and application feasibility [18, 23, 27, 28, 29, 30, 31]. Studies such as that of Gwynne et al. [4] have pointed out that the cost-effectiveness of training tools promotes their adoption for both individual and group testing, sometimes combined with serious game approaches [20, 32].
VR and IVR allow to not disrupt the workplace's productivity and, most importantly, engage the users emotionally [33]. They can also be employed to test the effectiveness

of different emergency systems, including the ones relating to wayfinding tasks as one of the fundamental issues in evacuation [19, 27, 31, 34, 35].

VR and IVR can enhance automatized design and evaluation of building safety procedures, avoiding unnecessary implementation in real-world settings, thus possibly reducing resource waste [24, 25].

As mentioned above, studies on VR and IVR have increased dramatically in the recent period, focusing on single features, related solutions, methodologies, techniques, and settings at both single hazard and multi-hazard. According to UNRR [36], "hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potentially interrelated effects."

However, these solutions introduce several limitations and are characterized by blind spots. In particular, the formulations of the requirements (regarding the user, the hazard scenario, the hazard effects propagating over time, and the built environment) appear to be too often weak and approximate or the re-representation of the elements does not appear to be precisely depicted, as is evident from the initial examination of the work.

Therefore, this thesis sets out to better characterize the initial settings and assumptions, interface functionality and projections, and analysis of the final results. Thus, the implementation of formal requirements to characterize VR and IVR emergency drill systems could be used to compare rigorous methods with naive assumptions and understand whether operational simplifications can still be tolerated to assess behaviors or train people adequately.

The thesis purpose is to investigate the correlation between crowding, emergency conditions, and the built environment by simulating risk scenarios that affect individual user exposure to the environment through the implyment of the Immersive Virtual Reality (IVR). The multi-hazard and multi-scenario approach of the thesis allows for a valid result by analyzing numerous case studies. Moro, by analyzing users' exposure from the perspective of users' perceptions, the results take into account individual vulnerabilities. Therefore, the results obtained will help to refine the emergency system of a built environment by improving user safety conditions.

Consistent with the predefined goals, the next Chapter 2 reports on the discussion related to the state-of-the-art by consulting and studying scientific papers. Articles about the use of virtual reality in emergency drills are analyzed. Accordingly, by the preliminary survey, weaknesses, and gaps are highlighted, thanks to which a framework is structured to develop the research project.

This is followed by modeling a virtual hospital environment using software such as Autocad, rhinoceros 3d, and Unity 3d and structuring different single/multi-hazards scenarios. The choice of a particular hospital, defined in later chapters, was made because it is considered critical infrastructure for:

-**User** (the variety of users within it (especially people with reduced capacity/disabilities));

-**Instruments** (the tools present/used to operate (very dangerous, sometimes flammable);

-**Architecture** (the planovolumetric complexity of the building).

Then 110 volunteers perform the tests wearing an HMD (Head Mounted Display) from which data are collected through self-generated reports, recorded videos, and by survey containing 19 post-drill questions. Therefore, results are collected and analyzed by making graphs and tables for easier reading. This is followed by a results discussion chapter in which the key findings are summarized and compared with data collected from the state-of-the-art.

Chapter 7 describes the choices made for the thesis project, the simulator design, and discusses the results obtained. Finally Chapter 8 concludes and describes possible future developments, giving strong consideration to focusing studies on people with physical impairments, and the type of emergency system to be integrated to improve the evacuation. The current literature does not explore or address the evacuation of vulnerable people at all. Studies conducted in hospitals have used visitors or medical personnel who can retrieve a patient in a hospital room and lead him or her out of the building.

# Capitolo 2

# State of The Art

This section brings together a previous literature review on the matter [20] and is devoted to expand the characterization of methods, techniques, and tools for performing VR and IVR drills, adhering to the rigorous and reproducible methodology proposed by Kitchenman [37] and modified by Calvaresi et al. [38]. Therefore, we start from the general remarks of previous works on VR and IVR based approaches [3, 4, 14, 16, 18, 20, 23, 26], this paper leverages 13 structured research questions that address topics including research institutions, level of abstraction of contributions, application scenario, intended recipients, and non-player characters (characterization and perspectives), system requirements and objectives, system evaluation/analysis methods, technologies, strengths, limitations, and future challenges of single and multiple-risk VR and IVR simulation systems. Subsequently, the rest of the chapter is organized as follows: Section 4.2 describes the methodology; The section 6 presents and analyzes the results. The section 7 discusses the information derived from the aggregated data, and finally concludes the state-of-the-art chapter.

## 2.1 Methodology

The methodological activity consists of three main activities, including: planning review of general and structured research questions; review execution-identification, selection and analysis of relevant articles; and review documentation-aggregation, discussion and documentation of the results obtained. Below, the research papers developed are referred to as primary studies.

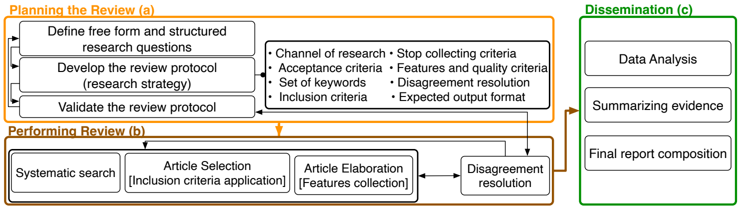



Figura 2.1: CAPTION.

Following the Goal-Question-Metric (GQM) approach, we set the generic free-form question as follows:

GQ : How are VR and IVR solutions for (multi-)hazard drills characterized, and what have they achieved?

Such a GQ has been decomposed into the following 13 structured research questions (SQR).

**Demographics.** To investigate the distribution of the interest in single/multi-hazard virtual simulators (in terms of time, country, and institutes), we set the following question.

**SRQ1:** How time- and geographic-wise are the research efforts distributed? i.e., when (year) and where (the geographical indication of the scientific institute).

**Abstraction.** To understand the nature of the contribution conveyed by the primary studies, we set the following question.

**SRQ2:** What is the abstraction level of the elaborated scientific contributions? (i.e., conceptual (C), prototype (P), or tested (T)).

**Application scenarios.** To understand the context and domain of the primary studies, we set the following question.

**SRQ3:** In which areas and settings have the users' behaviors been simulated via VR and IVR?
(e.g., structures, open spaces, etc.)

**Recipients.** To analyze the beneficiary and subject involved in the studies, we set the following question.

**SRQ4 (A):** Who are the users considered within the VR and IVR simulators/studies?

**Secondary Actors.** To evaluate the possible involvement of other subjects implicated in the research, we set the following question.

**SRQ4 (B):** What are the classes of the secondary users or non-player characters (NPC) considered in the VR and IVR simulators/studies?

**Requirements.** To formalize and cluster the needs expressed by the studies w.r.t recipients, environments, hazards, and interactions, we set the following questions.

**SRQ5:** Which requirements have been defined for the recipient(s), environment(s), (multi-)hazard (interactions, and level of stress, within the investigated systems?

**Objectives.** To understand the primary studies' directions, we set the following question.

**SRQ6:** What are the goals set by the elaborated studies?
(i.e., evaluation, training, entertaining, etc.)

**Methods, user characterization, and perspectives.** To understand the methodologies & techniques, and recipients characterization employed by the elaborated studies, we set the following questions.

**SRQ7 (A):** What are the methodologies/techniques used in the case study?

**SRQ7 (B):** User characterization. What are the users' cognitive/physical/motor skills used in the case study?

**SRQ7 (C):** What are the users' approaches/perspectives (first or third-person) through the virtual reality used in the case study?

**Technology and interfaces.** To understand which technologies and related interfaces have been employed, as well as user behaviors w.r.t. to them, we set the following question.

**SRQ8:** Which are the technologies employed in the researches (e.g., Oculus, smartphones, . . . ), and how are the replated interfaces characterized?

**Analysis methodologies.** To assess the evaluations performed by the primary studies, we set the following question.

**SRQ9:** How have the results been analyzed?

**Strengths.** To elicit the advantages/benefits provided by the primary studies, we set the following question.

**SRQ10:** What are the benefits produced by the primary studies?

**Limitations.** To acknowledge the drawbacks of the existing systems and facilitate further research, we set the following question.

**SRQ11:** What are the limits/barriers/uncertainties raised by the primary studies?

**Solutions.** To understand how the primary studies' authors have dealt with the known limitations (if mentioned), we set the following question.

**SRQ12:** Which are the solutions to the stated limitations proposed by the primary studies?

**Future Challenges.** To come out the ongoing/envisioned research directions of the primary studies' authors, we set the following question.

**SRQ13:** What challenges are awaited by the authors of the primary studies?

The selected research channels (web crawler) include google scholar, IEEE Xplore, Elsevier. The semi-automatic search through them has been performed querying the following list of keywords keeping the keyword "Virtual Reality" as the root of contextualization:
virtual reality * (hazard simulation + evacuation + multi-hazard simulation + simulator, users' behavior, hazard + users' behavior, multi-hazard.

The initial collection counted $\sim$ 1400 articles. According to the methodology [38], such a batch has been coarse-grain filtered applying the following seven *selection criteria* to the papers' abstract:

A) Relevance & Technologies: The paper must employ VR technologies for evacuation and hazard response.

B) Primary Study: Only papers providing a direct contribution on VR (e.g., models, architectures, implementations, or tests) are included. Secondary studies (i.e., surveys) are excluded.

C) Accessibility: To be included, the article's content should be accessible via one of the portals mentioned above.

D) Singularity/Originality: Duplicates or papers that have been extended are discarded, including only the extended/complete version.

E) Contribution characterization: the study must provide theories, frameworks, or tests relevant to the study.

F) Behavioral assessment: the papers must address human behavior during the evacuation drill via VR and IVR will be considered in the research.

G) Environment: The setting object of the study must be related to the built environment or open spaces in the proximity of built environments (possibly tangent to built or elements directly affected by hazards).

The applied criteria allowed the initial papers to be reduced to about 100. However, for some studies, processing the abstract only did not allow explicit "inclusion/exclusion." This ambiguity was eliminated by rapid reading the papers' body, which brought to 35 the number of relevant articles comprising the set to be analyzed.

## 2.2 Results

### 2.2.1 SRQ1: Demographics

Figure 2.2 and Figure 2.3 show respectively the geographic and chronological distribution of the analyzed works. It is obvious that the most economically developed countries lead the research on VR and IVR-based systems for emergency scenarios (i.e., China, Sweden, USA and Italy, Germany, and Japan). It is worth highlighting that 15 out of 30 papers represent collaborations between two or more countries, which have been counted uniformly for equity. From a timing perspective, while European countries and the US had a steadily growing trend in terms of publication between 2010 and today, China's contribution peaked in the biennium 2019 - 2021. Looking at the universities that have invested in the topic, it is noticeable that most of the studies have been carried out by Massey University for New Zealand, University of Würzburg (3 papers each), Tsinghua University for China, and Lund University for Sweden (7 papers each). Furthermore, while all the studies are carried out by at least one university, seven of them have been conducted in collaboration with private or public companies and institutes. The number of selected papers seems to be growing exponentially over the years, with a noticeable inclination from 2012 and a surge in the last two years. Indeed, 85% of the papers have been written after 2012. A possible reason may be the accessibility (technology- and cost-wise) of the IVR technology, although it dates back to the late 80s.

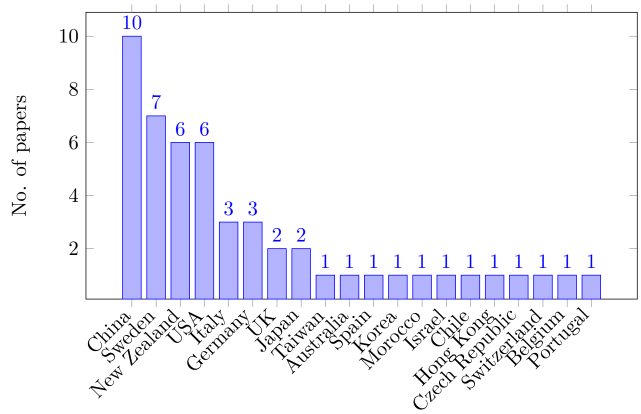



Figura 2.2: Number of primary studies per country of publication.

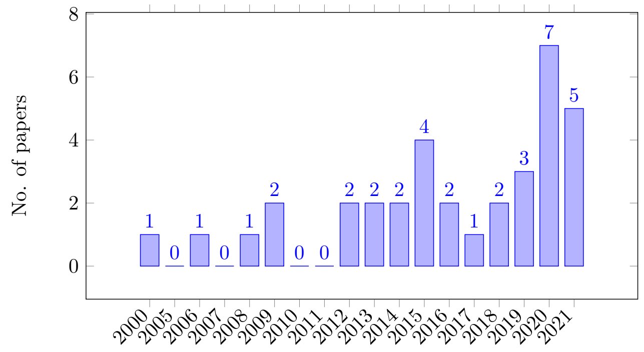



Figura 2.3: Number of primary studies per year.

### 2.2.2 SRQ2: Abstraction

The different papers are classified as conceptual (C), prototype frameworks/architectures without explicit analysis (P), and clearly tested frameworks and architectures with results/analysis included (T). To this end, two studies are conceptual, four are defined as prototypes and twenty-nine studies present tests and results. It is appreciable that this field of scientific research is applied and seeks to address real-world challenges. Indeed, having 82% (see Figure 2.4) of the contributions presenting tests and concrete applications for hazard drills via VR and IVR may suggest the maturity of the approach(es) and an increasing level of reliability of VR and IVR technologies (see Table 2.1).

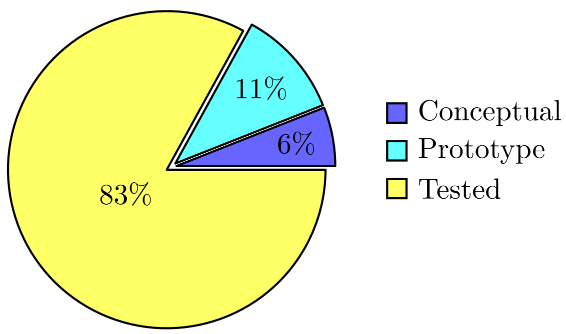



Figura 2.4: Typologies of abstraction according to the primary studies, and related frequency percentages.

Tabella 2.1: Primary studies organized by typologies of Abstraction.

| **Abstraction** | **Papers** |
|---|---|
| Conceptual | [39, 40] |
| Prototype | [41, 42, 43, 44] |
| Tested | [10, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56]<br>[57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70] |

### 2.2.3 SRQ3: Application scenarios

The elaborated studies targeted multiple applications. Figure 2.5 shows the characterization of the three scenarios' macro areas related to "built environment", which include buildings, tunnels, and stations. The main differences between the three classes are the geometric characterization (i.e., size and complexity of the plan), the interactions (i.e., the ability to follow predetermined paths [48, 50, 54], extinguish fires [42, 43, 49, 51], grabbing and handling various objects in the scene [44, 51, 56, 62, 63, 66], and simply opening doors [57, 59, 61]), and the (un)familiarity with the environment (i.e., workers vs. clients aware or not about the environment conformation). Moreover, it is possible to distinguish the scenarios within the main classes based on the intended use. For example, the "building" category includes nine different environments.

More than half of the studies (56%) has investigated emergency scenarios through the use of VR in buildings, (24%) have focused on subway or railway stations, and the remaining (21%) on tunnels. Within the buildings category, most of the studies involved hospitals and hotels environments. Within the station category, subway stations got most of the attention. Such choices suggest the possible factors discriminating scientific interest include (i) the presence of ill/sensitive people, (ii) likely overcrowded spaces, and (iii) limited knowledge about the surroundings.

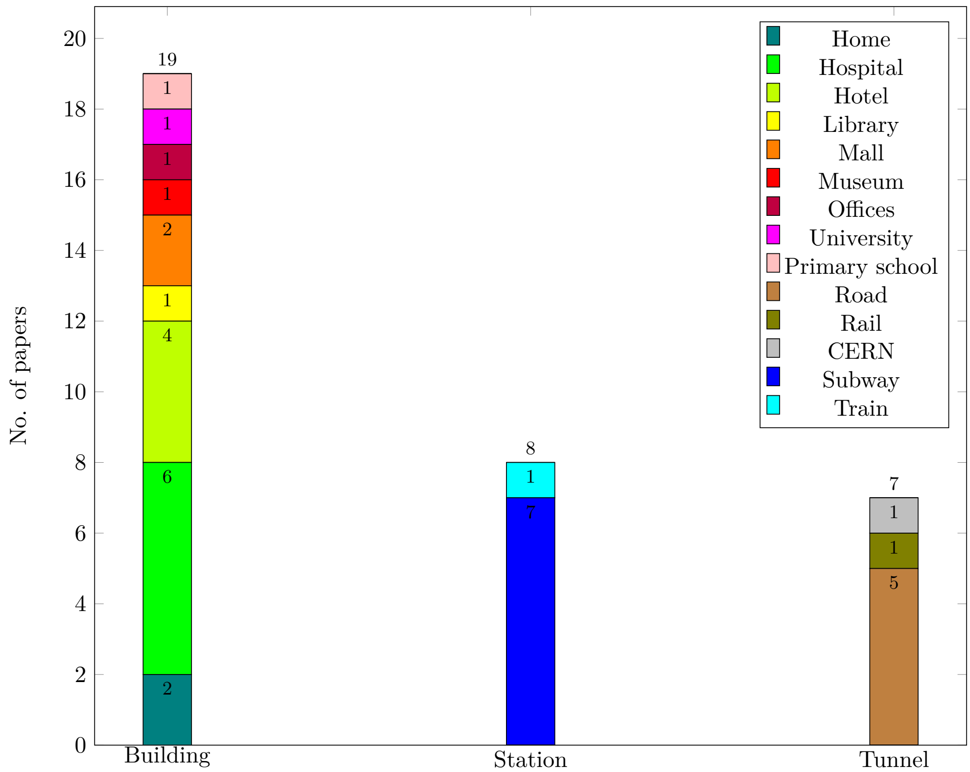



Figura 2.5: Number of primary studies depending on the application Domains, by including differences with respect to specific intended uses

### 2.2.4 SRQ4 (A): Recipients

The main characters examined in the elaborated studies can be in seven main classes, which are, obviously, related to the scenario (see Figure 2.6). Specifically, the occupants recipient of the systems are home residents, staff, students and professors, firefighters, visitors, drivers, and customers. This latter can be characterized as "people purchasing goods/services from a store or business" with limited knowledge of the surrounding. The class customers is composed of: housing guests – mainly present hostelry scenarios [59, 61, 62, 67], shoppers – mainly present in supermarkets [10, 71, 57] and libraries [46], and travellers – mainly present in subway stations [40, 43, 45, 53, 55, 72].

Unlike customers, visitors are defined as people who visit someone or somewhere, mainly socially (e.g., tourists). This category is dominant in hospitals as they are intended to be relatives or acquaintances of patients inhabiting the facility [44, 56, 64]. In turn, patients are the individuals who occupy the facility and receive medical care. Their knowledge of the surrounding might be higher w.r.t. the visitors. However, their functional capacity must be considered badly inferior. The scenarios staff include hospitality, medical, and possibly supervisory personnel. They are considered to have a discrete knowledge of the environment and possibly play a role in the evacuations [44, 56, 60, 64, 69]. Finally, firefighters are key players in the training and education case studies. They are responsible for mitigating the hazards (i.e., extinguishing the fire or reducing the flooding) and supporting the evacuation of the endangered occupants [45, 48, 50]. Drivers (people who drive a vehicle) are the protagonists for the road tunnel scenarios [47, 52, 65, 70, 73]. Students and professors are the "personnel" primarily endangered in schools and universities setups [66], libraries [46], and museums [54]. Finally, home residents are persons inhabiting an environment permanently or for long-terms [39, 51, 58].

Overall, it is possible to affirm that most of the recipients of the elaborated studies are people who use services or buy goods, who therefore have (at least) little knowledge of the environment in which they have been tested.

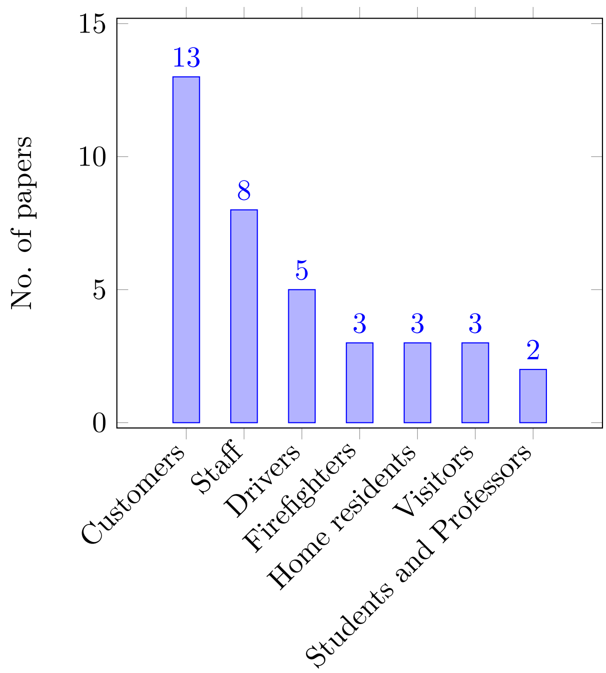



Figura 2.6: Number of primary studies with respect to the classes of Recipients.

### 2.2.5 SRQ4 (B): Secondary actors

Besides the primary "player/user", eight studies (24%) involve secondary actors as NPCs in the scene. The NPCs belong to the same categories characterizing the primary actors (see Figure 2.7). Their initiatives, actions, emotions, and plans are encoded or delegated to artificial intelligence (AI) engines. Although the NPC's "intelligence" might not be outstanding in all the implementation, their presence already ensures a more realistic immersive environment and experience (given the almost always crowded nature of the studied environments). Crowding, thanks to the presence of these secondary actors allows, to represent an obstacle to the course of the ongoing emergency by increasing anxiety, and stress to the user. The most represented category by the NPC is the occupants, followed by the others, thus following the same classes of Figure 2.6, as discussed for SRQ4(A).

### 2.2.6 SRQ5: Requirements

The requirements characterizing the studies interest the recipients, environments, type of hazard involved on the scene, interactions, and stress level within the system. The most common requirement is the user's starting point (inside/outside the

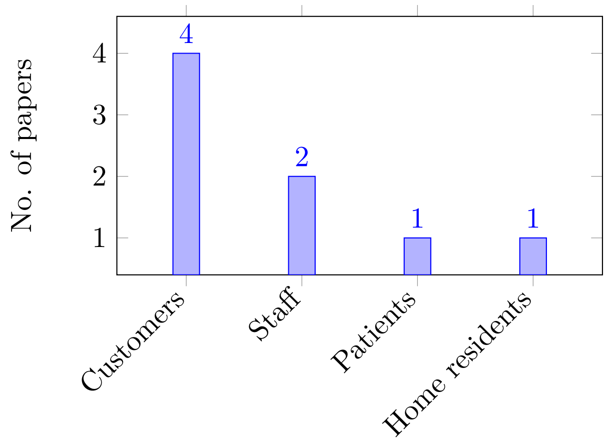



Figura 2.7: Number of primary studies considering the NPC's presence and their typology.

building) and an ending point (either inside the building – yet an area declared safe – or outside the building). All the primary studies give all users an optimal visual capacity (disregarding any user-related impairments). The only factors that impair their visibility are (multi-)hazard-related (e.g., fire/flash flood/earthquake/terror attack). Concerning the anxiety and stress level assessment (via sensors or survey after drills), eleven articles explicit specific technologies — detailed in SRQ7(A).

The familiarity (or not) with the environment, and thus also the knowledge of the procedures and evacuation routes, is the only crosscutting requirement concerning the user, which associates all the studies (see Figure 2.8), as also discussed for SQR4(A). In particular, (35%) of the studies (11) assumed full/partial knowledge of the built environment, given their possible familiarity with it. To ensure compliance with such a requirement, the users have been asked to practice and get confident with the virtual environment before executing the test. Conversely, (26%) of the studies (8) imposed no prior knowledge of the environment. The papers not explicating environmental requirements for the users are (23%) (7 studies). Three studies (10%) limited the knowledge assumption solely to staff members, not conferring any information to the visitors. These studies are set in hospital environments, thus leveraging the assumption that medical staff is more familiar with the environment than patients' relatives [44, 56, 64]. Finally, three studies (6%) divide the users in teams: the control group (no proper knowledge of the environment) and the treatment one (environmental awareness, e.g. through use of test scene plans and detailed escaping info) to analyze any differences in data collection during the test [54, 68, 70].

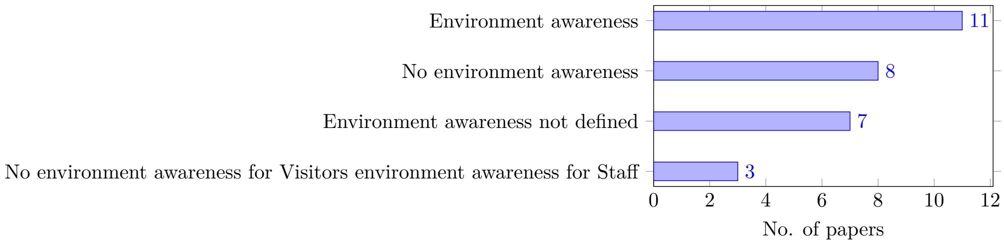



Figura 2.8: Number of primary studies considering the typologies of recipients requirements.

The environmental requirements have mostly been treated implicitly (see Figure 2.9). Indeed, the majority (11 studies) lack any formalization. Some studies mention the presence of alarm systems and emergency signage among the default settings. In particular, 3 studies present only emergency signage [57, 62, 65], while 2 studies mention only alarm systems [58, 69]. Ten studies present a combination of alarm systems and emergency signs. In real-world settings, these two components are both present in buildings to ensure efficiency during the evacuation process.

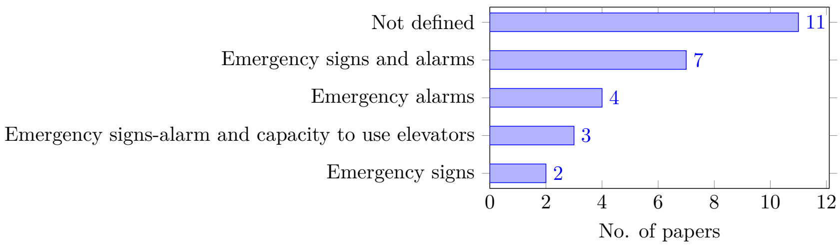



Figura 2.9: Number of primary studies considering the typologies of environment requirements.

Fire is the leading cause of accident and death for building occupants, essentially because risk assessment and mitigation tasks concerning this hazard are well codified by regulations which also widely include fire and evacuation training, as well as emergency planning as a priority task for building safety, all over the World. Indeed, among the hazards investigated, fire is the most prevalent (60%), possibly combined with earthquakes (3%) (see Figure 2.10). In the elaborated studies, fire is characterized as a static element in a given point without any or a very limited propagation. Earthquakes are characterized as a shaking scene with, possibly, falling and breaking furniture and elements of the scene. Floodings (6%) are characterized as a "similliquid" rising its level and filling a given room/area. Terrorist attacks (3%) are characterized as accidental and unpredictable explosions.

However, in 20% of the studies, the user has not been given any information about the hazard. The only indications have been to "find a way out and get safe". The hazards in such cases are represented by the activation of alarm sirens or voices.

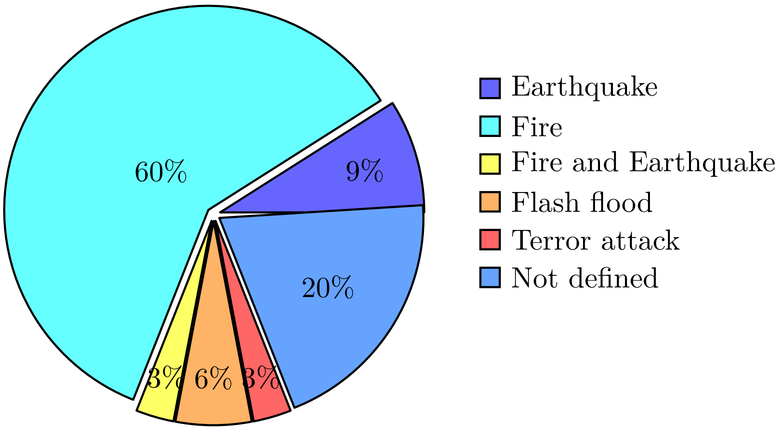



Figura 2.10: Percentage of hazards considered in the primary studies.

Overall, although some elements of the environments, users, and interactions have been (in)directly mentioned, there is a lack of formalization and alignment among the studies. This harms an extensive characterization, extendibility, and comparison among the VR and IVR systems for emergency drills.

Although the level of stress is highly influencing the decision-making process under pressure, 16 studies (47%) do not address its characterization explicitly (see Figure 2.11). Twelve studies (35%) identify smoke as the most relevant element connected to users' stress. Indeed, smoke is the first factor of death (by asphyxiation) and the main obstacle placed along the building layout. Therefore, having a realistic representation of smoke spreading in the built environment is crucial in both terms of graphics and dynamics. The obstacles are also required to be physical such as books, ceiling panels, office equipment, furniture, and exhibition elements present in museums. On the one hand, some studies limit their settings to ground obstacles [51, 56, 64]. On the other hand, more sophisticated studies combine obstacles on the floor with smoke [46, 50, 54].

The interactions among users and environment have different nature and complexity. For example, players can extinguish fire [42, 43, 49, 51], or grab and handle scene's objects [44, 51, 56, 62, 63, 66], and simply follow predefined rescue/safety paths and open doors (features in common among all the studies).

Finally, the interactions between the main player and the NPC(s) are shaped as:

- The player is surrounded by a crowd (of NPCs). The sole interaction is the body-bumping and freedom of movement reduction [55, 72].
- The NPCs can provide useful information supporting the evacuation process [46, 56, 64].

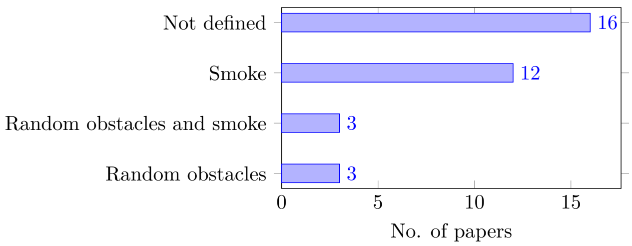



Figura 2.11: Number of primary studies considering environmental stressors due to the hazard and the built environment modifications

### 2.2.7 SRQ6: Objectives

Ten analyzed studies (29%) aim at evaluating the user behaviors when facing dangerous scenarios in VR and IVR. Thus, maximizing immersiveness and realism of the environment created are priorities. Therefore, they seek to detect the danger perception and understanding of the consequent undertaken actions. The remaining 25 papers (71%) target the behavioral (the outstanding objective) and technical analysis.

Overall, as shown in Figure 2.12 and Table 2.2, the ultimate finality of the studies can be clustered in:

- *educating* the occupants of a building about possible dangers demanding to evacuate the building;
- *testing* the user capabilities, and solutions' viability.

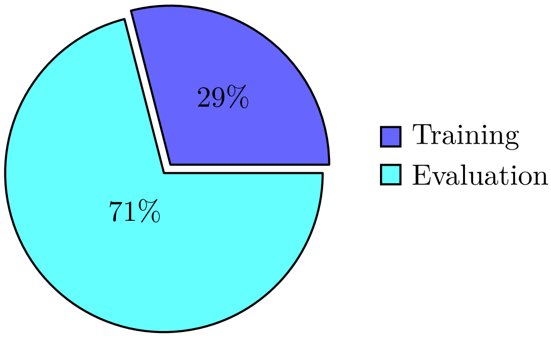



Figura 2.12: Percentages of primary studies with respect of performed tests objectives.

Tabella 2.2: Primary studies organized by Objectives

| **Objective** | **Papers** |
|---|---|
| training | [10, 41, 42, 44, 45, 48, 50, 52, 60, 69] |
| evaluation | [39, 40, 43, 46, 47, 49, 51, 53, 54, 55, 56, 57, 58, 59] [61, 62, 63, 64, 65, 66, 67, 68, 70, 72, 73] |

### 2.2.8 SRQ7 (A): Methods characterization

The study of the evacuation process (i.e., approaching a gathering area/an exit) is the focus of 32 studies. In particular, they assessed the travel time, speed, paths & trajectories, and distance covered to reach a given safe point. While the evacuation analysis is conducted on the data extracted from the experiments, the anxiety and immersion degree evaluation has been studied "off-line'," with surveys conducted at the end of the simulation. Nevertheless, in a few cases, the anxiety has been assessed during the simulation via sensors recording blood pressure and sweat (i.e., Heart Rate – HR, Galvanic Skin Response – GSR, electrodermal activity as BIOCAP) [39, 46, 67, 68, 72]. Finally, two articles solely focused on the paths selection driven by emergency signs [44, 64]. See Table 2.3.

Tabella 2.3: Primary studies organized by Methodologies and techniques involved.

| **Methodologies and techniques** | **Papers** |
|---|---|
| Evacuation | [10, 40, 43, 44, 45, 46, 47, 48, 49, 50, 51] [52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62] [63, 64, 65, 66, 67, 68, 69, 70, 72, 73] |
| Survey anxiety assessment | [47, 52, 54, 55, 63, 67, 70] |
| Survey VR experience | [41, 46, 51, 59, 62, 63, 65, 70, 72] |
| Sensors (HR, GSR, BIOCAP) | [39, 46, 67, 68, 72] |

### 2.2.9 SRQ7 (B): Users characterization

The user has been granted full access to the virtual environments without being imposed paths/areas in 29 studies. Only two studies report that users are obliged to follow a previously studied escape route [48, 50]. Except Farra et al. [60] who do not state it explicitly, the rest of the study define the test starting point, as also remarked in SRQ5. In particular, it can be:

- The users start the drills inside or outside the building, possibly been given the possibility of constructing environmental prior knowledge preceding the hazard(s) outburst [58, 62].
- Next to a car (in the case of tunnel-related studies) [42, 47, 52, 73].

The evacuation drills' ending point (target) is often placed outside the building (represented as passing throughout a perimeter building door) or "embodied" by a safe area (elevator, lobby, or stairs), see Table 2.4. Conversely, three studies do not need to explicitly define the exit point/safe area. In particular, Farra et al. [60] focus just on getting ready to face an evacuation, Uno et al. [39] provide a conceptual contribution, and finally Fujimi et al. [58] set the ending point when, seeing the hazard, the user decides to start the evacuation process.

Tabella 2.4: Primary studies organized by Ending point on the case studies.

| Ending points | Papers |
|---|---|
| Outside | [10, 40, 41, 42, 47, 49, 50, 51, 52, 54, 55, 56, 57] [63, 64, 65, 66, 67, 68, 69, 72, 73] |
| Safe area | [43, 44, 45, 46, 48, 53, 59, 61, 62, 70] |

Moreover, a few studies allowed the user to interact with the environment (i.e., grabbing objects and extinguishing fire) beyond simply opening doors [42, 43, 49, 51]. Besides possible spacial limitations, a common line is the time (to evacuate) limitation. Finally, three articles do not explicitly mention the interaction characteristics [39, 60, 73].

Summarizing, besides the NPCs' body impenetrability, structural impediments, bloodstains, and smoke may affect the users' field of view [45, 47, 48, 50, 52, 68]. Indeed, the user is intended able to move freely in more than half of the studies analyzed (85%) . This aspect is fundamental to allow the tester to get immersed in the scenario with no limits and restrictions of movement, like in a potential real-world scenario. However, all the studies have assumed the users to be healthy individuals. Indeed, the users have always an optimal (standard) visual capability and unharmed (standard) motion skills (same walking/running pace for all the users). Such a naive assumption push far back the effectiveness of the studies, given that physically/visually impaired subjects are subject to the hazards too (reasonably being affect more than healthy individuals).

The set of interaction a tester/user is able to perform includes to: follow predefined paths [48, 50, 54], extinguish fire [42, 49], find victims [42], grab and handle various scene's objects (i.e., pick up and use a watering can [62], and just being able to open doors [57, 61]. see Figure 2.13

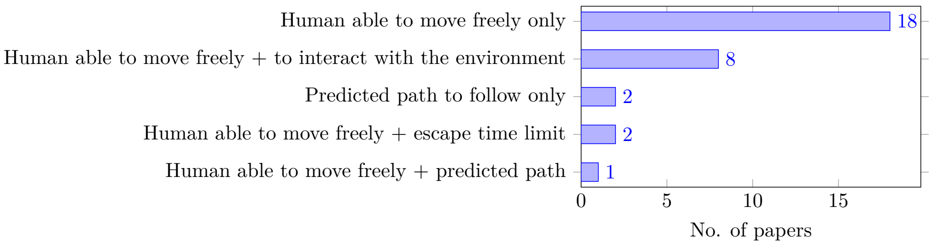



Figura 2.13: Number of primary studies considering the user's characterization in simulation.

Among the interactions mentioned above, Arias et al. [59] report that participants struggled with mechanisms set in place to open doors.

NPCs play an important role in several studies [40, 44, 55, 58, 72]. They can just implement a physical impediment or source of stress, or supply the users with useful information about the evacuation process [46, 56, 64].

### 2.2.10 SRQ7 (C): User's perspective

The user's perspective is not explicitly stated by the analyzed studies (83%). However, it comes straightforward. It can vary between $1^{st}$ and $3^{rd}$ person view, and the distinction seems to mainly follow the technology employed. For example, in the case of IVR (e.g., via Oculus or CAVE technologies), only the $1^{st}$ person view has been provided. Conversely, in the case of the PC-based VR, the analyzed studies provided either $1^{st}$ or $3^{rd}$ person view on the screen.

### 2.2.11 SRQ8: Technology and interfaces

The technologies actualizing the IVR are employed in 27 (76%) of the analyzed studies (see Table 2.5).

Tabella 2.5: Primary studies organized by Interface implemented.

| Interface | Papers |
|---|---|
| IVR | [40, 41, 42, 43, 46, 47, 48, 49, 50, 51, 52, 53, 54, 56, 57, 58, 59] [60, 61, 62, 63, 64, 65, 70, 72, 73] |
| VR | [10, 39, 44, 45, 66, 67, 68, 69] |

Nineteen studies have realized immersive environments via Head Mounted Display (a screen mounted on the head of the viewer through an ad-hoc helmet and can be monocular or binocular (i.e the reproduction of a small display optic in front of one (monocular) or each eye (binocular)) [40, 41, 42, 43, 46, 49, 51, 53, 54, 55, 56, 57, 58, 59, 60, 62, 63, 64, 65, 70, 72], and seven via Cave Automatic Virtual Environment (CAVE technologies [47, 48, 50, 52, 61, 73] which consist of a cube-shaped room and video projectors directed on its faces (see Figure 2.14)).

The primary studies focusing on VR employed a PC monitor [10], 6 LCD monitors and a smoke generator [67], and PC and Wii Joystick with visual and audio stimuli [68]) technologies. Finally, six studies did not specify the involved technology/interface.

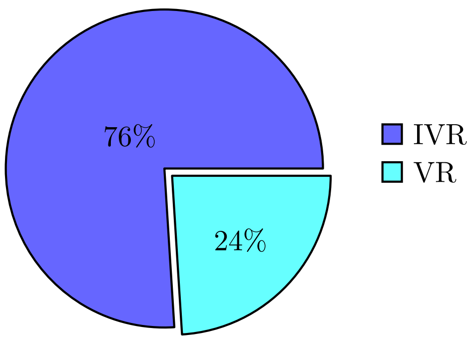



Figura 2.14: Percentages of primary studies considering the Interaction interfaces.

The underlying technologies powering modeling and implementation of graphic engines for both VR and IVR are multiple.

The most used modeling softwares to generate the environments are Revit, a BIM vector program, Sketchup, and Autocad, (see Figure 2.15). 3D Studio Max is also used as a modeling program. However, in the studies analyzed, it is generally used to integrate effects such as lights, materials, or objects within the created space. Unity 3D is the most used graphics engine for modeling (especially for environment animation), with Unreal Engine in second place. Finally, to increase the credibility of the virtual environment, semi-realistic effects are added, such as the dynamics and density of the smoke enveloping the environment, which increases with the passage of time and fire. Indeed, five case studies feature Fire Dynamic Simulator technologies [42, 43, 45, 46, 50]. An additional study [67] reports the use of smoke generators as an alternative to these fluid dynamics systems but only for VR use. Alternatively to these fluid dynamics systems, some studies report the use of smoke generators [67], (visual and audio stimuli) [68], and a chair-shaking system [64]. An example of a complete technological pipeline is Revit for modeling, 3D Studio Max for the integration of effects, Unity 3D to make the model interactive, and finally FDS software to generate and develop fire and smoke patterns [50].

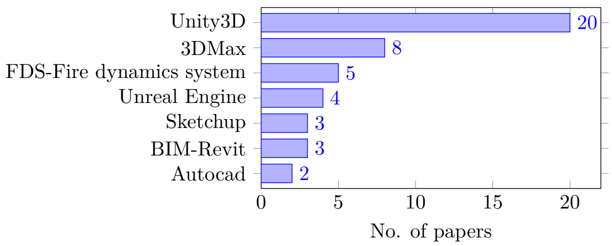



Figura 2.15: Number of primary studies considering the used software.

### 2.2.12 SRQ9: Analysis Methodologies

The methodologies used by the primary studies to assess their findings are quite heterogeneous (see Figure 2.16). Nine studies explicitly target the assessment of 's realism. The users who participated in the experiment have been surveyed right after completing the test. The stress level (especially in proximity of the danger) has been analyzed during the tests' execution [55], while similar aspects such as frustration and dizziness have been assessed both during and after the tests' completion [48].

Although VR and IVR can cause the disturbs mentioned above, the assessment of its usefulness in the process of educating/testing emergency drills has reported positive marks [40, 41, 46, 49, 51, 55, 59, 69] Furthermore, Feng et al. [56] found that visitors (mostly unaware of the environment) have dramatically improved their performances over the tests, reaching the level of the hospital staff (already confident with the environment). Furthermore, Chittaro et al. [68] states that the interactive team (players can choose and take dietary decisions on their behalf) had a better risk assessment than the non-interactive team. However, both have increased their knowledge of the evacuation process (proven via the post-test surveys).

Five papers also analyze the decision-making process and the escape routes taken during the tests. According to their analysis, $\sim 70\%$ of the players use the same routes taken at the entrance to escape (because it is the only one or the one they know) and trusted that more than the quest of following the emergency signals [46]. Additionally, Shih et al. [10], and Ronchi et al. [52] highlight that the safety routes might not be the shortest, yet they are the safest. Nevertheless, this aspect seems to raise little interest in the user, and it is overruled by many danger-related emotions. To solve this problem, Snopkova et al. [62], and Chittaro et al. [66] state that through a proper building/spaces design and putting signals in clear sight the tendencies to retrace known routes can be less appealing than following proper safety paths.

Thus, the signs' visibility is crucial, and their use must be encouraged [10, 47, 62, 66]. Greenlight is reported to be more tolerable than blue light and especially at a rate of 1 to 4 Hz [73]. Cosma et al. [65] did not find such differences for user evacuation behavior. The implementation of voice alarm systems can give critical information to ensure a smoother and more consistent evacuation process [61, 72]. Another relevant research employs smartphones to provide instructions to reach the emergency exits [53].

Two studies assessed anxiety, stress, behavioral choices, and escape time by splitting the users into two teams: one team having the possibility to move freely in the generated environment, the other team having to follow a predetermined route (simulating limited environmental knowledge) [54, 67]. The experiments found that the team with the ability to move freely took much longer to escape and was more stressed than the "limited-range" team.

### 2.2.13 SRQ10: Strengths

All the studies agree on the importance played by VR and IVR simulators to enhance the efficiency and effective learning of evacuation training [59, 70, 72],

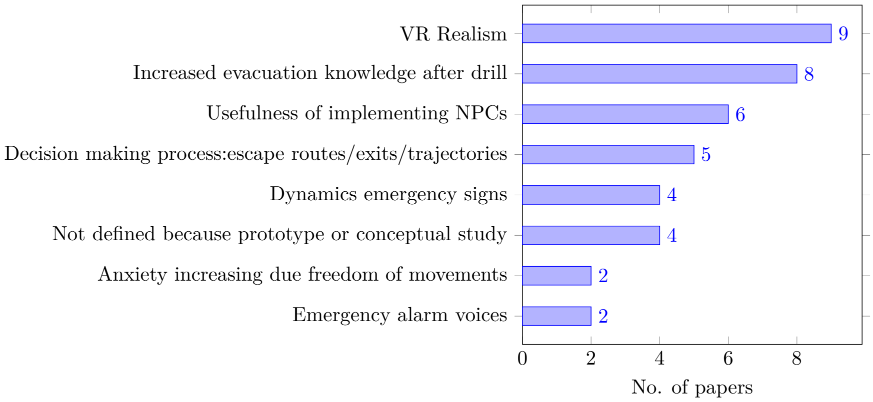



Figura 2.16: Number of primary studies considering types of analysis of the results.

although some limitations are still retrieved, as shown by SQR11 insights. The combination of led signage, voice alarm systems, and the use of devices such as smartphones have also shown promising results and benefits [49, 53]. Particular attention should be paid to the contribution of NPCs within the hazard scenario as they influence the decision-making and behavioral process of the user bringing it closer to the reality [55]. Finally, a further benefit is related to the use of fluid dynamic computation software such as FDS [45, 50] which boosts the credibility of the simulator and allow to achieve more realistic levels of engagement and stress.

However, it is worth highlighting that 20 papers did not explicitly elaborate on the strengths, benefits, and advantages of their research.

### 2.2.14 SRQ11: Limitations

Twenty articles (59%) do not mention nor address the limitations and barriers entailed in their studies. The rest of the papers point out four types of limitations:

- the participants are alone in the test environment, harming the credibility of the system [47, 51, 53, 57, 70];
- the lack of effects and/or sensors that can reproduce heat, humidity, smells, smoke density for a more realistic environment is reported in another [46, 47, 51, 57, 65].
- unpleasant users' sensation/feeling due to technological drawbacks. For example, some users have experienced dizzying due to the virtual environment's lack of fluidity — frame-rate irregularity, loss of focus, depth alteration) [51, 53, 61, 64].

- unbalanced users population, almost only young individuals took part in the studies[57, 73].

Some studies report combinations of these four major limitations as [47, 51, 53, 57].

### 2.2.15 SRQ12: Solutions

Most of the papers have delegated such an analysis to future research or just mentioned them as potential challenges. Only three studies mention solutions to cope with the limitations pointed out in SRQ11. In particular, one solution concerns the lack of NPC, proposing to coordinate simultaneous tests to have more players on the scene [46]. Another aspect defined is the employment of sensors to reproduce sounds, smells, and heat to increase the credibility of the generated virtual world [51, 54]. Finally, a study proposes the use of treadmill as a measure of overcoming the movement limitations of virtual reality [51].

### 2.2.16 SRQ13: Future challenges

Twentyfour studies (71%) expressed the intention (to be verified) to follow the presented studies. Some of the future challenges indicated by the primary studies overlap with the elicited limitations. Eight studies that provide the implementation of physical stimuli such as the sensation of heat, smoke production (via specific generators), and environmental sounds reproduction foresee the use of sensors, such as heart rate and sweat sensors, to perceive stress levels [41, 42, 46, 51, 63, 66, 67, 72]. Several studies propose to introduce the multi-players setting and behavioral group analysis [43, 44, 53, 67, 69, 70], aligned with the proposal of Zhang et al. [57] to involve a crowd-flow to explain social behaviors. Chittaro et al. [68] plans to implement the third-person perspective to investigate changes into the decision-making behavior of the individual given another (wider) perspective. Cavalcanti et al. [49] propose to involve an audience of users of different gender and age (including possible movement limitations) to have a more plausible framework and user representation. The environment also plays an important role in the study as the complexity of the building can give users anxiety, loss of orientation, and difficulty finding their way out. To this end, the studies such as [55] and [69] aim at modeling a more complex environment in the upcoming studies (i.e., more realistic objects on the scene with an accurate hazard-related representation).

Moreover, [48] and [68] highlight the need to implement multi-hazard and dynamic-hazard studies. It can be translated into a fire and smoke initiation and development, possibly via FDS (fire dynamics system) softwares.

Finally, recalling that VR and IVR training can instill a high level of stress on the user and increase the evacuation's knowledge retention, researches such as [56, 68] propose to study long-term effects via survey carried out at a relatively distant time from the day of the evacuation test.

## 2.3 Discussion

Elaborating on the results elicited by investigation, it is possible to assert the relevance of employing VR and IVR technologies for evacuation drills. Hence, the results obtained by the mostly practical studies (applied and tested) testify a growing performance efficiency [56, 70], emotional involvement [71, 67, 68] scientific interest, information retainment, enhanced outreach, a broader set of "testable" scenarios, and a wider spectrum of observable key variables in the users' behavior.

However, such solutions introduce several limitations and are characterized by several severe blind spots. In particular, the requirements formulation (concerning the user, the hazard scenario and the hazard effects spreading over the time, and the built environment) seems to be too often weak and approximate. The definition of formal requirements would pave the way towards standardization and, therefore, a more uniform and structured systems' evolution, thus providing:

1. extension of recipients' sample dimension and types also depending on the effective users of the buildings;

2. simulation-based representation of hazard effects (e.g., through FDS-based dynamics);

3. adequate level of accuracy and realism of the building environment in terms of architectural components and building components (including audio stimula);

4. improved levels of the main following literature factors concerning the concept of presence in the virtual environment [3]:
   a) sensory, as the “the degree of movement” in the environment;
   b) realism, as the closeness “to reality” that participants perceive considering both the scenes and the structures in the IVR environment, e.g. by focusing on fatigue-based approaches, or familiarity-related issues before the tests;
   c) involvement quality, that concerns “visual display and controllers” that participants use to accomplish the task in the IVR environment;
   d) control of IVR elements;
   e) distraction, as the “ease of adaptation” to the IVR environment.

Such actions would shed some light on the several naive assumptions that, as of today, strongly characterize the recipients/users. For example, among all the studies, the main user/player has no impairments – complete motor and visual skills. Nevertheless, designing and implementing the main player with several motions speeds, heights, visual capabilities, or grabbing/reaching settings would boost the inclusiveness and the significance of the system/study, which would finally consider ill, harmed, and disabled individuals among the recipients to be educated or trained against possible hazards. Furthermore, it is necessary to characterize better the initial setups and assumptions, the interface functionalities and projections, and the analysis of the final results. In this sense, the implementation of formal requirements and the actualization of a proper “framework” to characterize VR and IVR emergency drill systems could be used to compare rigorous methods with naive assumptions and understand if operational simplifications could still be tolerated to assess behaviors or adequately train people.

The technologies involved in VR and IVR drill systems have rapidly evolved. However, they are still relatively unexplored to their full potential, especially when coupled with wearable garments and sensors (involving more human senses at once). This affects the engagement level, which should definitely be increased to trigger higher levels of sensory, realism, and involvement quality, and reduce distraction factors.

It is worth highlighting that most of the attention is dedicated to (A) simulating indoor environments such as hospitals, hotels, and mall centers – rather than private environments (mostly neglected) – (B) limiting the scenario to the building itself –rather than also including the interconnected public outdoor space facing the building– and (C) considering the occurrence of a single hazard. In this sense, three main issues can be noticed to make future efforts more capable of facing challenging conditions.

About point (A), when staging such crowded environments, NPCs play a very crucial role. Yet, they are undeservedly under-addressed, and further efforts are needed, for instance, in coupling a single hazard with more realistic crowd phenomena via NPC [30]. Improving their representation/characterization (e.g., from a strategic or AI perspective) and involvement in the drills (either as obstacles or resources) would dramatically increase the benefits and realism of the systems.

About point (B), the correlation between indoor and public outdoor spaces could be relevant in view of the possibility that additional conditions of the built environment facing the building could imply different critical interactions for the occupants at the end of the evacuation, such as the arrival of rescuers' vehicles, overlapping of evacuation phenomena in case of crowded public spaces and/or wide complexes of buildings, overlapping of risks in outdoor due to multi-hazard scenarios (i.e., fires following earthquakes) [9, 23, 56].

About point (C), further research should move from hazard, as the main requirement, to the concept of risk as a leading factor, by considering that the risk depends on the combination of hazard, physical vulnerability, and occupants' exposure (thus including their number and density) and individual/social vulnerability, as well as their ability to cope with the danger and all the psycho-physiological variables pertaining to the user [74, 14]. In this general context, the hazards can have different natures, and when considering multi-hazard, the scenario would be dramatically more complicated, inducing greater psychological arousal and retention of the information [75]. Thus, "simply" evacuating a building using the emergency routes and exits as represented by the current systems might not be sufficiently motivating. For instance, in a multi-hazard scenario like in the case of fire following an earthquake, building damages should be summed to fire spreading, thus making users undergo additional stress conditions. Meanwhile, the same built environment scenario could be analyzed by making users face different hazards, one at a time, to assess users' behaviors and risk-reduction strategies under different scenarios.

In this way, hazard representation can also be linked to physical vulnerability variations (e.g., layout, wayfinding signs, alarm, other emergency systems, and facilities), thus also pursuing the effectiveness test of fundamental solutions for occupants' evacuation support [19, 34, 76]. Further research should also urgently develop formal requirements for the identification of users' characterization issues by also actively involving more vulnerable individuals (e.g., with motion or visual impairments, patients) as recipients (see SQR4 (A)). NPCs' characterization assumes a relevant rule for social vulnerability factors connected to the aforementioned crowd phenomena and underlying exposure issues. Given the above, typological (relevant due to statistical recurrence) combinations between hazards, environment features (and so vulnerability), and users' factors (exposure and vulnerability) can be then used to focus on the most meaningful scenario conditions for behavioral analysis and training activities expecting the users' preparedness to increase.

# Capitolo 3

# Framework

From the analysis of the literature through the 13 structured research questions, (see Chapter 2) the heterogeneity of the methodological tool applied in the papers and the variables chosen in the experiments was clear. In fact, the data collected regarding the formalized methodologies, technologies, and devices used for scenario modeling do not adhere to any standardized code, and as a result, this confusion in experimentation could represent a poor ability to compare data from different experiments, also generating misleading results. However, the strengths, shortcomings, and future challenges highlighted by the papers themselves were attractive to base the development of this thesis on. This study has the task of employing virtual reality in the built environment to verify the user's behavior when faced with danger, his or her reaction, and thus the adherence or non-adherence to the evacuation system prefixed in planning. It was therefore useful to first formalize a framework that would mitigate the gap and confusion found in the studies analyzed in the previous chapter, which was useful in later developing the simulator design. This work was made possible by collecting all aspects derived from the existing literature. Aspects pertinent to a virtual environment design are first reported. These factors: are the characterization of the scenario, environment, user, hazard, objectivity, developed interfaces employed in researches. Defined these aspects are studied in detail variables. The list of these aspects, which will be useful in modeling the thesis experiment, is given below.

#### Scenario

VE applied and hazard/multi-hazard combination selected.

### Environment Characterization

**-Context:** Hospital lane(s), Homes, Malls, Road tunnel, Train tunnel, Subway station, Train station. All papers selected one context.

**-Structural composition:** Ground floor, first floor, rooftop, stairs, elevators. All papers selected one of them.

**-Safety areas:** Area on the roof, emergency assembly area outdoor, courtyard, high point, bunkers. [46, 41, 47, 48, 49, 50, 10, 52, 53, 54, 55, 56, 57, 59, 61, 62, 73, 72, 63, 64, 65, 66, 67, 44, 69].

**-Restricted areas:** inaccessible area, and architectural elements (doors, elevators, windows) not able to be open.

**-Pathways:** Integrated Hazard Dose (coefficient). [45].

**-Fixed objects:** identification of windows, walls, and other elements in the building non-actionable.

**-Actionable:** Main objects in the scene (obstacles, fire extinguishers, leverages, elevators, doors) that the user can interact with. [46, 41, 48, 49, 42, 50, 51, 43, 53, 54, 56, 59, 60, 40, 63, 64, 66, 44].

**-Movable object:** Secondary objects (of minor importance to the purpose of the evacuation drill) in the scene (water can, boxes, chairs, plants, clothes, devices) that the user can grab and handle. [58, 44].

**-Signal(emergency)/colors cultural encoding:** Depending on where the experiment takes place corresponds to a layout ( Italian (UNI)/ European (EN)/ International (ISO)). [73, 77].

**-Additional tools:**

- IoT distributed sensors. [78, 79]

-Augmented reality for re-routing.

### User (Recipient) characterization

**-Health condition:**

-Physical condition: standard or injured.

-Height (POV):from to 120 - 170 cm.

-Feed speed: from 0.8 to 3 km/h. [80, 81].

-Visibility: depending on the methodology used you get a scale of visually impairments (from clear to blurred visibility).
-Advancement mode (walking, running, limping, crawling, wheelchair).
-Age range: making classification by age range.
-Gender: Male, female, transgender, not identified.

**-Environment Knowledge assessment:**

-Structural composition (planimetry: full/ partial/ none). [56, 60, 63, 64, 44, 69].
-Pathways and exits (full/partial/none). [46, 41, 48, 49, 50, 51, 10, 53, 54, 55, 56, 57, 58, 59, 61, 40, 62, 72, 64, 67, 68, 44].

**-Role:** names of members of an organization, company or group (patients, staff, visitors, relatives). All papers analyzed in the Sota.

**-Starting point:** Point where the user starts the drill (inside the built environment like corridors/rooms or outside as courtyard/street/main entrance ). All papers except [60].

**-Equipment:** What types of devices are used (firefighters' tools, staff medical tools). [42, 50, 60, 69].

**-Performance:**
- Stress level/anxiety assessment via surveys made before and/or after the evacuation drill. [47, 52, 54, 55, 63, 67].
-Escaping time: measured run time. [47, 49, 50, 43, 10, 52, 53, 54, 55, 57, 58, 59, 61, 40, 62, 65, 66, 67, 68, 69].
-Escaping route: route taken. [47, 43, 10, 52, 53, 54, 55, 57, 61, 40, 62, 63, 65, 67, 69].
-Escaping exit: exit taken. [47, 59, 61, 40, 62, 67, 69].
-Retained information: multi.test or survey after drill. [46, 48, 49, 51, 55, 56, 57, 60, 61, 62, 68].
-Evacuation strategy: reaction to the hazard in the scene/pre-movement action.

[47, 52, 66].

**-Interaction:**

-NPCs (Non-player characters): in the environment designed as obstacles, guide, giving any information. [46, 55, 56, 58, 40, 72, 64, 44].

-Multi-players: collaborative /competitive teams, e.g., info for improving performance.

-Pre-existing technological knowledge (fluid/familiar/unfamiliar/contrary.

#### NPCs Characterization

**-Role:** names of members of an organization, company or group (patients, staff, visitors, relatives, police, firefighters). [46, 55, 56, 58, 40, 72, 64, 44].

**-Health condition:**

-Physical condition: standard, injured.

-Feed speed: from 0.8 to 3 km/h. [80, 81].

-Advancement mode (walking, running, limping, crawling, wheelchair).

-Age range: making a classification by age range.

-Gender: Male, female, transgender, not identified.

**-Interaction:** actions and interaction with the users (giving unfo, giving help, obstacles). [46, 55, 56, 58, 40, 72, 64, 44].

#### Hazard Characterization

**-Nature:** kind of hazard applied to the simulation (fire, flood, terror attack, earthquake): All papers except [59, 60, 61, 62, 73, 65, 69]

**-Effects on the environment:** as spreading fire, spreading smoke, water raising, localized/generalized destruction, random objects displacement, emergency exit and route become not available, invalidation of exit/pathways): [45, 46, 47, 48, 42, 50, 51, 43, 10, 52, 54, 56, 40, 64, 65, 66, 67, 44]

**-Impediments:** due to reduction visibility, routes reduction.

**-Delay and Duration:**measured by time/event-drive. Event-driven/duration till the end of the users' life or the reach of a safe area.
**-Location of hazard activation:** where the hazard is located in the proposed scenario (indoor/outdoor/specific room/corridor). [45, 47, 48, 49, 42, 50, 51, 43, 10, 52, 53, 55, 58, 40, 66, 68].

**-Extinguishing hazard:** presence of hazard extinguishment in the built environment according to the local/national law (none/partial/total): [50].

**-Limitation:** given the height, propagation of fire/smoke, etc.

#### Objective Characterization

**-General objective:** as reaching safe area, helping NPCs, helping other players, triggering alarm, extinguishing fire. All papers analyzed.

#### IVR interface and perspective

**-VE category:**what type of device was used to render the built environment and test volunteers (IVR (e.g. Oculus, Cave), VR (monitors), AR (special glasses)). All papers studied.

**-Navigation visualization:**. Defining the user's point in navigation. [45, 65, 67, 68, 44].

**-UI (user interface):** presence of built interfaces in software or computerized devices, focusing on look or style (clean, dashboard elements as Health-bar, coins, arrows). [68].

#### User-VE interaction

**-Real-world actuators:** Application of physical elements for making simulation more engaging (e.g., shaking chairs for more earthquake experience, heat lamps, smells, smoke generators). [64, 67].

**-Wearable garments:** Application of physical elements, as sensors for anxiety assessment (e.g., Heart-rate (HR) and Galvanic skin response (GSR)). [46, 39, 72, 67, 68].

**-Posture:** posture mode of the player involved in the experiment (e.g., sitting, standing, walking)All papers analyzed.

#### Test Protocol Definition

**-Variables and tools:** Variables configuration and behavioral choice or Info retention, obtained with a survey performed after 5/7/10/15/30 days [60].

So thanks to the study and analysis of the literature addressed in the state-of-the-art chapter, it was possible to collect the variables, decode them and place them to make it easier to key them through this helpful framework to address the next step, which is in building the simulator.

# Capitolo 4

# Simulator design

The framework defined in the previous chapter has been helpful to alleviate when making the choice, all the factors, and variables that are inherent in such a project. Our idea is to develop a serious game with the goal of first understanding the evacuation behavior of various people and then integrating accouterments, such as improved evacuation systems, that can improve safety management.
Through this technology, n really experience firefighting, and flooding, and learn the results of different possible actions. In addition, IVR allows them to record videos useful in deciphering behaviors that in physical evacuation tests would be difficult to pick up. In support of this thesis, the paper [82] admits that fire tests overlook evacuation test failures because dead people cannot give any feedback. More, according to this paper, in design, engineers calculate RSET (required safe escape time) and ASET ( available safe escape) as if people evacuate robotically, but this is not the case, as many non-negligible aspects come into play. Psychological, social, physical, political (regulatory and regulatory), and cultural elements all have an impact on how danger is perceived. The individual-environment-risk paradigm is the foundation for how fire risk is perceived.This feature also emphasizes the lack of consideration for multi-hazard and other risk evaluations, such as flood scenarios. The dominant role of trust, together with that of human environments (everyday and emergency), the physical environment, and the safety atmosphere in which the event occurs, are mentioned among the elements defining the perception of risk. These various aspects of fire risk perception demonstrate that it is a synthesis of cultural and psychometric paradigms. According to reports, the act of leaving a building is viewed as a psychological one that involves both emotion and cognition [14, 80].

Below we outline the most important aspects taken into consideration for the implementation of the simulator following the framework outlined in the previous chapter. We highlight the dependent hazard systems, the roles of the users involved within the virtual environment, and finally, the alert systems applied.
After that, the related scenarios born from the combination of these factors are structured and lastly, the methodological approach implemented to compare the data collected from the tests is defined.
Other aspects of the framework are studied in the next chapter to describe in more detail each variable considered for simulator implementation in the software used.

## 4.1 Scenario Design

### 4.1.1 Hazard

The existing literature focuses on the study of single hazards neglecting the possibility that a tsunami may be generated by one earthquake or that several fires may originate from one tsunami.
See, for example, the December 2004 earthquake and subsequent tsunami in Sumatra, which killed 227,898 people in total, or the tsunami resulting from the earthquake that struck the island of Java (in Indonesia) in July 2006.
Otherwise consider other floods not from tsunamis, but from concentrations of rain poured into a relatively small area causing extensive damage.
Considering more recent times, the focus shifts to the earthquake and tsunami that occurred in Japan in March 2011 causing 15899 casualties, according to current statistics, most of which were due to the tsunami caused by the sudden tectonic movement off the beaches of Japan. (See Figure 4.1).

(a) Sumatra Tsunami 2004

(b) Java Island Tsunami 2006

(c) Japanese Tsunami, 2011

(d) Senigallia flooding, 2022

Figura 4.1: Combination of catastrophic flooding events.

These examples are a testament to a more general and true view that sometimes people may be involved in facing not a single hazard, but a combination of them. So, the project is devoted to defining three macro-scenarios (hazard-dependent) applied in the simulator: **Flooding / Fire**, as single-hazard scenarios, and **Flooding+Fire**, as multi-hazard scenarios.

For the fire scenario, the space outside the building is considered a safe escape point for the user.
For the flood scenario, two escape points are considered: the roof or a high ground present nearby.
For the multi-hazard scenario, on the other hand, the only point considered safe is a high rise.


Figura 4.2: Single and multi-hazard implemented in the scenarios.

### 4.1.2 Environment

This is followed by the characterization of the environment or rather the chosen building context. The study focuses on analyzing a **HOSPITAL**, considered a critical facility. The density factor, the instrumentation used, the users present (with strong physical and cognitive limitations), and the architectural complexity are some elements that arouse interest in addressing this issue.
The paper [83] reports on how to assess the risk and vulnerability of a building, how to identify the risk, and its magnitude, and how to plan for evacuation, reporting especially that hospitals have a poor escape plan.
Modern hospitals adopt an improved volumetric complexity policy in their design compared to older ones to facilitate both staff service and safer evacuation in case of need.
This does not make the old hospital obsolete and unusable, but more attention should be paid especially to ensure the maximum safety of the occupants inside, through

the implementation of more sophisticated fire extinguishing systems or integration of more modern safety management policies.
For this reason, the choice fell on the U.S. Mid Coast Hospital in Maine, an existing hospital building that is architecturally complex in terms of intersecting corridors. Presence of vertical connections such as stairs and elevators, diversified for medical and public use, are present in the building.

Figura 4.3: Hospital as built environment chosen for the project.

### 4.1.3 Characters

It can be said that the hospital environment is frequented by many people. This makes the facility a building with a relevant density factor.
What is intriguing is that the occupants who use this building have different physical/motor and cognitive peculiarities.
We can find different roles with varying degrees of knowledge of the environment and in good physical condition, such as family members of patients, who come from outside and are probably unfamiliar with the building context. Patients are another category to be treated as they are afflicted with physical impediments, such as partial blindness or motor limitations, but on the other hand, they may have partial knowledge of the environment they are in, such as the treatment area in which they are required to stay for a certain time. Finally, we also report the presence of medical staff who are required to provide service to patients and who have a high degree of knowledge of the built environment in addition to presenting good health conditions.
As mentioned, the characters involved in a hospital environment (family members, patients, and medical staff) show differences in terms of familiarity with the environ-

ment, and this is also reported in [44, 56, 64].
One of the fundamental keys to the project which is almost "innovative" compared to the literature reviewed is the identification of a gap. All papers employ users with good health conditions in their tests, neglecting the presence of people with physical limitations. Especially papers involving a hospital as an environment do not give any mention regarding tests for people with motor impairments. Consequently, the choice of the hospital environment involved ratifying the different roles of the occupants who are involved. In the study design, different roles employed in the three macro-scenarios were formalized, emphasizing, however, that patients with disabilities are still able to evacuate independently. Below are the different roles employed in the simulator in order of physical and cognitive condition: For this reason, the choice fell on the U.S. Mid Coast Hospital in Maine, an existing hospital building that is architecturally complex in terms of intersecting corridors. Presence of vertical connections such as stairs and elevators, diversified for medical and public use, are present in the building.
**-VISITORS:** with good physical condition and little familiarity with the environment;
**-MEDICAL STAFF:** with good physical condition and greater familiarity with the environment;
**-PATIENTS (visual impairments):** with poor physical condition and partial knowledge of the environment;
**-PATIENTS (motor impairments/limping):** with poor physical conditions and partial knowledge of the environment.


Figura 4.4: Users engaged in the scenarios.

From the various roles defined and implemented in the project, the starting point of the test is highlighted. For visitors visiting their family members (patients), the starting point is placed outside precisely for consistency of the role they play, while for staff and patients the starting point is highlighted inside the building.

### 4.1.4 Emergency layout

Attention is paid to the alarm systems that can be employed in the realized environment.
In this regard, the literature lacks this consideration and simply reports an alarm starting to sound. This does not give any information regarding the risk involved, whether it is either fire or other.
For a cultural background, more often than not, an alarm that starts sounding is strongly correlated with a fire that has been revealed, but that we cannot see, given the location in another building location.
This thesis may hold since earthquakes can hardly be predicted, and when an earthquake occurs immediately everyone is aware of the risk.
Flooding, on the other hand, can be detected in advance, causing the most appropriate evacuation machinery to be set in motion to lead as many people in danger to safety as possible.
The Tsunami in 2011, megaphones placed in Japanese cities saved additional lives by instructing citizens to take shelter by reaching high ground points.
So in this section, it is also of relevant importance to study the type of warning system employed within the built environment.
In the thesis project, scenarios adopting the standard and integrated systems were defined for single-hazard and multi-hazard scenarios, obviously considering the static emergency signage applied by default in each scenario.
In more detail, the flood scenario is divided into dependent alarm sub-scenarios.
One sub-scenario provides an audible alarm, while another provides a voice emergency system integrated with the siren. The voice reveals to the occupants the type of hazard in place and instructs them on the safest escape route to follow.
Same for the fire scenario, which is also divided into two dependent alarm sub-

scenarios. One case is where an audible alarm is provided and another scenario is where the alarm is accompanied by IoT technology capable of generating dynamic signage.


Figura 4.5: Emergency systems implemented in the scenarios.

Relative to the multi-hazard (flood+fire scenario), only an integrated alarm system is adopted: siren+voice since the standard alarm data (alarm sounder) can be inferred from the single hazard scenarios defined above.

Figures 4.6, 4.7, 4.8 show the structure of the different scenarios defined and implemented in the built environment. A total of 20 scenarios were divided by hazard (single or multiple), by different roles (visual impairment, motor impairment, visitor, and medical staff), and by emergency systems used.

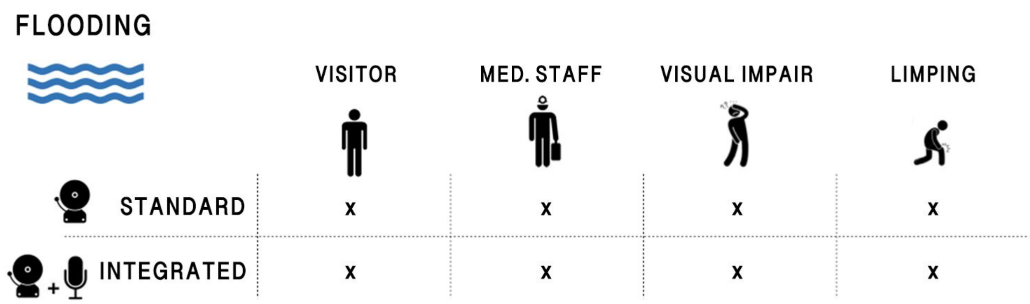



Figura 4.6: Single hazard (flooding) scenario.

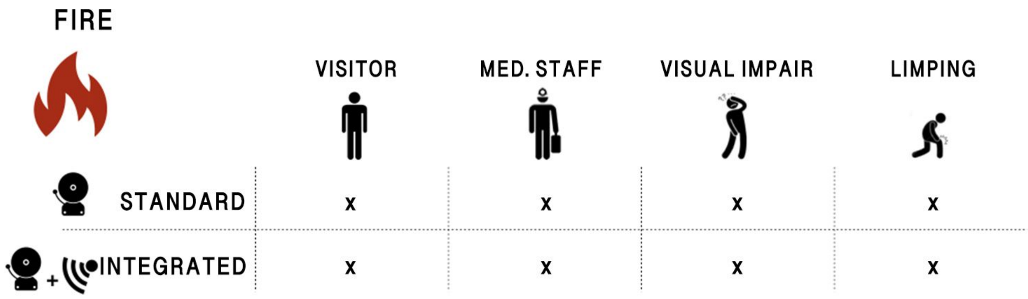



Figura 4.7: Single hazard (fire) scenario.


Figura 4.8: Multi-hazard (flooding+fire) scenario.

### 4.1.5 Reliability test for static emergency signs (Corridor test)

Before addressing the methodology of the thesis project, we are going to conduct a preliminary test to verify that the emergency signage implemented in the system is efficient and thus detectable by players during the hospital evacuation.
The dimension of the signage and the approach with which the test was conducted considers the methodology of paper [1] The building was equipped with static emergency signage inside the building and the "corridor" test was carried out, in which three corridors called A, B, and C were taken, all having similar dimensions:
-Height 3.2 m;
-Width 2.44 m (corridors A and C), 3.60 m corridor B
-Length > 30 m.
The choice of three corridors, shown in Figure 4.9 dictated by the fact that three emergency signs are employed, giving different directions: straight, right, or left. The emergency signs respect the standard indications of NFPA 101, NFPA 170, and therefore of ISO 7010. The size adopted is 50 cm wide and 23 cm high. Further

information on the brightness of the applied signage is explained in the following Chapter 5.

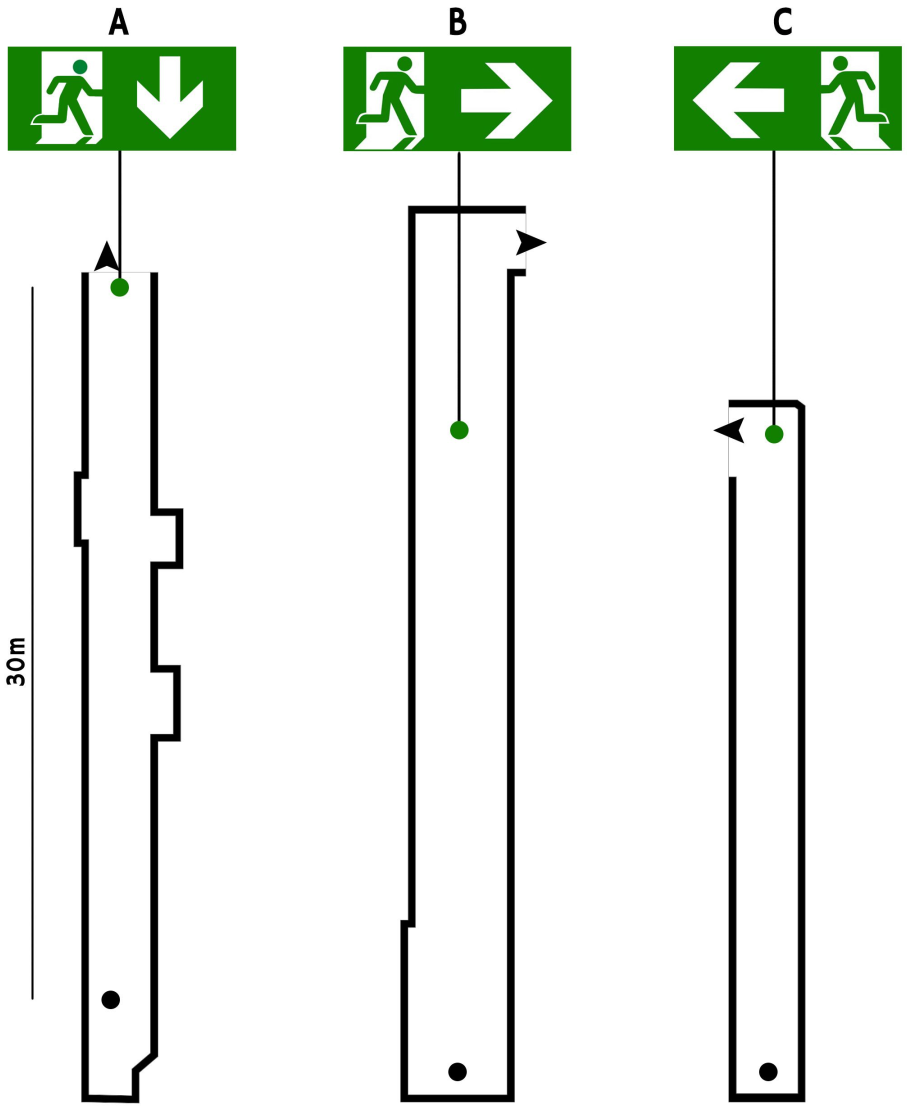



Figura 4.9: Representation of the corridors to analyze the efficiency of the implemented emergency signage.

The test involves the use of natural lighting from the immersive virtual reality system and not powered by the implemented standard luminance, just to be coherent with the emergency system in place.

The test, therefore, aims to verify at what distance the user can recognize the presence of the "Detection" emergency sign, and at what distance he can, on the other hand, recognize the indication of the "Confidencee" sign.

Unlike physical reality, virtual reality implements the rendering of the built environment through the use of HMD (Oculus Quest 1) with a limitation of 72 FRP (Frames per Second).

While knowing that this is a limiting aspect of the testers' performance, an effort was made to meet still the minimum requirements dictated by current regulations and the paper [1] as well as to verify in real-time that the entire test developed with the maximum possible rendering.

The experiment involved 36 testers from each corridor, for a total of 108 tests. The number of volunteers was decided to achieve relatively high reliability of the result through the use of the G*Power program. Entering the data into the software extrapolated a probability of 92% as the final result (see Figure 4.10). This, therefore, guarantees the power of the test to be carried out and the reliability of the final result as mentioned before.

Thirty-six volunteers were presented and were preliminarily asked about the "age range," the type of working background, and whether or not they use glasses/lenses (vision correctors).

The age range is divided into three age groups ( A = 18/30 years, B = 31/42, and C = +43).

Next, users were instructed on the proper use of the joystick and the Head-Mounted display.

Finally, testers were asked to report when they could recognize the signal ("Detection") and when they could recognize the signal indication ("Confidence").

Also, videos of each test were recorded to more accurately measure the moments of Identified and Confident detected by the players.

The tester was placed at a distance of 30 m from the emergency sign, so he could

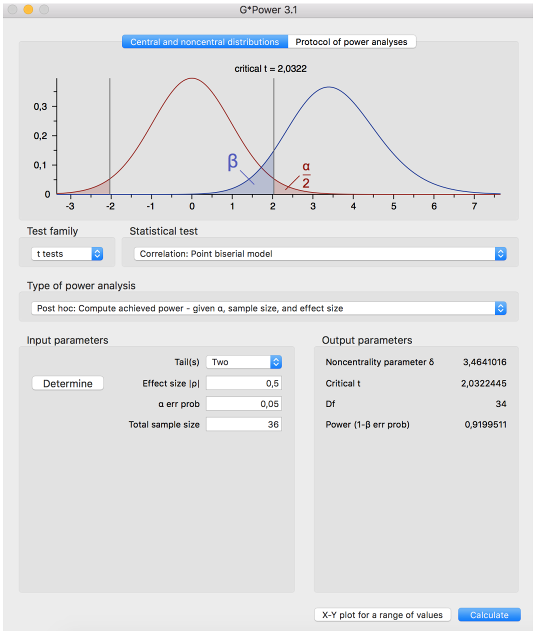



Figura 4.10: G*Power strength applied in the Corridor test.

advance toward the emergency sign by moving the joystick, revealing the presence of the signal first, and the indication later.

Below are the averages of the results collected before and during the test, while the data for each individual test were entered within an excel sheet and are available from Annex A.

By Figure 4.11 testers were mostly youth or adult volunteers.

Inherent to the working profession it is noted that half of the testers are students/Ph.D. students followed by workers and six testers were professors, see Figure 4.12 From Figure 4.13 there is homogeneity between people with and without glasses/lenses.

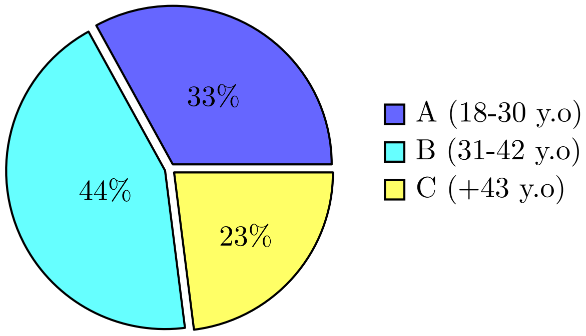



Figura 4.11: Age Range of testers involved in the corridor test.

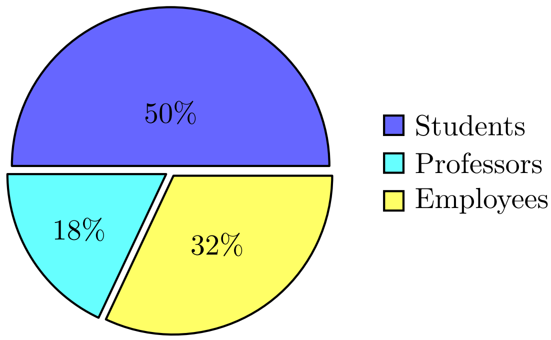



Figura 4.12: Percentage of testers' job profession.

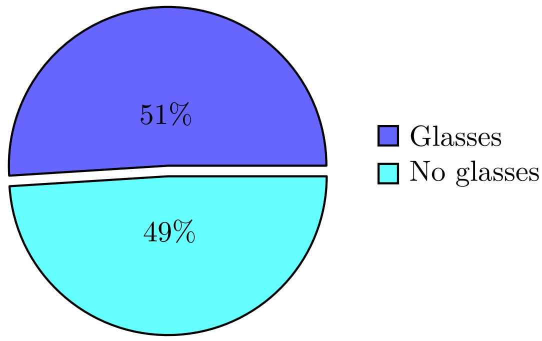



Figura 4.13: Percentage of testers equipped with galsses/lenses or not.

### Corridor A

As shown in Figure 4.14, most users detected the presence of the signal at 30 m. This indicates that the signal is of a size that can be picked up immediately.
Among other things, a margin of divergence between the maximum and minimum data collected, in terms of distance, is found to be 35 cm.
Figure 4.15 reports that the "Confidence" of the emergency signal is at an average of 21.9 m from it with a divergence of 4.60 m. None of the testers made any errors in

the interpretation of the signal indication.

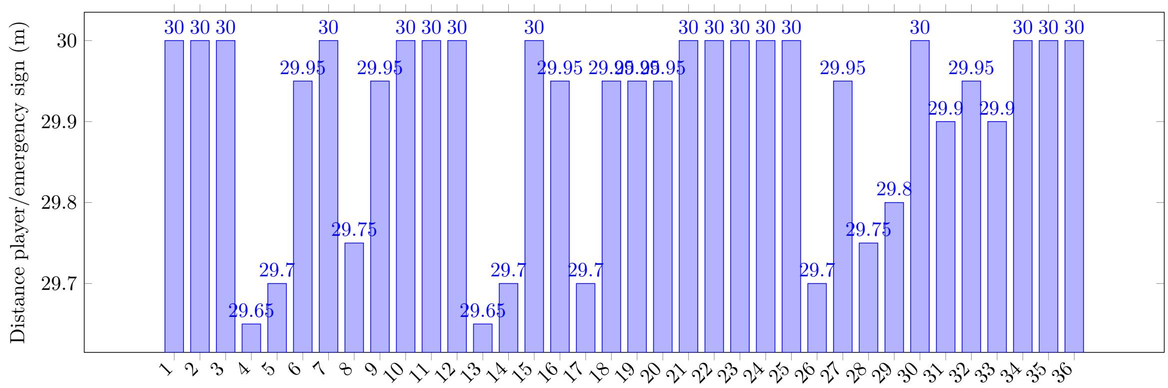



Figura 4.14: Distance (in meters) of the detection of the emergency signal.

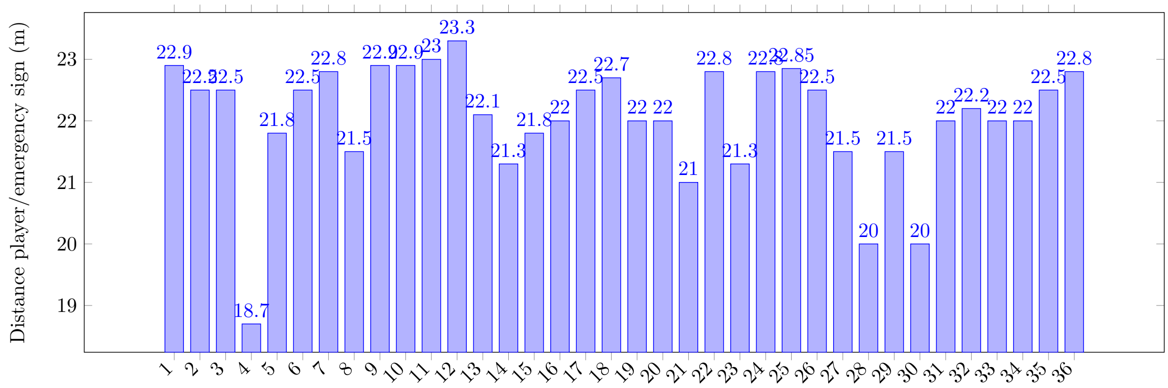
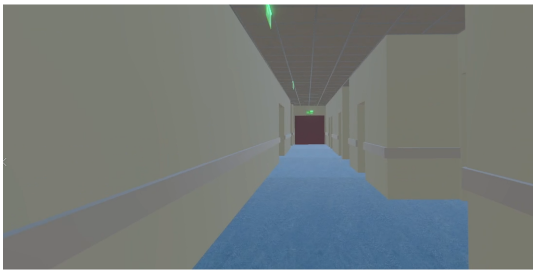



Figura 4.15: Distance (in meters) of the confidence of the emergency signal.

(a) View of signal detection.



(b) view of signal confidence.

Figura 4.16: Views of signal detection and confidence (corridor A).

#### Corridor B

Figure 4.17 shows most users identified the presence of the signal at 30 m. Again, the signal was well detected by the testers.
A divergence margin of 40 cm is found. Figure 4.18 reports that the "Confidence" of the emergency signal is at an average of 22 m from it with a divergence of 4.45 m. More, testers made no errors in the interpretation of the signal indication.

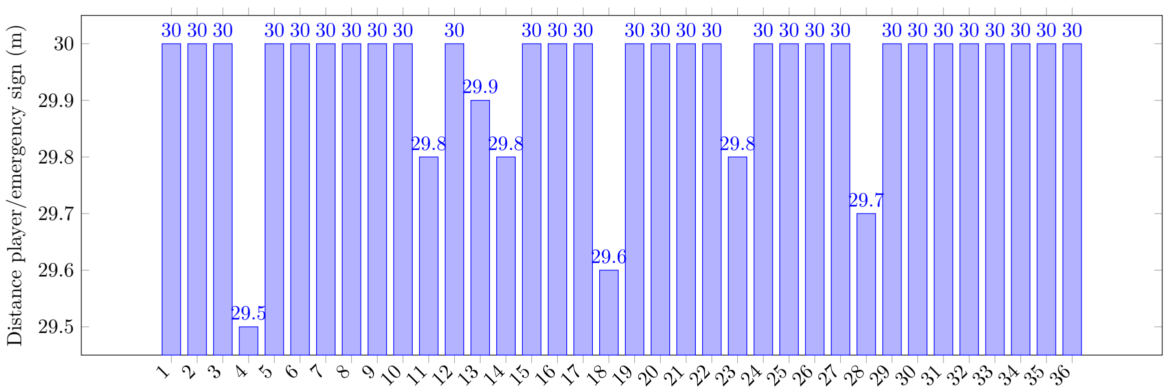



Figura 4.17: Distance (in meters) of the detection of the emergency signal.

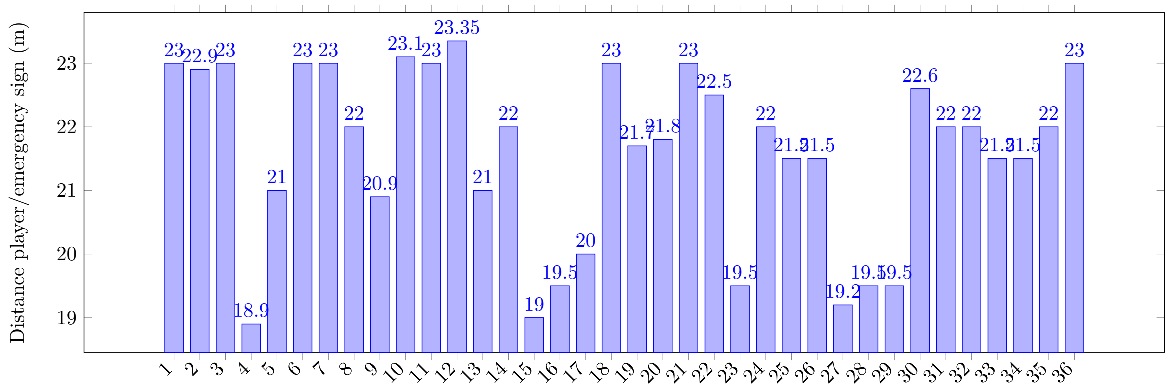
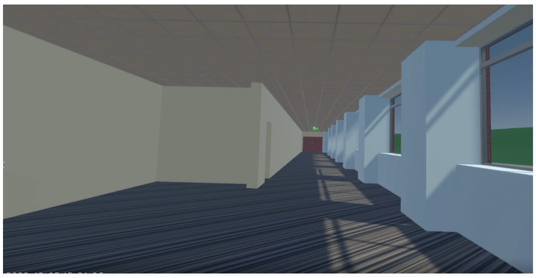
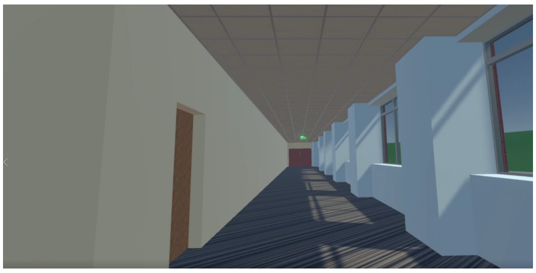



Figura 4.18: Distance (in meters) of the confidence of the emergency signal.



(a) View of signal detection.



(b) view of signal confidence.

Figura 4.19: Views of signal detection and confidence (corridor B).

### Corridor C

Also in this case the position of the signal occurred at an average of 30 m, with a divergence of 1.80 m, see Figure 4.20 Regarding the confidence of the signal, the average detectable reported in Figure 4.21 is about 22 m with a divergence of 4.90 m. In this case, no tester made a mistake in citing the type of indication.

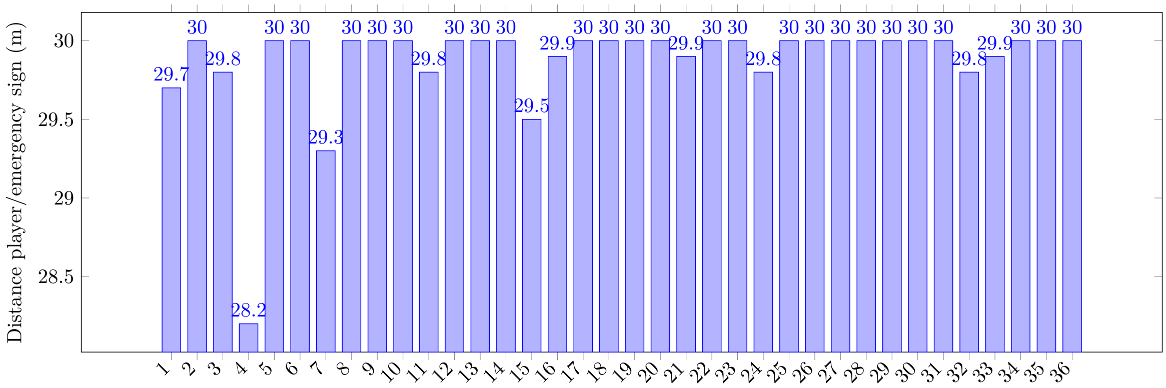



Figura 4.20: Distance (in meters) of the detection of the emergency signal.

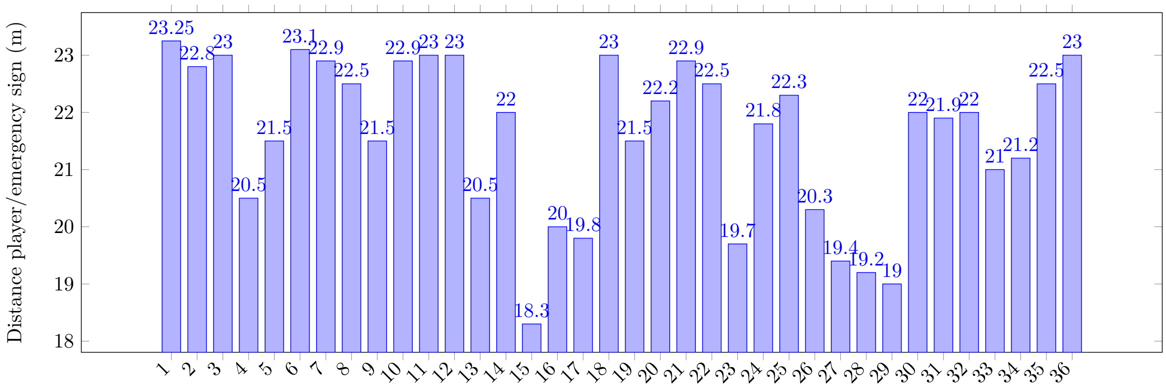
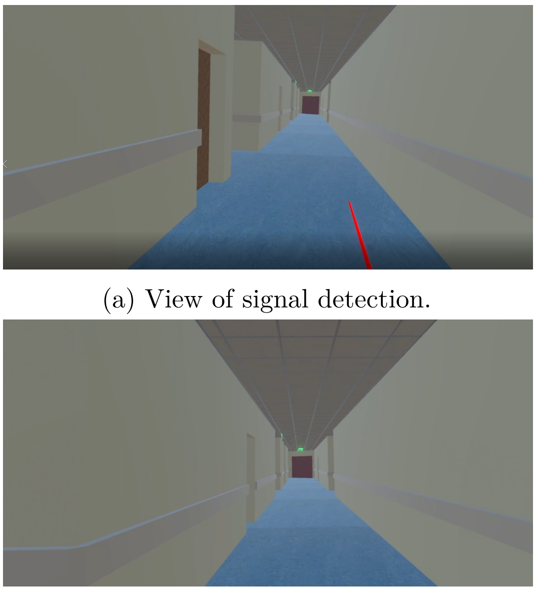



Figura 4.21: Distance (in meters) of the confidence of the emergency signal.



(a) View of signal detection.

(b) view of signal confidence.

Figura 4.22: Views of signal detection and confidence (corridor C).

Below (Figure 4.23) is a graphical representation, which summarizes the different points where the players first detected the signal (black dots) and subsequently recognized the indication of the static emergency system(red dots). In addition, the light blue line represents the minimum distance (18m) for 5cm high emergency signage, as reported in the paper [1] the black lines represent for each corridor the average when the players identified the signal, and in red when the tester recognized the indication given by the signal. The green line represents the minimum distance for which the emergency symbol can be recognized according to the formula used by the paper [1].

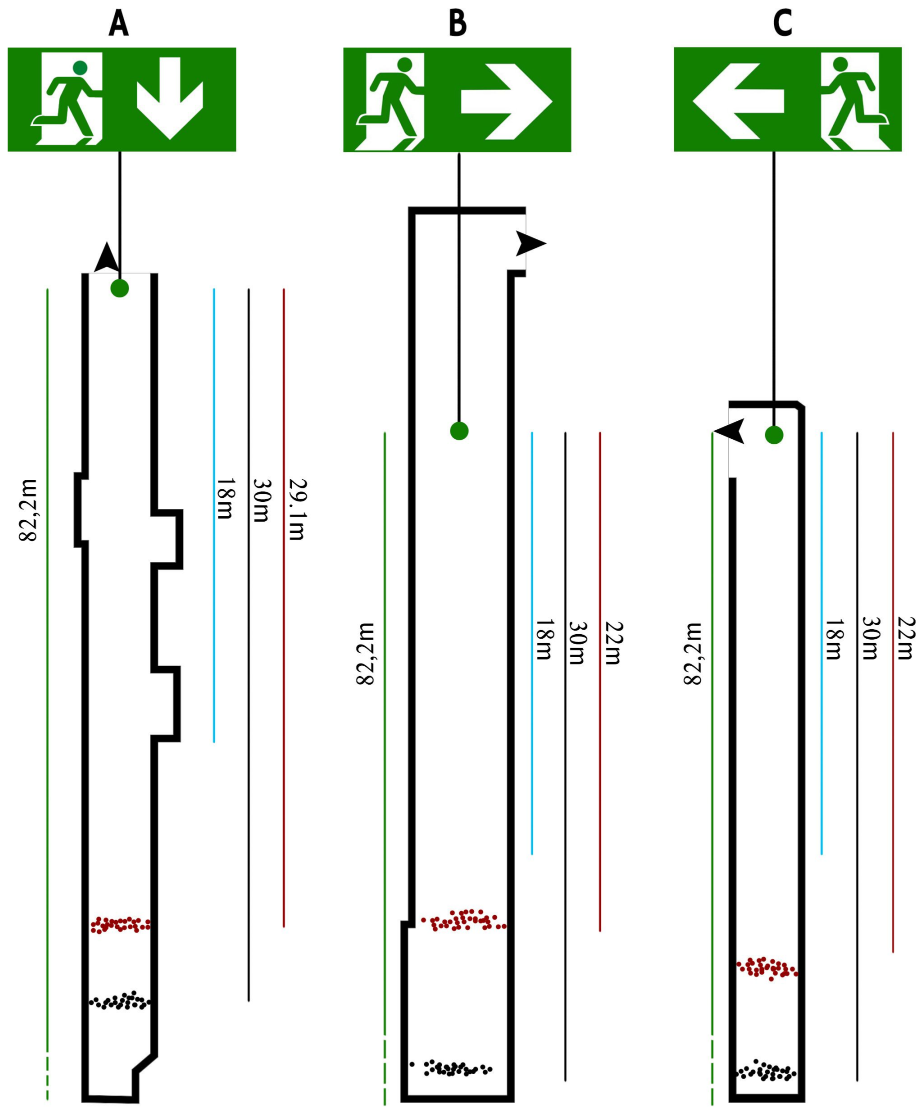



Figura 4.23: Representation of measurements regarding identification (dots in black) and signal confidence (dots in red). Blue line: minimum distance according to [1] for 5cm high emerg.sign; Black line: signal detection average distance; Red line: signal detection average distance; Green line: minimum signal detection distance, sized in the scene (0,5 m x0,23 m), according to [1].

## Discussion

Figure 4.24 shows that most testers detected the presence of the distress signal at a distance between 30 meters (maximum) and a minimum of 29.30 meters. As a result, the final values appear to be consistent and especially suitable for compliance with the paper [1].

Signal confidence, on the other hand, occurred at an average distance of about 22 m (see Figure 4.24), with values ranging between 24 m (maximum) and a minimum of 18.70 m.

Again, the test and especially the correct sizing of the static emergency signage is considered valid, again considering the paper mentioned above.

Attention is again drawn to the fact that the test took place in a virtual built environment rendered at a maximum of 72 FPS through the use of a Head-Mounted Display (Oculus Quest 1).

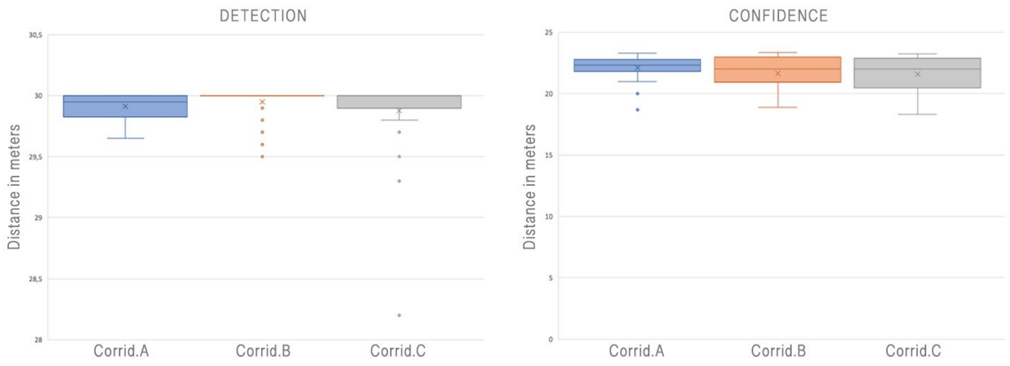



Figura 4.24: Measurement of the recognition and confidence testers have for each corridor

## 4.2 Methodology

110 volunteers participated in the test, who were initially required to provide personal information before the test, which was followed by a survey to ascertain the experience's pros and cons.
The subject is covered in greater detail in Section x.
The built environment considered, the people involved, and the risk applied are important aspects that can greatly influence the behavior of the user involved in the test and sometimes elicit errors in the evacuation process.
We compare the different emergency systems used (standard vs. integrated) and how the users behaved concerning the role they played in the evacuation test for each scenario. In this case study, we compare this issue by implementing the methodology of sensory affordance. A collection of activities that an object asks you to execute on it is what is meant by the term "affordance", which is an attempt to suggest a method in visual perception. Action potentials known as affordances are those brought on by the simple act of seeing an object [84].
Through functional affordance, one assesses whether the user responded to the stimuli induced by the applied system in a manner consistent with how one would expect. In other words, it assesses whether the user performed well and was able to get to safety. This factor can be picked up by the Health-bar system that was implemented in the experiment. A bar capable of signaling whether the user got too close to the hazard putting his life in danger. Sensory affordance is used to define whether the user has seen the hazard signal. This can be identified by analysis of how many times the emergency symbol or NPC or hazard has appeared in his field of view. Finally, with cognitive affordance, one assesses whether the user correctly carried out the instructions received from the static and or vocal signage. A further aspect taken into consideration is the collection of data from the drill (time taken, and the area occupied) for each scenario to highlight the user's performance during the evacuation.

Again from the collected data, the qualitative aspect of performance can be obtained by considering the ratio: optimal path (not said to be the shortest path) and actual path taken by the user. If the result is close to unity then the user has performed satisfactorily, otherwise, poor performance is considered if the result is close to zero.

For clarity, the affordance methodology comes to the aid of capturing adherences when a direct comparison cannot be implemented in the face of different dependent hazard systems. Indeed, taking into consideration occupied areas, distance traveled, and escape time with different hazard scenarios would cause misleading results. Different combinations with the variables considered are defined below.

### 4.2.1 Comparison of standard vs. integrated emergency system

1. We compare by affordance the applied warning systems (standard vs integrated). See Figure 4.25.There is a homogeneous distribution in terms of interpreted roles in both single-hazard systems. The type of hazard in place is neglected. This implies that occupied area, distance traveled, and escape time are not studied.

   In fact, from this comparison of warning systems, the integrated system is expected to be more efficient than the standard one.

2. We consider by affordance the applied warning systems (standard vs. integrated) for each single-hazard system independently, see Figures 4.26 and 4.27. There is a homogeneous distribution in terms of the roles interpreted by the users. We then compare the performance that occupants perform in the fire and flood scenario to standard alarm system vs. integrated alarm system.

   From this comparison of alarm systems, it is expected that the integrated system is more efficient than the standard one.

3. By ensuring the independence of the single-hazard scenarios (fire and water) and the homogeneity of the roles played by the users, the occupied area and escape time can be studied to see whether better performance is achieved with integrated warning systems.

   Again, the integrated system is expected to be more efficient than the standard

| FLOODING | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| INTEGRATED | x | x | x | x |

| FIRE | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| INTEGRATED | x | x | x | x |

| FLOODING+FIRE | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| INTEGRATED | x | x | x | x |

Figura 4.25: Emergency standard system vs integrated system.

| FLOODING | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| STANDARD | x | x | x | x |
| INTEGRATED | x | x | x | x |

Figura 4.26: Comparison standard vs integrated emergency system according to flooding scenario.

| FIRE | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| STANDARD | x | x | x | x |
| INTEGRATED | x | x | x | x |

Figura 4.27: Comparison standard vs integrated emergency system according to fire scenario.

one.

4. Different integrated emergency systems are compared to assess which one is the most engaging, disregarding the type of hazard. To achieve this, the performance of the player carried out in the exercise is evaluated by affordance study (functional, sensory, and cognitive) (see Figures 4.28).

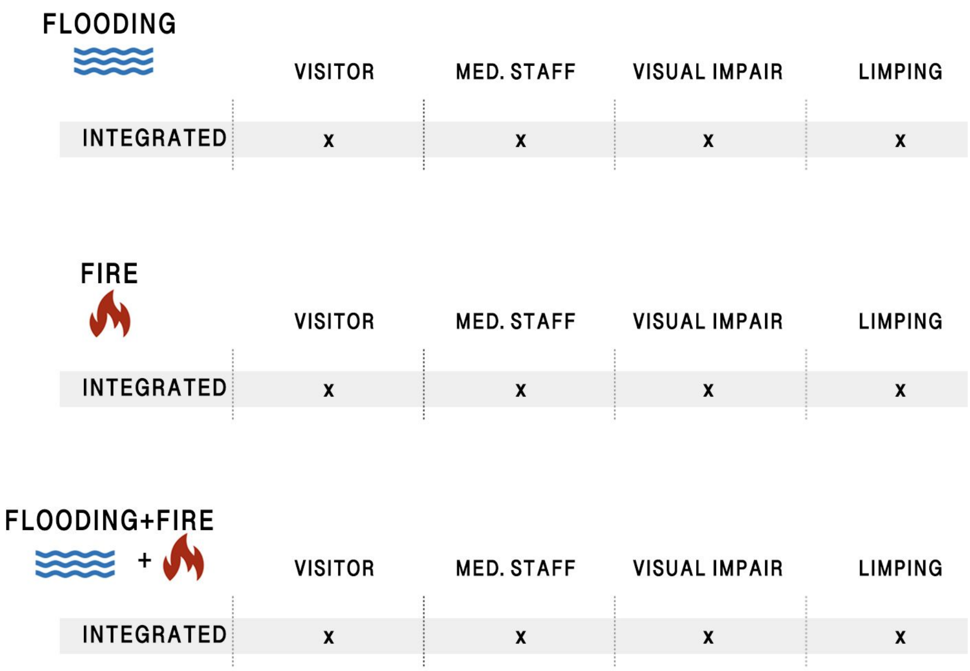



Figura 4.28: Comparison of the integrated emergency systems.

These comparisons can evaluate real solutions for the decrease of risk to people, and the identification of critical points in the emergency process paying particular attention to the warning systems and signage used.
From these considered variables, data are extracted that will allow the two systems ( standard vs. updated) to be compared with each other and thus formalize the effectiveness of the system addressed.
The data are not affected by the role the user plays because they are evenly distributed in each system considered. On the contrary, the different role allows for a

complete and truthful picture consistent with the hospital space.

### 4.2.2 Comparison of different roles

1. The affordance of different roles is studied by ensuring independence between each other. Hazard is neglected. Adherence to the stimulating elements (signage/NPCs/Hazard) is evaluated.

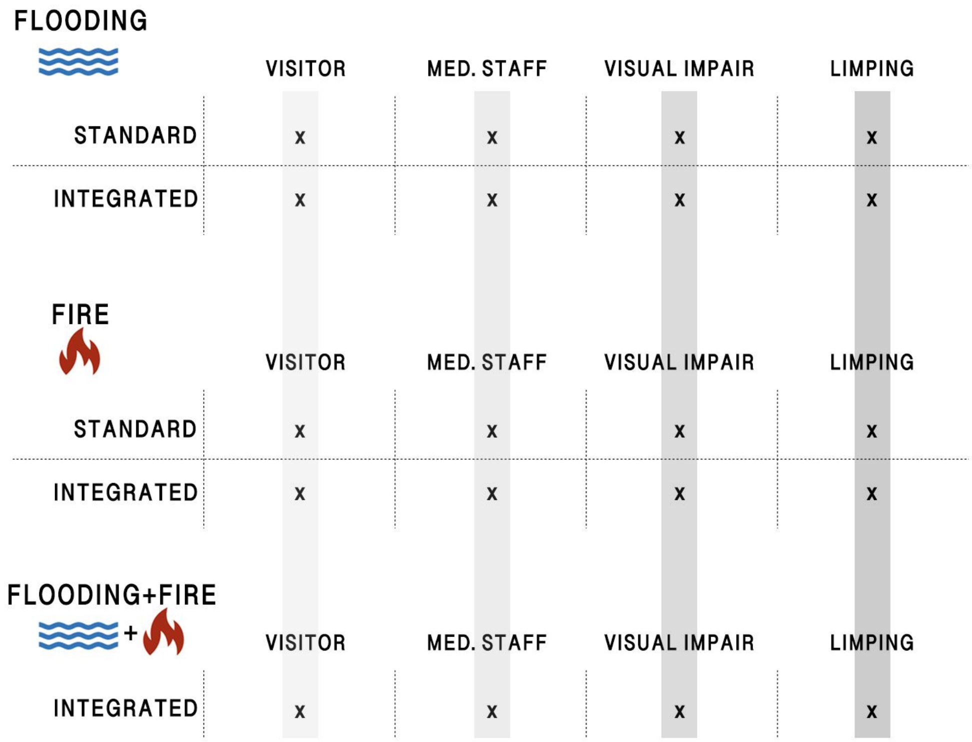



Figura 4.29: Affordance study per single roles.

2. Comparison through affordance is studied between people with good physical conditions (medical staff and visitors) and people with physical disabilities (visual impairments and motor impairments). Hazards and knowledge of the environment are neglected. See Figure 4.30.
   It is believed that people with good physical condition may have a better chance of reaching a safe spot than people with disabilities.

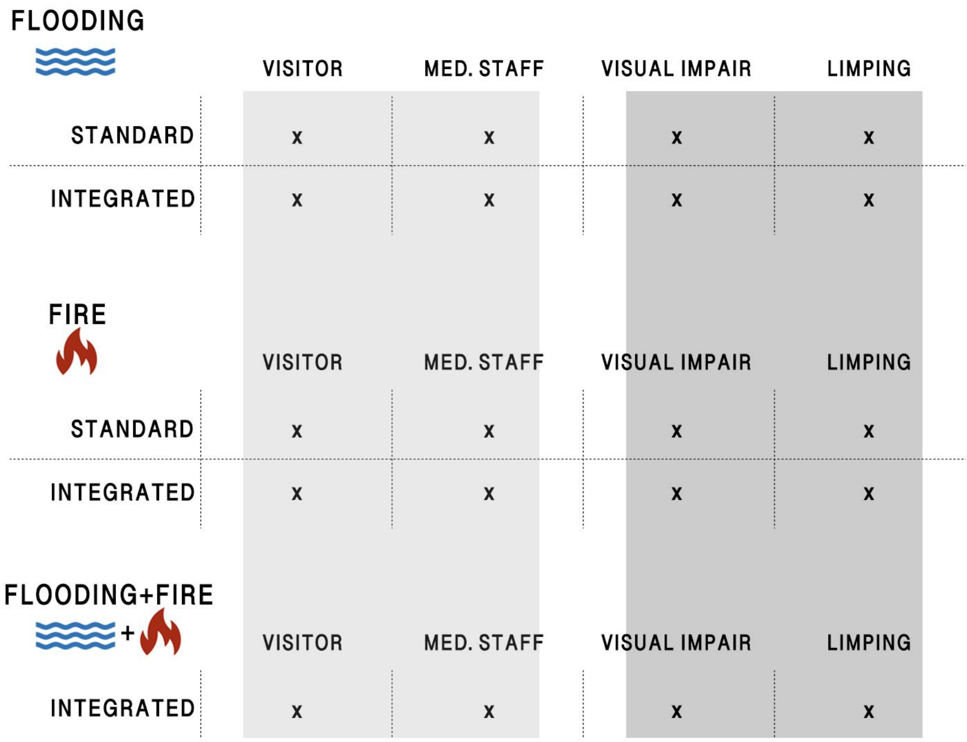



Figura 4.30: Affordance of good health condition vs. bad health condition.

3. More specifically, the affordance of roles having good physical characteristics (visitors vs. medical staff) is assessed. The hazard in place is neglected. The staff is expected to perform better than the visitors because they have more knowledge of the environment.

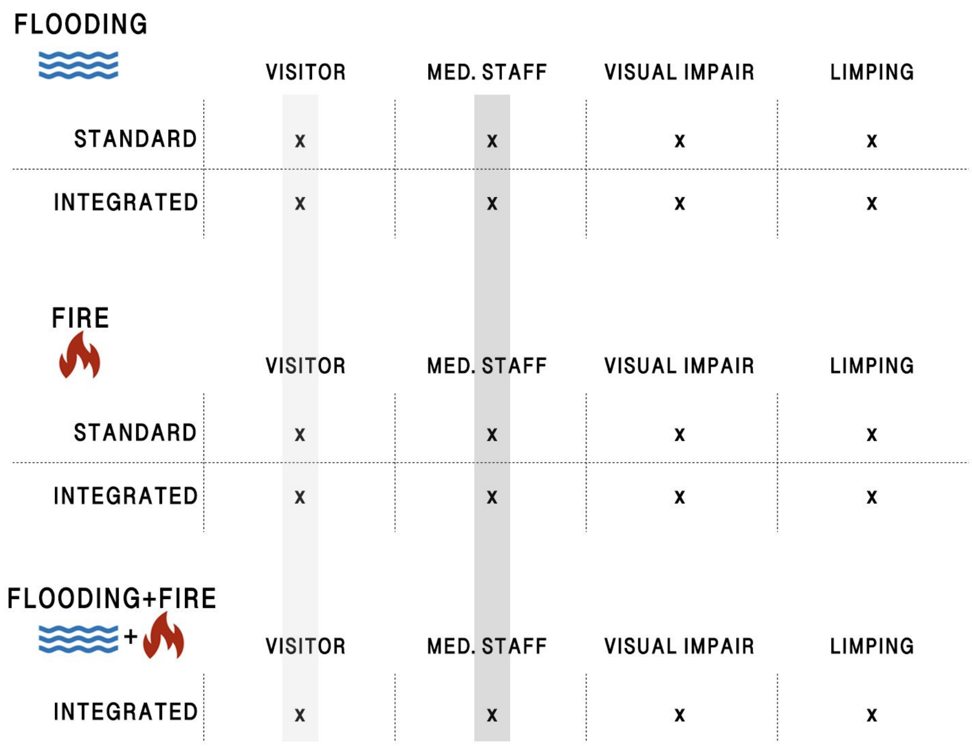



Figura 4.31: Affordance of visitor vs. medical staff categories.

4. The affordance of roles having physical impairments (visual impairments/motor impairments) is evaluated. The hazard in place is neglected.
   Given the partial knowledge of the environment by both compared roles, it is explored which category enjoys greater ease in getting to safety.

**FLOODING**

| | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| STANDARD | x | x | x | x |
| INTEGRATED | x | x | x | x |

**FIRE**

| | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| STANDARD | x | x | x | x |
| INTEGRATED | x | x | x | x |

**FLOODING+FIRE**

| | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| INTEGRATED | x | x | x | x |

Figura 4.32: Affordance of visual impairment vs. limping categories.

These comparisons can give a clear indication of the reaction of the characters depending on their role in the built environment. In addition, one can point out which categories in the simulator are found to be most in need of help and for this reason be able to make structural/functional improvements to improve evacuation for people with disabilities.
Finally, a survey is written to be completed at the end of the test, with the task of collecting highlights, emotions felt, and any gaps noted in the tests. This feedback is useful for improving the simulator made.

# Capitolo 5

# Simulator implementation

This chapter describes all the work processes that have been carried out, chronologically, for the implementation of the simulator described above. The information on the type of computer used to build the virtual environment is reported, therefore the description of the hospital, and the acquisition of the planimetric material.
Then we describe the softwares used for the restitution of the plants in Autocad vector form and the realization of the 3D model, using Rhinoceros.
Finally, the Unity 3D program is described, which made it possible to add effects, textures, and animations within the built environment.

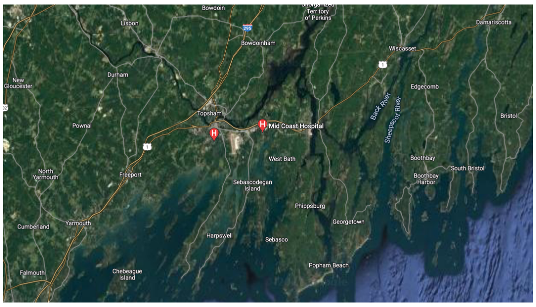
## 5.1 Computer configuration

A computer with the following characteristics was used to build the simulator:
-OS Name: Microsoft Windows 10 Pro
-Version: 10.0.19044 Build 19044
-System Type: x64-based PC
-Processor: Intel(R) Core(TM) i9-10900K CPU @ 3.70GHz, 3696 Mhz, 10 Core(s), 20 Logical Processor(s)
-BIOS Version/Date: American Megatrends Inc. 1410, 04/09/2020
-SMBIOS Version: 3.2
-BIOS Mode: UEFI
-Boot Device: Device HarddiskVolume1
-Installed Physical Memory (RAM): 32.0 GB

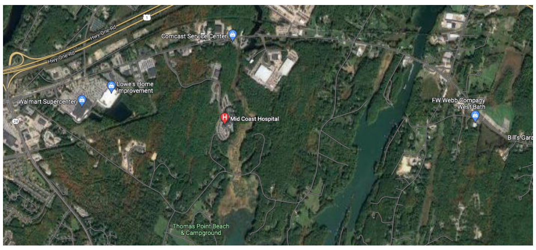
-Graphic card: NVIDIA GeForce RTX 3090

## 5.2 Hospital overview

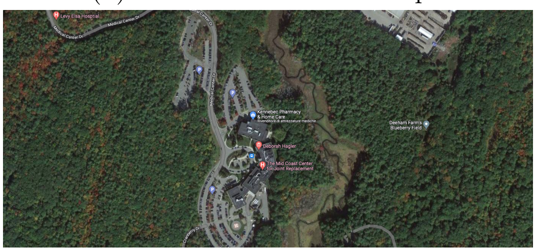
First, the Mid Coast Hospital in Maine, USA, was identified as the most suitable for our case study given its complexity in the plan and its particular geographical location. The area under consideration can be considered to be at high risk of flooding because it is a marshy bay area. In addition, the hospital is close to a dynamic catchment area, that is, the area close to the structure could flood with typhoons rising northward from the Atlantic Ocean. In addition, the elevation difference between the riverbed and the hospital turns out to be only 5 meters. The building, therefore, presents suitable conditions to be able to deal with the flooding issue. Figures 1 and 2.




(a) Overview of the geological conformation



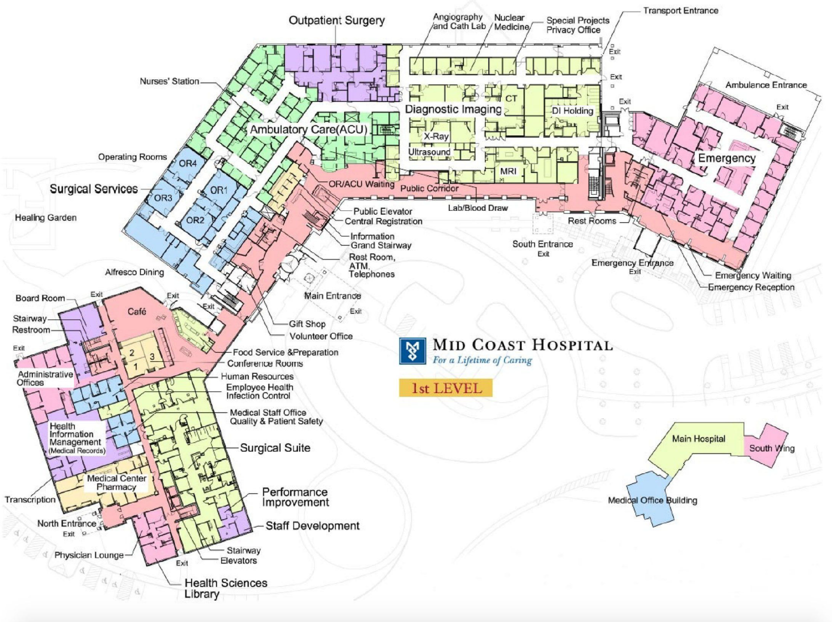

(b) Overview of the landscape



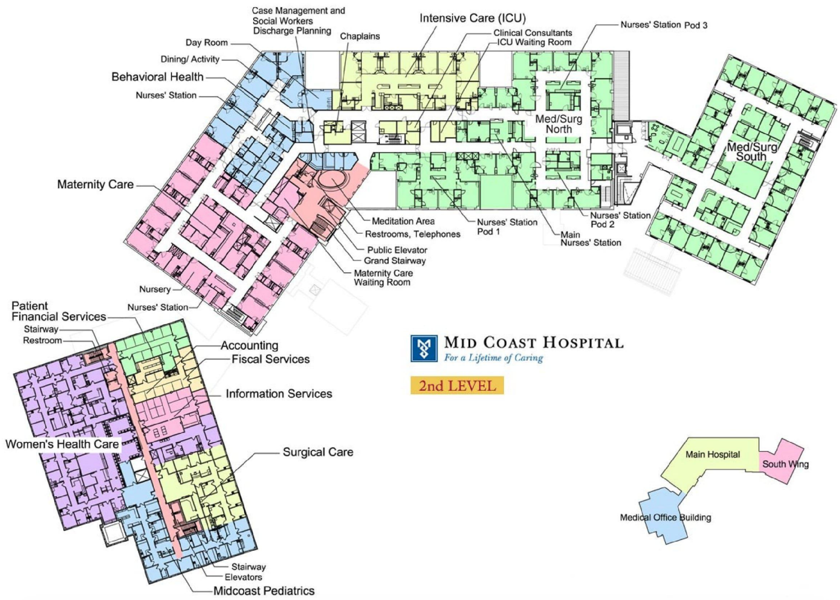

(c) Hospital's and river's overview

Figura 5.1: Visualization of the landscape context of the hospital

In detail, the hospital became operational in 1991 and has a capacity of 93 beds. From a plan-volumetric point of view, the facility consists of three main structural bodies of two floors each, divided into departments by type of function (see Figures 3 and 4).




(a) Hospital Ground Floor




(b) Hospital First Floor

Figura 5.2: Hospital's plans

I: an administrative part;

II: the larger body for the treatment of patients;

III: the area dedicated to the emergency room.

To simplify the structure, only the hospital body that treats the admission of patients was considered, i.e., the main structure and the one that has a more complex plan morphology in terms of the intersection of corridors, and services for patients and visitors (e.g., there is space dedicated to the public such as the reception, and the outpatient area where patients are admitted).

## 5.3 Autocad restitution

The .jpeg pictures on the official hospital website https://www.midcoasthealth.com/findus/floorplans.aspx presented very low quality and consequently, the reproduction of such plans on Autocad was particularly difficult. For this reason, before vector reproduction of the floor plans on Autocad, a thorough study was made of the peculiar architectural aspects of a hospital facility by questioning the current regulations in the United States, namely the NFPA. Specifically, architectural notions were taken from NFPA 101 (Life Safety Code), 2021 edition, Chapter 19: Existing Health Care Occupancies.
From reading this chapter, floor plans were reproduced with sizing that complied with current regulations, and similarities were found with the initial pictures.
Important was sizing the patient treatment area corridors: between 5 and 8 ft. Outside the treatment area, the corridors could adopt a width of 44 inches.
The width of stairways had to be greater than 56 inches in the case of at least 2,000 occupants. The width of exits had to be at least 8 ft. The adopted net height in the two floors, again according to regulations, had to be at least 3.2 m. In the project, it was decided to build the two floors respecting a gross height of 3.5 m each. We converted the measurements with the international metric scale always making use of the NFPA 101 standard.
Once all the data were obtained, plans of the two floors and the roof were drawn up

in 2D using Autocad software, version 2016. During the restitution of the plans in Autocad, the idea of making the building walkable was considered.

The total gross area of the building turns out to be 15000 square meters considering the ground floor, second floor, and roof. The area for public use turns out to be 1805 sq.m., while the remaining part is dedicated to the medical area.

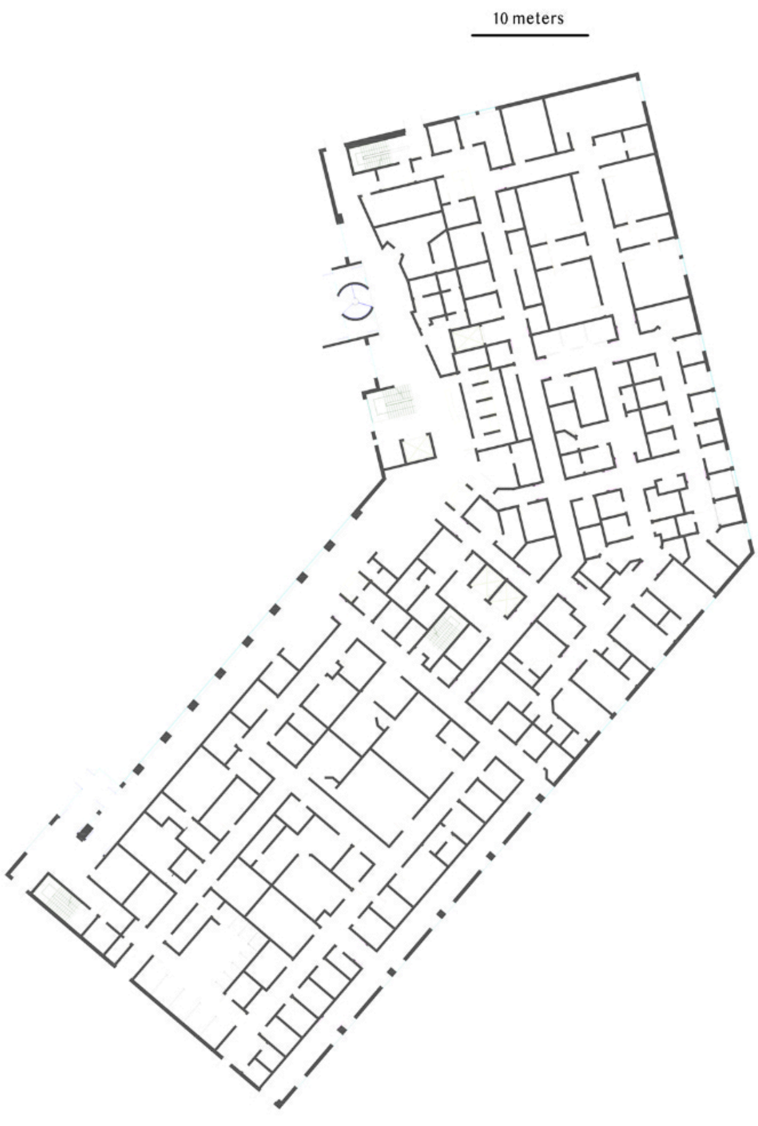



Figura 5.3: Hospital Ground floor made by Autocad.


Figura 5.4: Hospital First floor made by Autocad.

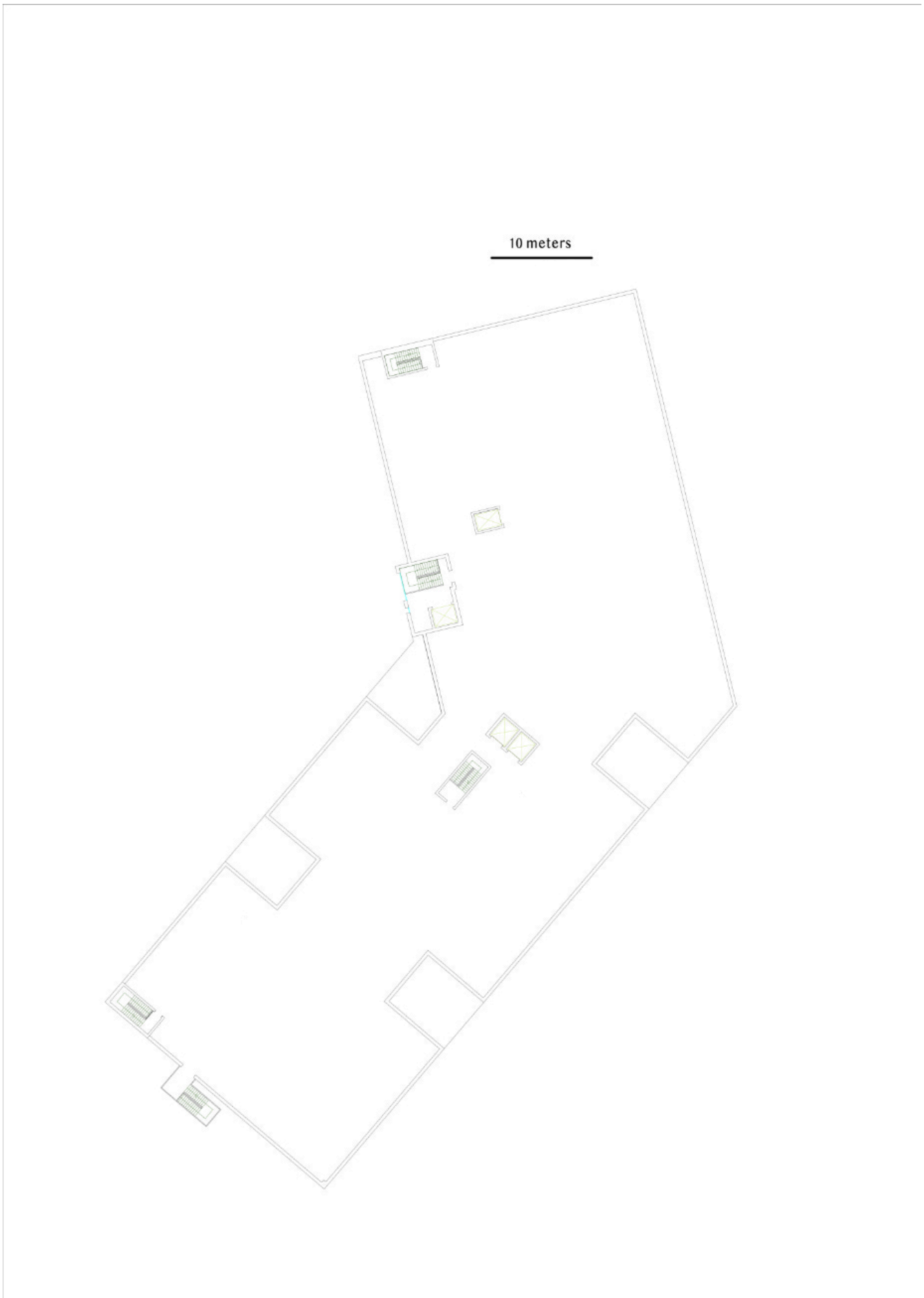



Figura 5.5: Hospital Rooftop made by Autocad.

## 5.4 Rhinoceros 3D modeling

With the plans returned in Autocad, .dwg files were imported into Rhinoceros, version 5.4 (5E407).

The plans were extruded and a 3D model was obtained, respecting the 3.5 meters per floor.

The facades were constructed taking into consideration the exterior photos of the hospital.

This allowed for semi-real restitution of the hospital in 3D. In this case, stairs were made of tread: 30 cm and a height of 14.5 cm per step.

Windows were placed at a height from the ground of 1.2 m and doors between 2.1 m and 2.4 m.

All vertical connections (elevators and stairs) were modeled with the purpose of reaching the roof.

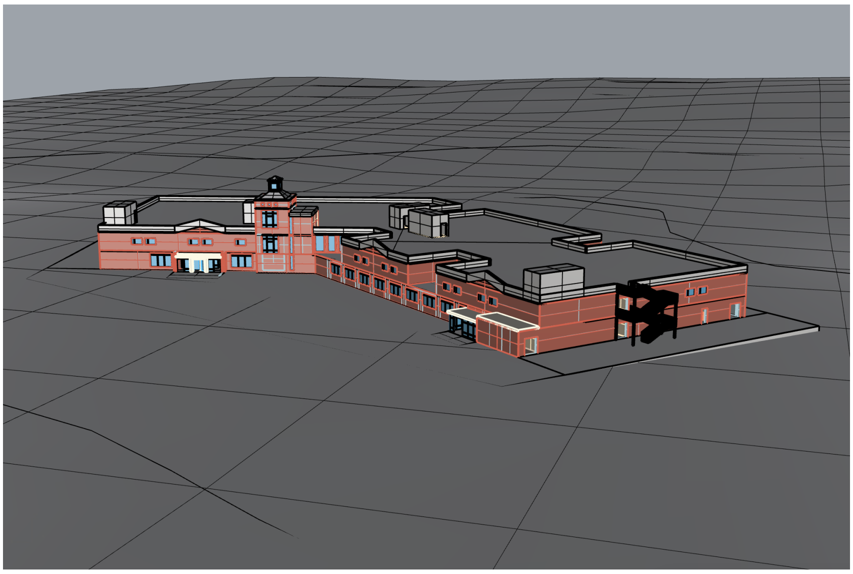


Figura 5.6: Hospital 3D Model.

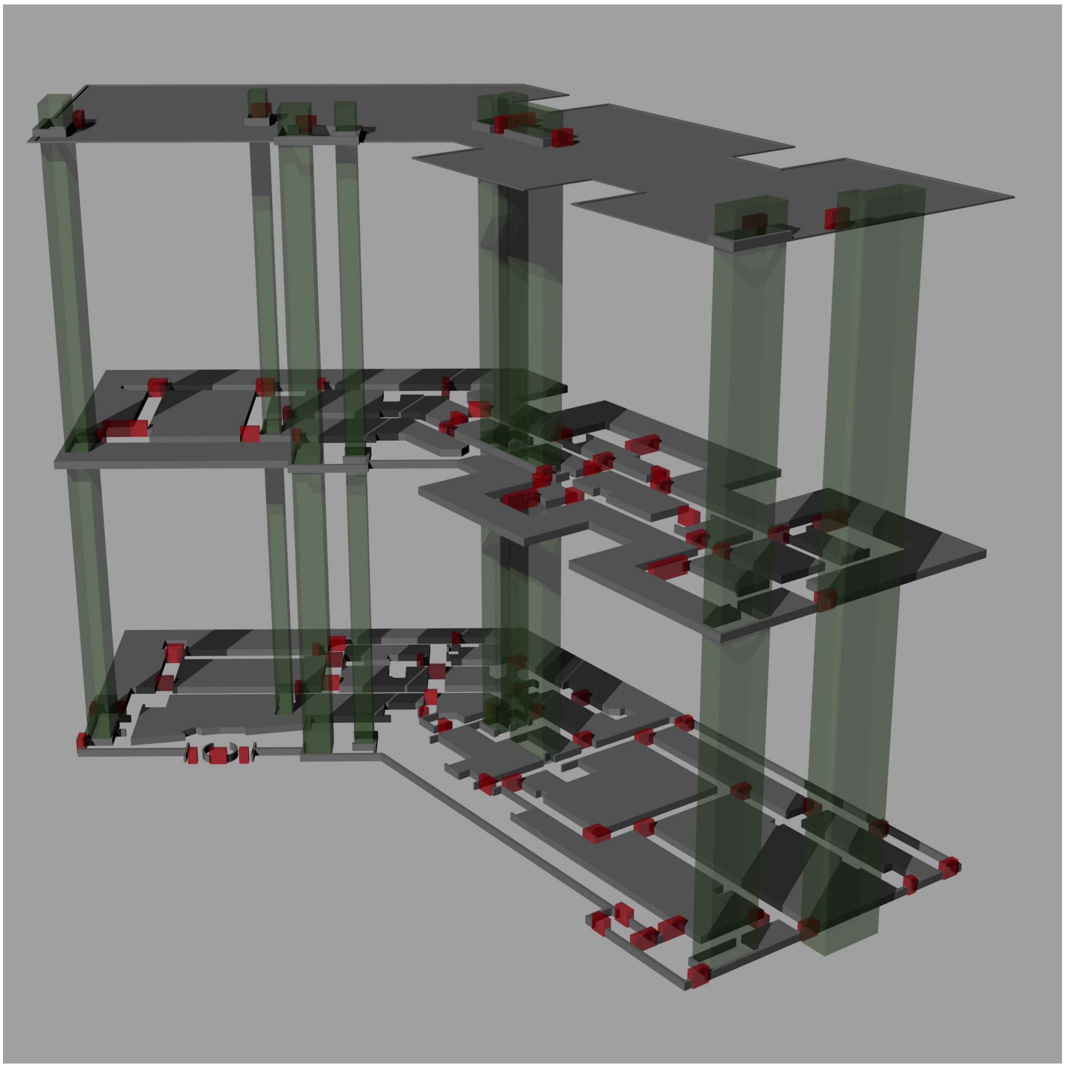


Figura 5.7: Hospital "*sandwich*" structure. Red boxes are the checkpoints (described below)

## 5.5 Unity 3D modeling

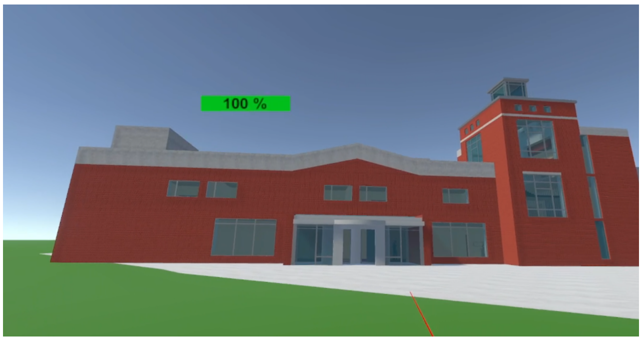
From Rhinoceros software, the file was exported to fxb. and imported accordingly into Unity 3D version 2020.3.17f. and the Universal Render Pipeline (URP) was used. Universal Render Pipeline (URP) is a pre-built, writable rendering pipeline built by Unity. URP provides easy-to-use workflows for artists to quickly and easily create optimized graphics on a wide range of platforms, from mobile devices to consoles and high-end PCs.
The XR Interaction Management package for immersive reality was first downloaded. That is, allowing the player to wear the device (Oculus quest 1) and be catapulted into the constructed virtual environment.

### 5.5.1 Environment integrations

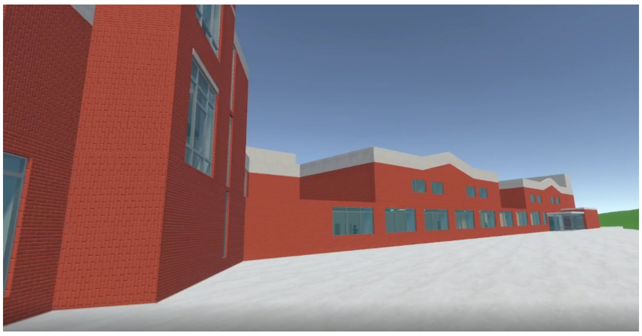
3DCADMAPPER was used to create the geological context surrounding the hospital. The identification of the area of interest made it possible to 3D print the morphological conformation of the outdoor environment. By systematically searching the Internet for indoor and outdoor photos of the hospital, it was possible to include textures that could provide greater verisimilitude to the virtual environment.
As for the doors, two categories were first identified. The doors of the inpatient rooms dedicated to patients were considered to be non-openable. The doors dividing the different departments and the exit doors, could, on the other hand, be opened. To make the doors openable, an animation was added, and the opening of the doors occurs when the player interacts with a triggerbox located near the doors.
Within the simulator, the two categories of doors have been colored differently: the patient rooms are brown, while the doors dividing the treatment areas, and the corridors, have been given a purplish coloring.
The exit doors, especially the emergency doors are gray in color, except for those located near the main entrance which were considered glass.
Inherent to the emergency doors are identified 9 elements arranged on the ground floor as: 2 north side, 0 east side, 3 west side, 4 south side. 1 emergency door is located on the first floor and connected directly to the external stairs.

The main entrance is equipped with three revolving glass doors to which, of course, an animation was added that is always activated through the interaction of the player with the triggerbox placed in relevance to the entrance.
The implementation of the four elevators in the hospital of which 1 is public (placed near the reception area), and 3 dedicated to the medical area was quite a challenge. We considered the elevators capable of being used in all scenarios (flood, fire, and flood+fire) but limited their use to the ground floor only with the possibility of reaching the roof directly, i.e., without allowing the player to descend or take the vehicle to the first floor.
Elevator animation involved employing a trigger box placed on the ground floor as the elevator call signal. The elevator wait was set at 6 seconds and 2 seconds to allow the elevator doors to open. An additional 2 seconds to close again and 6 seconds to reach the roof. That is, an average elevator speed of 1.16 m/s was calculated.
The stairs were constructed with a tread of 30 cm and a rise of 14.5 cm and equipped with a width consistent with that cited by NFPA 101.
The building has 4 interior staircases, including one public staircase located near the reception area and 3 dedicated to the medical area. In simplifying the environment, it was decided to add an exterior staircase, made of metal to allow escape in case of emergency.

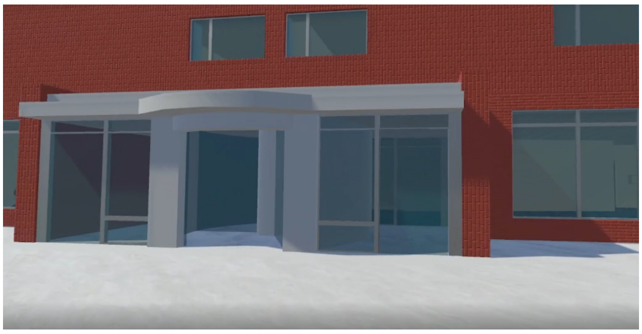
(a) External hospital view.




(b) External view of the hospital (by ground floor).



(c) External view of the hospital (by ground floor).



(d) Hospital main entrance.

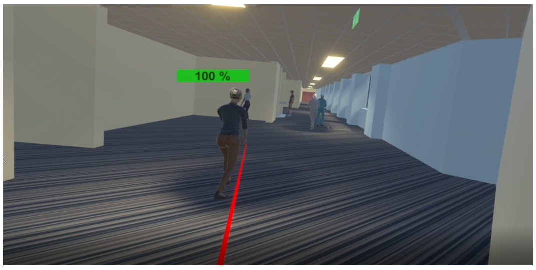
Figura 5.8: Views of the Mid Coast Hospital (in Unity3D).

### 5.5.2 Checkpoints adoption

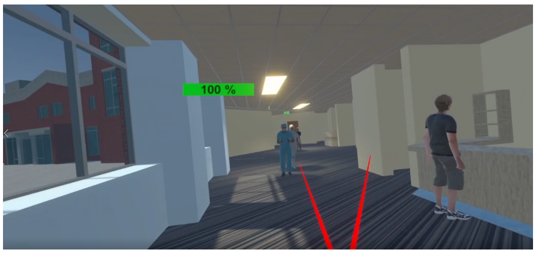
Triggerboxes have been placed at the doors (purple) that divide the patient treatment areas and at the intersections between the corridors.
This arrangement allows, through an attached script, to describe the path made by the player during the test.

### 5.5.3 Standard lighting

Building standard lighting was achieved through the use of an emissive effect placed at the ceiling light fixture and a "spotlight" light source. The lighting complies with the lighting standard cited in NFPA 101 for hospital environments.
A "Lighting on off" script capable of turning off the standard lighting the moment the alarm begins to sound was added to the standard lighting.




(a) View of the reception without hazard.




(b) View of the reception standard lighting.


(c) View of the standard lighting.

Figura 5.9: Views of the quiet environment (with no hazard on).

### 5.5.4 NPCs implementation

The hospital is a particularly crowded environment and therefore characters representing different categories (visitors, medical staff, and patients) have been implemented using NPCs (Non-Player Characters). The Mixamo program was used to create the NPCs with different roles and with different animations.

The variety of Non-player Characters employed in the scene made the environment a lively place.

Some occupants have been implemented in the environment able to walk, or simply stop near the reception, waiting for someone or talking on the phone.

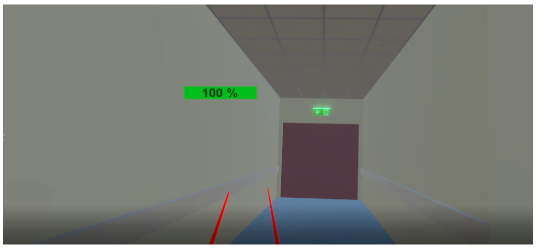
Others were added instead in the alarm situation. Their behavior involves running towards the main exits or climbing stairs and consequently reaching the roof.

The player, therefore, finds himself in the situation of being able to be involved in the movements of NPCs, probably also making important mistakes in the decision-making

process.
The Nav Mesh Agent option was used to guarantee NPC's movement within the environment. Linked to the Nav Mesh Agent, it was necessary to make the environment "Static- (Navigation option)" and "baked" to allow the movement to take place. In addition, options such as the Capsule Collider, and the Rigid Body have been added to be a three-dimensional body that cannot be crossed and therefore represent an obstacle, sometimes, for the player.

### 5.5.5 Emergency signage

For emergency signs, reference is made for color and sizing to NFPA 170, or in general to ISO 7010 (Graphical symbols-Safety colors and safety signs). We have therefore added the signage with dimensions: 23 cm in height and 50 cm in width. This choice was also made taking into account the testimony of paper [1].
Inherent in the lighting of the signs, however, a script has been added that allows the signs to turn on when the alarm is triggered.
lighting was made possible thanks to Unity's "emissive" option calculated per $candle/cm^2$. Also in this case the intensity complies with the regulatory indications of NFPA 101, chapter 7.9.2.1.
Furthermore, a static light was opted for, and not flash, as it is more accepted by the occupants, as reported in the papers [85, 86].
These characteristics adopted preliminarily were subsequently verified in the hospital scenario through an independent test, carried out before the evacuation tests.




(a) View of the emergency signage hazard on.


(b) View of the emergency signage hazard off.

Figura 5.10: Views of the static emergency signage.

### 5.5.6 Health-bar

The implementation of the Health-bar was made possible by making a Canvas layer to which a script was applied. The Health-bar has the task of verifying that the player has behaved appropriately during the evacuation and especially has not come too close to the hazard.

The Health-bar has been given a green coloring indicating the overall amount of life, and interaction with the hazard decreases this value by showing the red background. In addition, the percentage of life has been added ( from a maximum of 100% to a minimum of 0%, to have a clearer quantitative reading.

The Health-bar is placed at the top left of the player's view through the options "Render Camera" : Main Camera" and "Plane distance: 0.5 m" (i.e., the distance between the Health-bar and the player's view).

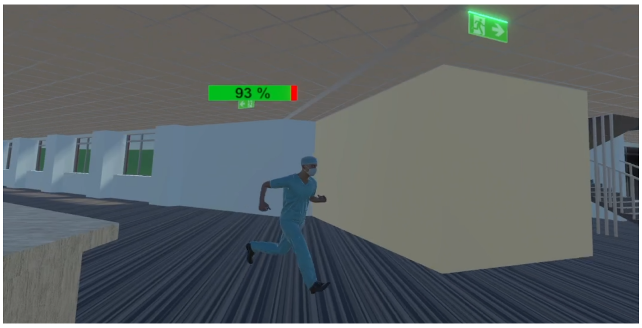



Figura 5.11: Health-bar representation in the scene.

### 5.5.7 Hazard integration

The inclusion of the flood hazard was done by downloading the "Stylized Water" package from Unity Assets.

Once the water rendering options and effects such as Surface Foam, Intersection/Waves the sound effect were applied via Audio Source.

Animation of the water was made possible through the "Animation" option. The speed at which the water invades the built environment is 0.6 m/s.

Considering the speed of the water, a trigger box was placed 0.6 m below the "Water" layer respecting the directions of the paper [87].

The animation of the water ends when it reaches a height of 174 cm above the walking level of the building.

The applied trigger box is responsible for decreasing the life of the player at the time when the interaction between the two occurs.

Hazard Water is triggered manually via script by pressing the letter "W" on the computer keyboard.

Hazard "fire" was realized through the realization of smoke and fire.

The "Particle System" option enabled the realization of smoke. In this regard, the options: looping, start time, start speed, max particles, and spreading shape were handled.

Fire, on the other hand, was produced with the "Visual effect-Fire modeled" option.

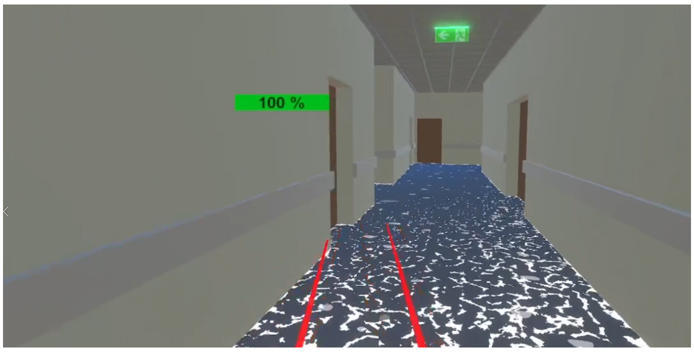
2 fires were placed near the main exits of the reception area.

1 fire was placed in a corridor on the ground floor and another on the floor before near the main stairs of the reception area.

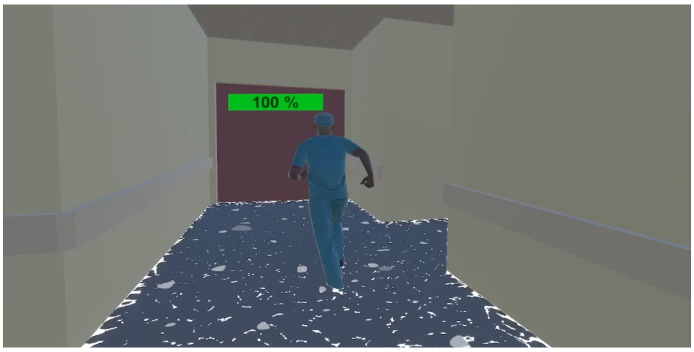
The "Fire" hazard is triggered manually by script by pressing the letter "F" on the computer keyboard.

Finally, several trigger boxes have been made that are activated by script consistently with how the smoke spreads in the environment.

The Water+Fire multi-hazard follows the same components mentioned above. Thus, they are operable with the "W" and "F" keyboard commands (manually).

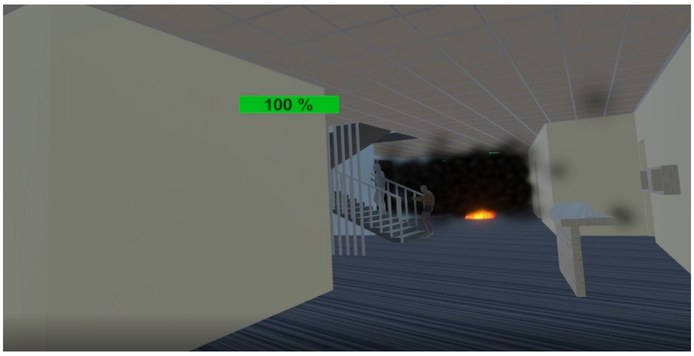



(a) View of the water in the scene.

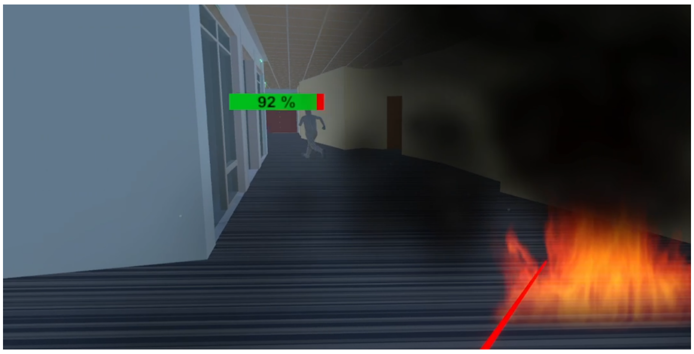



(b) View of the water in the scene.

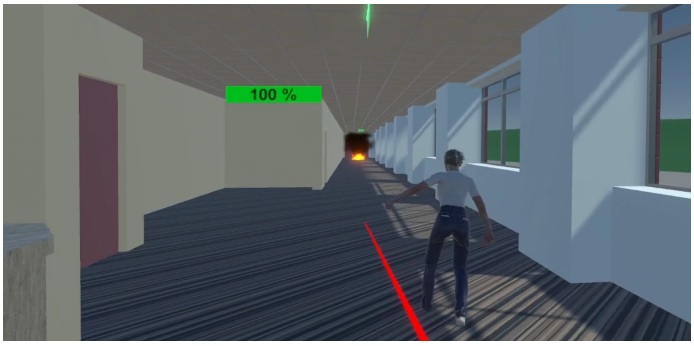
Figura 5.12: Flood scenario renderings.



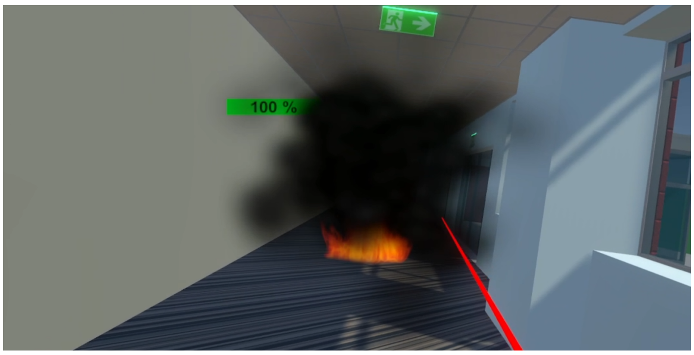

(a) View of the fire next to the main entrance.




(b) View of the fire next to the main entrance.




(c) View of the fire next to the secondary entrance.




(d) View of the fire next to the secondary entrance.

Figura 5.13: Fire scenario renderings.

### 5.5.8 Ending points definition

The formalization of hazards is followed by the determination of the endpoints deemed safe.
For the realization of the "endpoints," the type of hazard in place is considered. In the case of the single hazard "Water" (flooding) it was considered to put trigger boxes at the exits of the stairs, elevators on the roof, and the hill adjacent to the hospital.
In the case of the "Fire" scenario, on the other hand, it was decided to place trigger boxes near the emergency exits and main entrances.
In the multi-hazard "Water+Fire" scenario, a single safe endpoint was defined: the hilltop near the hospital.
Depending on the various scenarios, the corresponding "ending points" are activated.
Each trigger box has a script capable of making the game end once that ending point is reached.

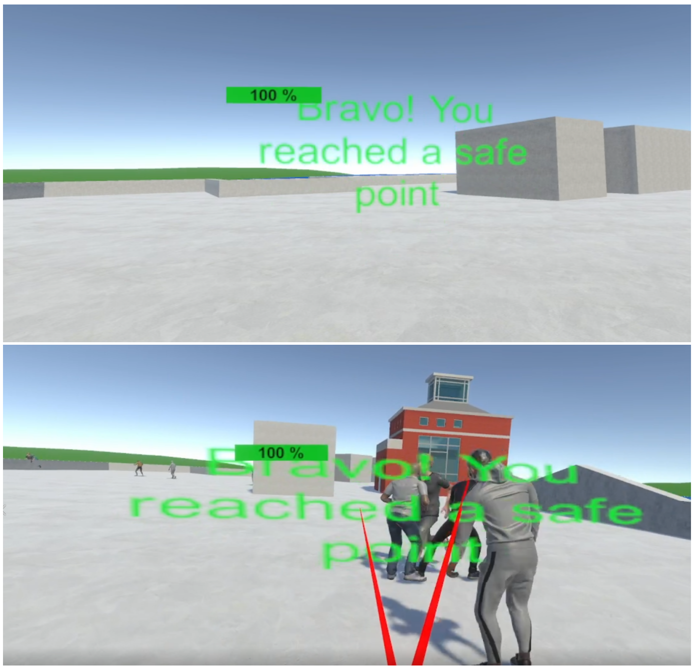



Figura 5.14: Example of reaching a safe point

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### 5.5.9 Standard emergency system

In the standard case, the emergency sound system applied in the hospital involves the implementation of an Audio Source layer of a siren downloaded via Mixkit (https://mixkit.co/free-sound-effects/siren/).
The alarm is activated manually by pressing the "space" key on the keyboard. This is made possible by the script attached to the Audio Source layer.

### 5.5.10 Integrated emergency system

One of the latest implementations that have occurred in the simulator is the implementation of integrated emergency systems. Two systems are highlighted: the voice-sound alarm and dynamic emergency signage.
The voice-sound alarm is characterized by the accompaniment of a female voice to the siren, which detects to the occupants the type of hazard in place and gives instructions on the correct evacuation to be implemented. In the case of the flood hazard, the voice reads:
*"Flash flood on, reach the roof! elevators are available to be used."* In the case of the multi-hazard (flooding and fire) the integrated system reads:
*"evacuate the building, reach a high point!"*
Inherent to the dynamic emergency system applied in the "Fire" scenario, a floor system (within 40 cm of the ground) consistent with NFPA 101 was planned to be used.
This system involves augmented reality technology through the activation of arrows placed 40 cm above the ground that are visible through a device (self-phone, AR glasses).
The arrows turn out to be 50 cm x 50 cm x 10 cm in size placed 4.5m apart (see Figure 5.17.Red dots represent the location of outbreaks on the ground floor.
Their shape complies with the "chevron" type (ISO 7010 standard, thus NFPA 170) and the color adopted complies with current regulations. The arrows have been provided with luminosity as the standard signage, consistent with NFPA 101.
The arrows are activated the moment the alarm is triggered (siren only).
The system used in the simulator assumes a priori the presence of wireless, rerouting

technology to detect the hazard and activate dynamic emergency signaling to evacuate the occupant. This thesis project is not interested in studying the technology employed, but in evaluating the user's decision-making process through the use of augmented reality and thus the validity of this integrated emergency system.
To this, the system makes a dynamic signage map. The user will be shown, via device, the safest route to be able to evacuate the building safely.
Knowing the location of the fires in the environment, a dynamic signage map is realized.
In the test, all arrows arranged in the environment do not appear because they could create disorientation.
The criterion of operating the shortest, as well as the safest, path was adopted depending on the last Checkpoint the player passed through before the alarm went off.


Figura 5.15: Integrated emergency system (arrows).

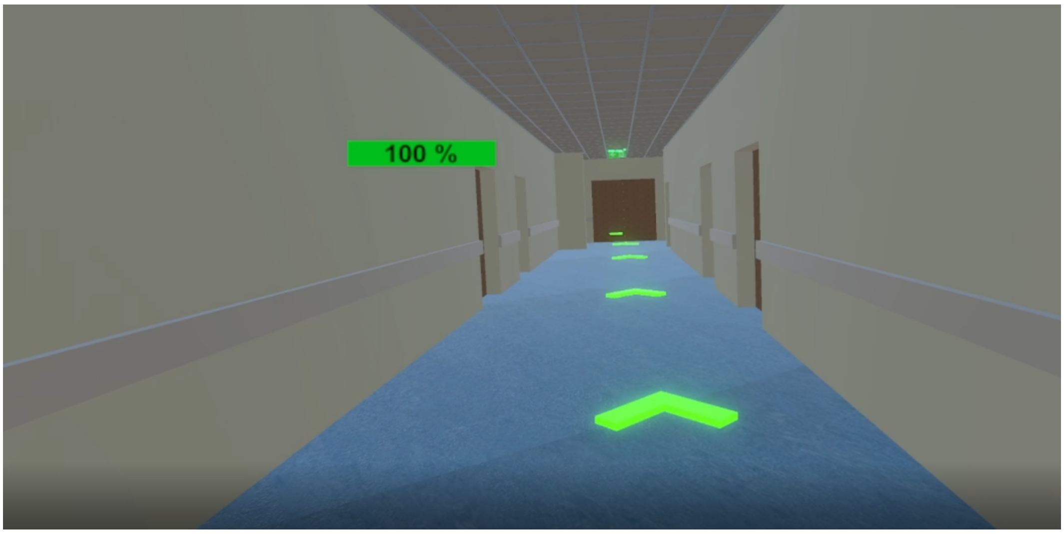



Figura 5.16: Augmented reality rendering.

### 5.5.11 Player characterization

The "Locomotion System" script has been added to be able to allow the player to move within the environment. Related to it is the "Snap Turn Provider (action-based)" script, granting the ability to rotate the view via the right joystick, and the "Continous Move Provider (action-based) to move forward or backward in the scenario via the left joystick. Within the script, it was possible to adjust the speed of the player depending on its role in the scene.

Taking into consideration the paper [88] a speed of 0 to 3 m/s was ensured for users such as medical staff, visitors, and visually impaired people, while for the "limping" role the speed was set to a maximum of 0.8 m/s.

To represent the condition of "visual impairment" to the user, a layer was added with a "Volume" script attached, using the Motion Blur and Bloom options: "lens dirt." This layer allowed the user to have an uncomfortable view and more importantly made the user highly sensitive to the lighting present in the scene.


Figura 5.17: Point of view of a player with visual impairment.

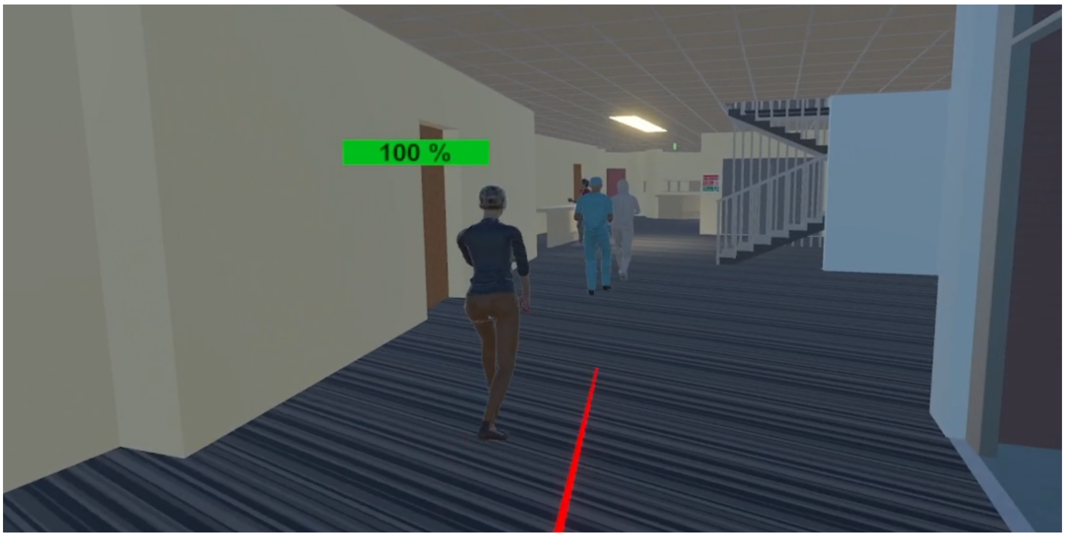



Figura 5.18: Point of view of a player without visual impairments (visitor/staff/limping).

### 5.5.12 Further effects

An audio source capable of rendering people's screams at the moment the alarm starts sounding was also added to the building realization.

# Capitolo 6

# Results

### 6.0.1 General guidelines for organizing and creating the test sample

The test involved 110 volunteers, gathered from among the department and nearby factory.

Each tester was invited to enter a specially arranged room in the department to carry out the exercise.

Before the test, questions were asked of the tester such as:

-The gender;

-His/Her "age range" consists of three categories: A = 18/30 years, B = 31/42 years, and C = +43;

-His/Her occupation;

-If he had any virtual or immersive reality experience;

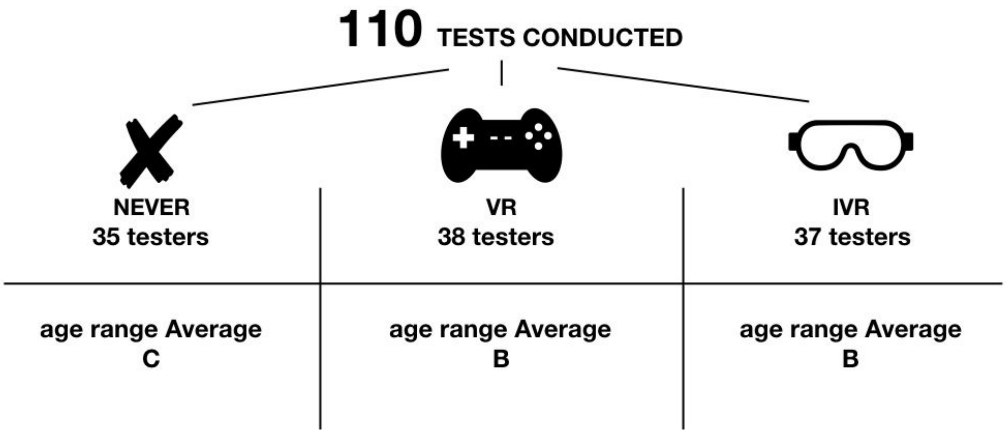
-If he has ever performed evacuation drills.

Figure 6.1 highlight that of the 110 testers, 35 had never had the opportunity to interact with virtual reality technology, while 36 revealed that they had played video games at least once. The remaining 37 testers said they have had interactions with immersive virtual reality (use of devices such as Oculus).

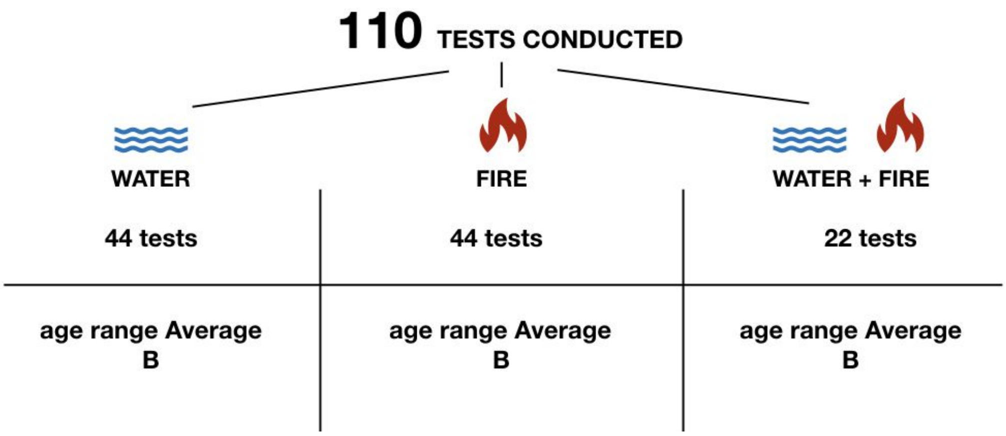
Most of the people who have not had an approach to virtual technology turn out to be older, while those who have played video games and tried immersive technology be between the ages of 31 and 42.

By this overview, it was decided to split the total sample of 110 testers ensuring homogeneity of the "age range," such that performances from the tests conducted could be balanced and comparable.

In fact, in all three macro-scenarios (hazard-dependent) the distribution of the sample was done by ensuring an average age range of B.




(a) Age breakdown of people with and without knowledge of virtual and immersive reality.




(b) Age breakdown of people in the three macro scenarios.

Figura 6.1: Subdivision of the testers for the tests.

Figure 6.2 describes the breakdown of the analyzed users among the 20 scenarios (hazard-dependent, role, and the emergency system applied).

**FLOODING**

| | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| STANDARD | 6 | 6 | 5 | 5 |
| INTEGRATED | 6 | 6 | 5 | 5 |

**FIRE**

| | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| STANDARD | 6 | 6 | 5 | 5 |
| INTEGRATED | 6 | 6 | 5 | 5 |

**FLOODING+FIRE**

| | VISITOR | MED. STAFF | VISUAL IMPAIR | LIMPING |
|---|---|---|---|---|
| INTEGRATED | 6 | 6 | 5 | 5 |

Figura 6.2: Hospital First floor made by Autocad.

As mentioned, therefore, the testers were divided into different roles.
For the "Visitors" role, we gave no information regarding the building and escape routes, etc. The user accordingly started from outside the building and was free to move around until the alarm went off and then the evacuation drill started.
For the "Medical Staff" role, on the other hand, we allowed the tester to observe the building floor plans and made him acquainted with the virtual environment before the start of the test.
In this case, the test started with the tester inside the hospital environment.
For the "Limping" and "Visual impairment" roles, we allowed the tester to have partial knowledge of the floor plan (of the ground floor) and made make a relative acquaintance with the virtual environment, close to its starting point (in the treatment area), positioned inside the building.
Once we granted these cognitive features of the environment to the tester, depending on the role it played, the player was instructed in the proper use of the joysticks and the Head-Mounted Display (Oculus Quest 1) so that he could move in the virtual environment without major problems.
The test involved starting the user in a standard quiet situation. They were free to walk in the virtual environment until the alarm started and then evacuation.
The test ended when users reached points deemed safe or they could die when the Health-bar reached 0%.
At the end of the test, each tester was asked to answer an "after drill" survey containing 18 questions/revelations, listed below.

-Type of hazard present in the scene;
-What was your role in the scenario?
-What was your health condition in the scenario?
-I was stressed (under pressure) during the evacuation;
-During the evacuation, I felt concerned about whether I would be able to get out before the hazard/hazards got too close.
-The behavior of the other people during the evacuation was believable and coherent with the expectations.
-During the evacuation, I was surprised by the exits the other people were taking.

-I lost sense of direction.

-I experienced difficulties during the evacuation. If yes which ones?

-The motion felt natural

-I experienced motion sickness

-The simulation engaged me

-These types of simulations, and technologies used, can be useful for training and educating about drills

-The environment and the hazards were well-designed and realized.

-Concerning the environment, what did you like the most?

-Concerning the environment, what did you Not like? the most

-Concerning the other characters in the scene, what did you like?

-Concerning the other characters on the scene, what did you Not like?

At the end of the test, the volunteer was thanked for the availability and support of the study project.

The results obtained by self-generated report at the end of the evacuation drill and the videos collected for each test were evaluated following the methodological process of Section 4.2.

### 6.0.2 Comparison of Standard and Integrated Emergency Systems

Neglecting the type of single-hazard (fire or flood) in place and considering only the comparison of standard emergency systems vs. integrated systems we would have a sample of 44 users (of the standard system) vs. 44 users (of the integrated system). A large number of users compared allows for reliability of the final figure at 64%. This figure was made possible using G*Power software as shown in Figure 6.3.

Figure 6.4 reports the functional, sensory, and cognitive affordance, i.e., the number of times the NPCs, Hazard, and static emergency signage appeared in the player's field of view at the time the evacuation is in progress (active alert).
It is meant to be repeated that the number of times the user noticed these factors does not give any validity as to whether the user complied/followed the directions. The study that is done regarding affordance is only for semi-quantitative purposes,

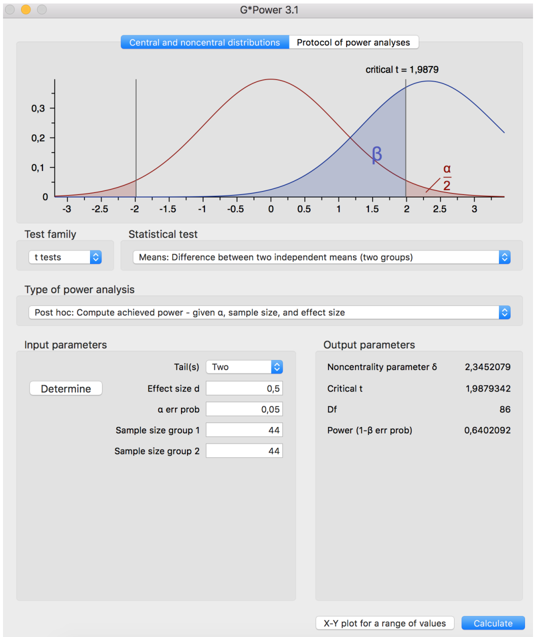



Figura 6.3: Reliability of the sample under examination.

and therefore only the strength/efficiency of the emergency system employed is studied through this tool. These data were extrapolated by carefully watching the videos collected for each drill.

| | standard | integrated |
|---|---|---|
| Npc | 84 | 58 |
| Hazard | 96 | 34 |
| Signage | 216 | 158 |

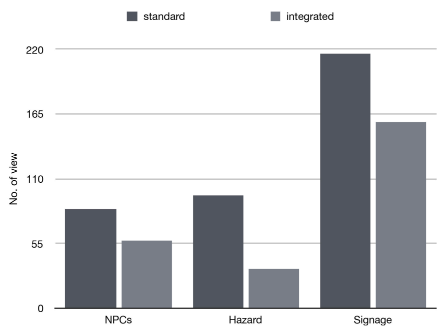



Figura 6.4: Affordance of the scenarios (no hazard statement).

In general, the above graph shows that players were most attracted to static hazard signage. This is followed next by interaction with hazard and finally with NPCs. This could mean that users adopted good behavior, sticking to the emergency system instead of paying much attention to other elements involved in the scene.

Regarding the comparison between the two emergency systems used, there is a

decrease in the display of NPCs, Hazard, and emergency signs, in the scenario where the integrated emergency system is present.
This could mean that users, having had more information about the hazard from the integrated system, adopted a better evacuation mode.
This statement finds its source in the performance performed by the users. This result is given by the of the final life (in percentage), made possible by the Health-bar, with which the players finished the test (See Figure 6.5).
From this point of view, it can be seen that with the integrated system the players had fewer interactions with the static emergency signs, but they still managed to implement a better performance than with the standard emergency system.

| | PERFORMANCE (SCORE IN %) |
|---|---|
| Standard | 65,14 |
| Integrated | 94,32 |

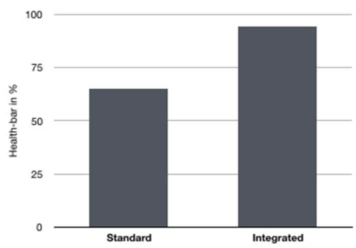



Figura 6.5: Standard vs. Integrated system score.

### 6.0.3 Comparison of Standard and Integrated Emergency Systems Flood/fire hazard

This section aims to compare more specifically standard emergency systems vs. integrated systems at the same single-hazard (flood and fire).

#### Flood scenario

In this case, the sample is reduced to a maximum of 22 tests of the standard system compared with 22 tests of the integrated emergency system. This aspect results in the probability given by G*Power (See Figure 6.15) being 37%. A probability below 50% does not offer the reliability of the final data, but the project went ahead considering this lack.

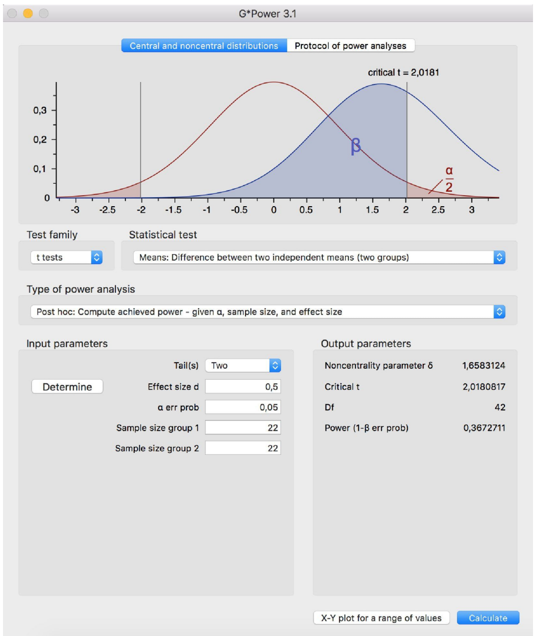



Figura 6.6: Reliability of the sample under examination.

The flood scenario saw players behaving substantially no different between the standard alert and integrated system conditions. The integrated system in the flood scenario involves a voice informing people of the danger and instructing them on the proper evacuation process. It appears from the data that users may not have grasped or been strongly influenced by the integrated system. Considering affordance, i.e., the interaction that occupants had with NPCs, as a method of comparison, there is not much difference.

There is, however, a decrease in how many times the player saw the danger but paid more attention to the static emergency signage (See Figure 6.8).

| | Standard | Integrated |
|---|---|---|
| NPCs | 42 | 41 |
| Hazard | 43 | 25 |
| Signage | 83 | 94 |

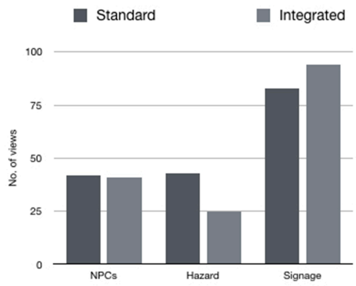



Figura 6.7: Affordance of the scenarios.

A clearer key to interpretation is given to us by the performance that players performed during the test.
Here we show that the users managed to get to safety with an average percentage of the life of 91.18 versus 82.82 for the standard emergency system.
Again we show the comparison of the performance made by the users during the drill depending on the emergency system applied. This was made possible by the percentage of life with which the tester finished the test.

| | PERFORMANCE (SCORE IN %) |
|---|---|
| Standard | 81,82 |
| Integrated | 91,18 |

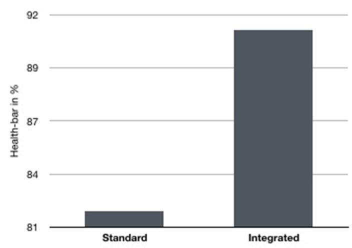



Figura 6.8: Standard vs. Integrated system score (Flooding).

Because the flood scenario is studied, the occupied area and escape time (under hazard on condition) for different emergency systems applied (standard vs integrated) can also be compared. To make the occupied area graph, the average of the areas covered by the players was used. The area covered by the conventional emergency system is shown in $m^2$ in Figure 6.9. It should be noted that the reception is located at the main entrance, which is the place that is most frequently crossed. While the integrated system in Figure 6.20 exhibits a noticeable reduction in the occupied area, which is seen in the decreased color density. The location close to the main stair in the reception is the one that is the most fully filled.

Concerning the escape time, the average escape time of the users was calculated.


Figura 6.9: Overall density of covered areas in comparison to the standard emerg. system. Users will frequent the area more frequently the more intense the color.


Figura 6.10: Overall density of covered areas in comparison to the integrated emerg. system. Users will frequent the area more frequently the more intense the color.

| OCCUPIED ARE IN M^2 | Standard | Integrated |
|---|---|---|
| Visitors | 941 | 749 |
| Staff | 563 | 695 |
| Visual impairments | 900 | 289 |
| Limping | 807 | 781 |
| Average | 802,75 | 628,5 |

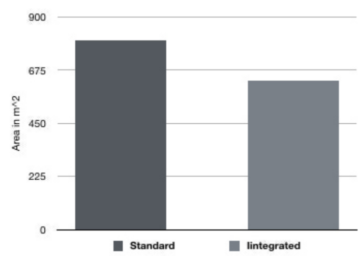



Figura 6.11: Comparison occupied area between Standard system and Integrated one.

It can be seen from the plans that there has been a decrease in the occupied area by players in the system where the Integrated System is present compared to the Standard one. This is evidenced instead in the above graph where there has been a reduction of about 200 $m^2$.

To view the routes and occupied areas of the individual players, see (Annex B). Regarding escape time, a performance improvement to evacuate the building, by players, of more than 10 seconds through the integrated emergency system is noted.(See Figure 6.12).

Attention is also paid when evaluating the average totaled escape times of the

| Escaping time (sec.) | Standard | Integrated |
|---|---|---|
| | 97 | 31 |
| | 12 | 12 |
| | 33 | 87 |
| | 101 | 66 |
| | 158 | 20 |
| | 32 | 88 |
| | 31 | 201 |
| | 45 | 26 |
| | 83 | 45 |
| | 123 | 27 |
| | 48 | 43 |
| | 53 | 57 |
| | 30 | 54 |
| | 84 | 43 |
| | 73 | 52 |
| | 41 | 49 |
| | 50 | 37 |
| | 97 | 62 |
| | 100 | 96 |
| | 87 | 58 |
| | 94 | 88 |
| | 85 | 50 |
| **Average** | 71 | 59 |

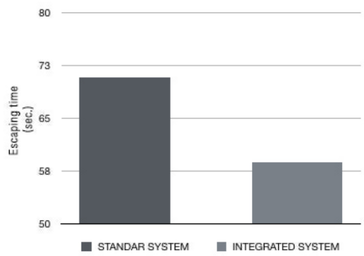



Figura 6.12: Comparison of the Escaping time (Standard vs. Integrated system).

various categories among the different applied emergency systems.
Figure 6.13 shows in general that in the standard emergency system the categories totaled relatively higher escape times than in the applied emergency system.
In detail, it can be seen that the players who played the role of Visual impairments, in the standard system, turn out to be the best-performing category with an average of 56 seconds taken to reach a safe point. This is followed by the Medical staff category with an average of 63 seconds.
These data are reliable because the visual impairments and "medical staff" players had partial and complete knowledge of their environment, respectively, as well as good motor conditions.
Different discourse for visitors and limping. In fact, the visitors, who, while enjoying good physical condition, did not know the environment, took an average of 70 seconds to evacuate the building. While the motor disability of the limping category affected the escape time by scoring an average of 95 seconds.
With the integrated emergency system, significant reductions in escape time averages were noted in each category.
Again, visual impairments performed better than the other categories with an average of 50 seconds, while limping was still the last performing category with an average of

75 seconds.

The performance of the categories in the scene is corroborated by the final score

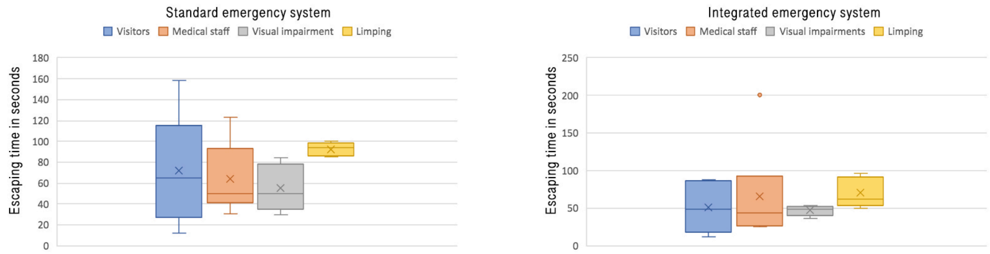



Figura 6.13: Comparison of the Escaping time (Standard vs. Integrated system) per roles.

with which the players finished the evacuation test.

In this case, Figure 6.14 highlights the differences in final scores, calculated by the final value of players' lives in percentage, between standard and integrated emergency systems.

An initial observation shows consistency with the adopted escape times. The visual impairments, who scored a short escape time, are the ones who reported the highest score with an average of 100%. Both medical staff and visitors scored an average score of 83%, while the Limping category that took the longest time to escape, affected by motor impairment, had an average score of 60%.

In comparison, the applied contingency system found marked improvements in the final score for each category. Both staff and visual impairments were able to achieve safe points with an average final score of 100%, while visitors with an average of 83%.

Finally, Limping remains the last category to secure safe points with an average of 80%.

As repeated, the comparison of the emergency systems applied in the scene finds consistency between escape time and final score. After this first observation, it is found that the integrated system, flood scenario, provided an improvement in user performance (considering the occupied area, escape time taken, and final life), although no surprising differences in affordance are found.

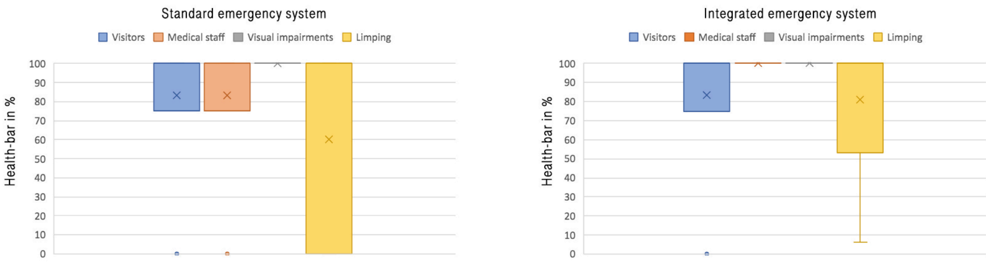



Figura 6.14: Comparison of the scores (Standard vs. Integrated system) per roles.

## Fire Scenario

Also in this case, the sample is reduced to a maximum of 22 tests of the standard system compared with 22 tests of the integrated emergency system. This aspect results in the probability given by G*Power (See Figure 6.15) being 37%. A probability below 50% does not offer the reliability of the final data, but the project went ahead considering this lack.

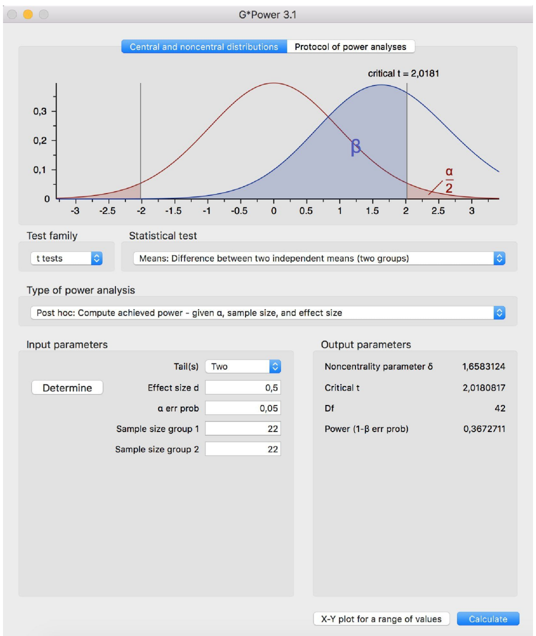



Figura 6.15: Reliability of the sample under examination.

In contrast to the flooding scenario, the fire scenario found significant differences between the standard alarm condition and the integrated system. The integrated system involved in this scenario sees augmented reality employed, through dynamic signage representations. In fact, the affordance depicted in Figure 6.16 notes that the interactions between the elements displayed in the environment are greatly reduced. Especially notice that even static emergency signage has been neglected in favor of dynamic signage.

| | Standard | Integrated |
|---|---|---|
| NPCs | 42 | 17 |
| Hazard | 53 | 9 |
| Signage | 133 | 64 |

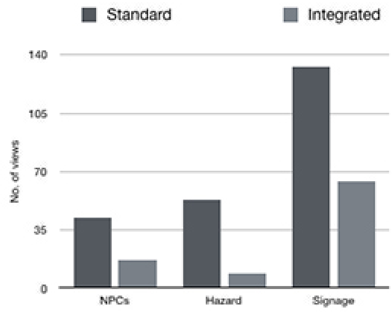



Figura 6.16: Affordance of the scenario.

Under the considerations made above regarding the decrease in affordance constituents in the scenario with the integrated alarm system, the player still adopted a behavior such that it reached a safe point and thus stayed alive.
Figure 6.17 shows the comparison of occupant performance made in the scenario with the standard alarm system and integrated alarm system. In the integrated system, it is found that all testers managed to save themselves without reporting any damage in terms of life. Different conditions, however, in the fire scenario with the standard emergency system where the average performance of the players stands at $48,45\%$.

| | PERFORMANCE (Score %) |
|---|---|
| Standard | 48,45 |
| Integrated | 100 |

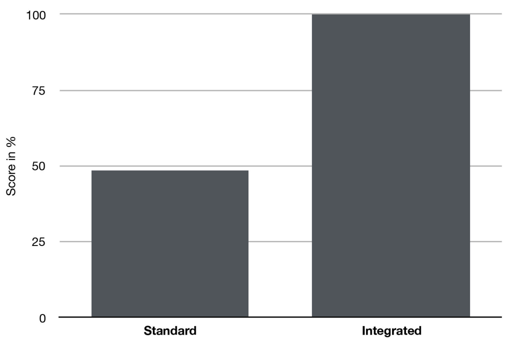



Figura 6.17: Standard vs. Integrated system score.

The area covered by the conventional emergency system is shown in $m^2$ in Figure 6.18. It should be noted that the reception is located at the main entrance, which is the place that is most frequently crossed. While the integrated system in Figure 6.19 exhibits a noticeable reduction in the occupied area, which is seen in the decreased color density. The location close to the main stair in the reception is the one that is the most fully filled.

Concerning the escape time, the average escape time of the users was calculated.


Figura 6.18: Overall density of covered areas in comparison to the standard emerg. system. Users will frequent the area more frequently the more intense the color.

The plans show that there has been a decrease in the area occupied by players in the system where the Integrated System is present compared to the Standard System. This decrease is most clearly shown in the graph Figure 6.20 where the reduction is 267 $m^2$.


Figura 6.19: Overall density of covered areas in comparison to the integrated emerg. system. Users will frequent the area more frequently the more intense the color.

| OCCUPIED ARE IN M^2 | Standard | Integrated |
|---|---|---|
| Visitors | 898 | 600 |
| Staff | 1120 | 665 |
| Visual impairments | 842 | 599 |
| Limping | 551 | 480 |
| Average | 852,75 | 586 |

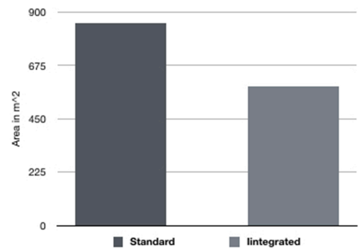



Figura 6.20: Comparison occupied area between Standard system and Integrated one.

Inherent to the escape time, calculated by averaging the times of all players, there is an improvement in building evacuation performance of 30 seconds through the integrated emergency system. (See Figure 6.21).

In this scenario, attention is also paid when evaluating the average totaled escape times of the various categories among the different applied emergency systems. Figure 6.22 shows in general that in the standard emergency system the categories totaled relatively higher escape times than in the applied emergency system.
In detail, it can be seen that Limping players, in the standard system, scored an average, in terms of escape time, of 55.

| Escaping time (sec.) | Standard | Integrated |
|---|---|---|
| | 94 | 32 |
| | 124 | 17 |
| | 97 | 3 |
| | 35 | 56 |
| | 62 | 29 |
| | 34 | 35 |
| | 48 | 13 |
| | 62 | 33 |
| | 118 | 29 |
| | 133 | 27 |
| | 106 | 28 |
| | 73 | 32 |
| | 27 | 40 |
| | 132 | 39 |
| | 92 | 45 |
| | 44 | 63 |
| | 50 | 35 |
| | 43 | 63 |
| | 58 | 100 |
| | 62 | 70 |
| | 100 | 95 |
| | 17 | 58 |
| **Average** | 73 | 43 |

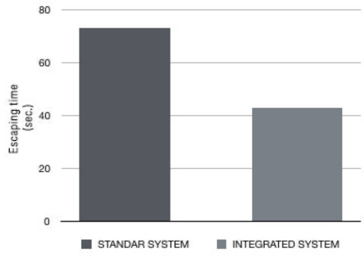



Figura 6.21: Total occupied area related to Integrated System.

This is followed by the Visual impairment category with an average of 70 seconds. Visitors took 75 seconds to get to safety, while medical staff was the lowest performing category, taking 90 seconds, on average, to reach a safe point.

With the integrated emergency system, significant reductions in average escape times were noted in each category. In particular, it is noted that medical staff was the category that managed to evacuate the building sooner than all other roles, with an average of 27 seconds.

This was followed by the visitors with an average of 30 seconds, the "visual impairments" players with 47 seconds, and finally, given the motor difficulties and reduced speed the Limping category with an average of 85 seconds. The performance of

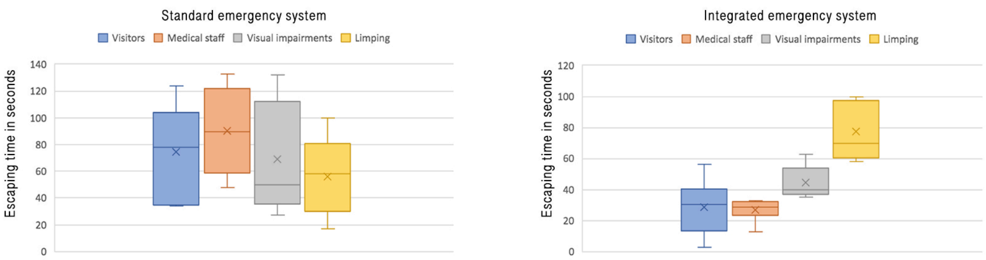



Figura 6.22: Comparison of the Escaping time (Standard vs. Integrated system) per roles.

the categories in the scene is corroborated by the final score with which the players finished the evacuation test.

In this case, Figure 6.23 highlights the differences in final scores, calculated by the final value of players' lives in percentage, between standard and integrated emergency systems.

Surprisingly, it can be seen that with the integrated emergency system, there was a marked improvement over the standard system in each category.

In the standard system, the medical staff was able to evacuate the building safely, as well as the visitors with an average of about 60%.

This is followed by Visual impairments and Limping with an average of 48% and 25%, respectively.

In comparison, the integrated emergency system allowed all the players involved in the fire scenario to come to safety with an average, in terms of final life expectancy, of 100%.

The integrated system in the fire scenario includes the use of augmented reality.

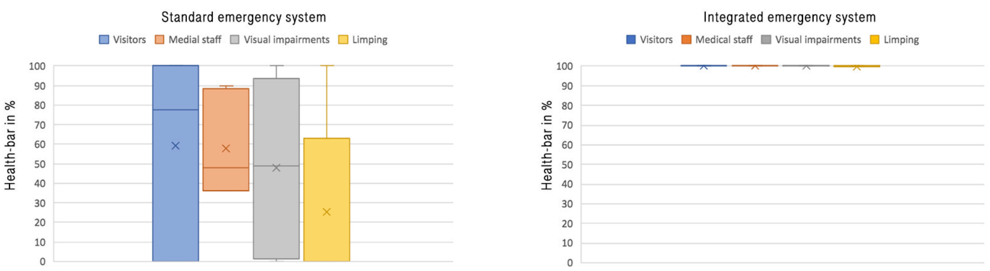



Figura 6.23: Comparison of the scores (Standard vs. Integrated system) per roles.

So, it is inferred that the integrated (augmented reality) system ensured that users were all able to get to safety. In addition, again with the same emergency system, the performance performed by the players found fewer interactions with the affordance elements (NPCs, Hazard, and static emergency signage).

### 6.0.4 Comparison of integrated emergency systems

The comparison sample is reduced to a maximum of 22 integrated system tests (flooding scenario) compared with 22 integrated system tests (fire scenario) compared with 22 integrated system tests (multi-hazard). This aspect causes the probability given by G*Power to be 37%.(Figure 6.24).

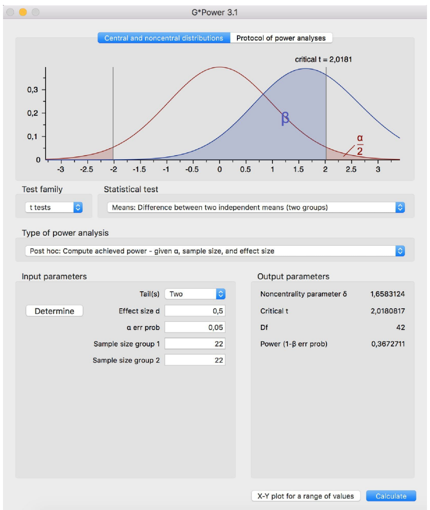



Figura 6.24: Reliability of the sample under examination.

The use of affordance (functional, sensory, and cognitive) as used in the previous cases was used to compare the different integrated warning systems.
Figure 6.25 shows numerically how many times NPCs, hazard and static emergency signage appeared in the player's view.

| | Flood | Fire | Flood+Fire |
|---|---|---|---|
| Npc | 41 | 17 | 44 |
| Hazard | 25 | 9 | 55 |
| Signage | 94 | 64 | 133 |

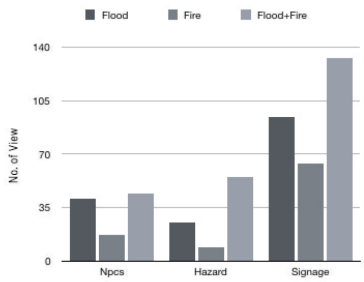



Figura 6.25: Affordance of the scenarios.

The collected data show that users paid much attention to the search for static emergency signage.
Among all integrated systems analyzed, it is shown that the system applied to the fire scenario (augmented reality, experienced a significant reduction in interaction/visualization of NPCs, Hazards, and static signage.
At a noticeable reduction of visualization of the "affordance" tool elements in the fire scenario, with such an integration system, it is noted that all of them reached a safe area with the maximum life (See Figure 6.26).

| PERFORMANCE (SCORE IN %) | Flood | Fire | Flood+Fire |
|---|---|---|---|
| | 100 | 100 | 0 |
| | 100 | 100 | 68 |
| | 100 | 100 | 100 |
| | 100 | 100 | 0 |
| | 100 | 100 | 0 |
| | 0 | 100 | 76 |
| | 100 | 100 | 62 |
| | 100 | 100 | 87 |
| | 100 | 100 | 100 |
| | 100 | 100 | 100 |
| | 100 | 100 | 100 |
| | 100 | 100 | 68 |
| | 100 | 100 | 94 |
| | 100 | 100 | 0 |
| | 100 | 100 | 0 |
| | 100 | 100 | 100 |
| | 100 | 100 | 64 |
| | 100 | 100 | 0 |
| | 100 | 100 | 100 |
| | 100 | 100 | 95 |
| | 6 | 100 | 5 |
| | 100 | 100 | 46 |
| **Average** | 91,18 | 100,00 | 57,50 |

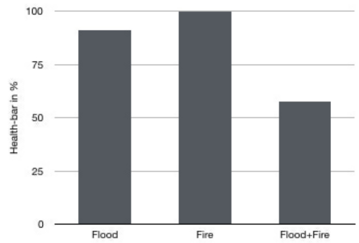



Figura 6.26: Various integrated emergency systems score.

For the multi-hazard (flood+fire) scenario instead, players observed NPCs, hazards, but especially static emergency signage more times.
This means that they found it more difficult to get to safety, and this is also evidenced by the score with which they finished the test, with an average of just 57%.
From this, it can be inferred that the system integrated into the single-hazard fire, which involves rendering dynamic signage (continuously rerouting), performs better than the sound+vocal alarm system employed in the other two scenarios (single and multi-hazard).

### 6.0.5 Comparison of individual roles.

Concluded the study regarding the different emergency systems applied in the thesis project, the analysis of the different roles follows. This study aims to verify that there are behavioral differences among users depending on their roles in the scene. At first, the different roles, independent of each other, are analyzed.
In this case, the sample is at a maximum of 30 tests for the categories visitors and medical staff, while for the categories visual impairments and limping the sample consists of 25 users. Consequently, the probabilities calculated by G*Power are 38% and 32% respectively (See Figures 6.27 and 6.28).

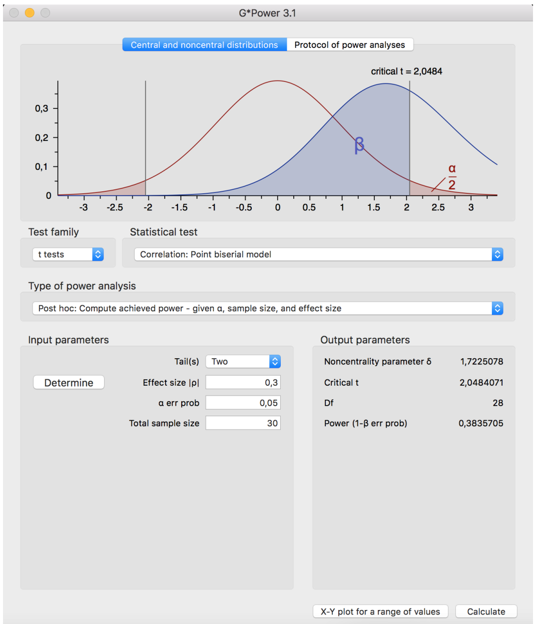



Figura 6.27: Reliability of the sample under examination (Visitor and Medial staff roles).

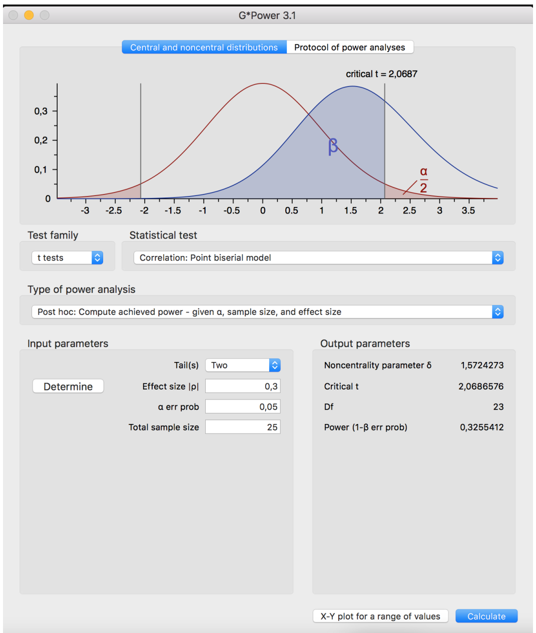



Figura 6.28: Reliability of the sample under examination (Visual impairments and limping roles).

As shown in Figure 6.29 the different affordances of each category.

| | Visitors | Medical Staff | Visual impairm. | Limping |
|---|---|---|---|---|
| Npc | 40 | 51 | 43 | 52 |
| Hazard | 43 | 53 | 48 | 41 |
| Signage | 120 | 146 | 122 | 119 |

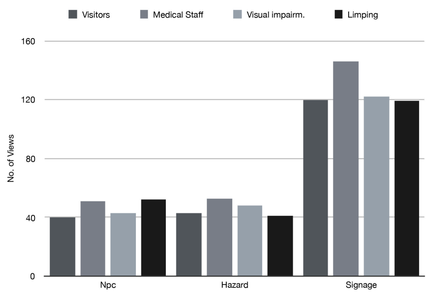



Figura 6.29: Affordance per each role.

Initial analysis shows similar behavior among all categories. All occupants paid more attention to static emergency signs. Behavior is consistent in the case of an evacuation in progress.

This is followed by viewing or interacting with the hazard, except for the limping category, and finally, attention paid to NPCs.

These data are comforting in that the behavior of all players was the same and consistent as in an evacuation drill. In the event of an evacuation, priority must be given to looking for/seeing signs and possibly following them. As it is repeated, we

do not intend to evaluate through the affordance tool the quality of the system, but only to have a semi-quantitative approach.
In this regard, one could evaluate the quality of affordance through the study of the performance performed by the players. This can be done by recording the final score obtained from the average Health-bar value as a percentage of each category (See Figure 6.30).

| Performance Score in % | Visitors | Medical Staff | Visual impairments | Limping |
|---|---|---|---|---|
| | 100 | 0 | 100 | 0 |
| | 100 | 100 | 100 | 100 |
| | 0 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 0 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 6 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 0 |
| | 0 | 100 | 3 | 0 |
| | 100 | 36 | 49 | 26 |
| | 0 | 51 | 0 | 0 |
| | 0 | 45 | 87 | 100 |
| | 76 | 36 | 100 | 100 |
| | 79 | 88 | 100 | 100 |
| | 100 | 90 | 100 | 100 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 100 | 100 |
| | 100 | 100 | 94 | 0 |
| | 100 | 100 | 0 | 100 |
| | 100 | 100 | 0 | 95 |
| | 100 | 100 | 100 | 5 |
| | 0 | 62 | 64 | 46 |
| | 68 | 87 | | |
| | 100 | 100 | | |
| | 0 | 100 | | |
| | 0 | 100 | | |
| | 76 | 68 | | |
| Average | 73 | 85 | 80 | 63 |

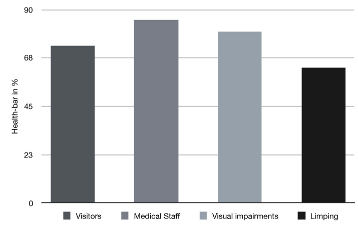



Figura 6.30: Average of the scores of each category.

Comparing the affordance and the performance played by the users, it can be said that the staff managed to get to safety with an average lifetime of 85%, followed by the visual impairment category with 80%, the visitors with 73% and finally the limping category with 63% average.
The final score finds homogeneity with the number of views of NPCs, Hazard, and signage.
The key takeaway is determined by the fact that depending on the number of visualizations made by the various categories, they were able to get to safety.
Another consideration must be made concerning knowledge of the environment and physical conditions. The staff performed very well compared to the other categories due to good knowledge and good physical conditions. The visual impairments, endowed with partial knowledge of the environment were able to get to safety. This was followed by visitors with little knowledge but with good health conditions.
Finally, the limping category, endowed with partial knowledge of the environment but due to their impaired motor skills had more difficulty evacuating the building without interacting with the hazard.

### 6.0.6 Comparison of macro categories according to their health conditions.

Considering previously that the performance performed by the various roles may be due to health conditions and knowledge or otherwise of the environment, this section proceeds to compare the players' performances considering their health conditions.
From this consideration, it follows that the total sample was divided into two subgroups for comparison. It is about 60 tests (visitors+staff) against 50 tests (visual impairment+limping). A large number of samples for each group ensures the strength of the final data analyzed.
In fact, at G*Power the probability of guessing the objectivity of the results is 73%,(See Figure 6.31).

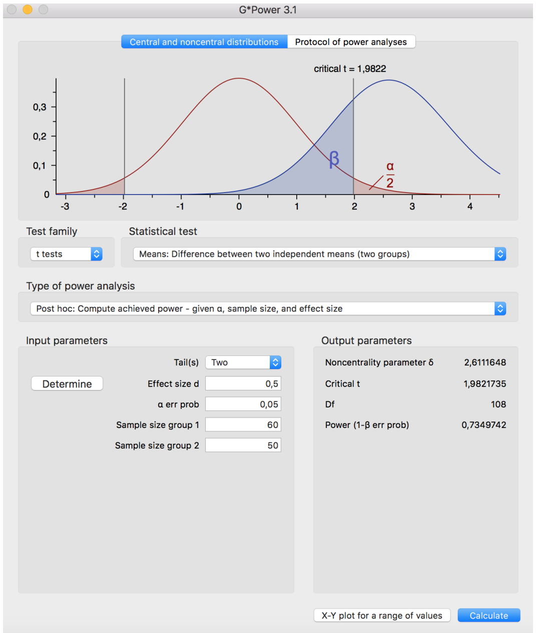



Figura 6.31: Macro groups Reliability (Visitors+Medial staff vs. Visual impairments+Limping).

Indeed the comparison sees users with good health conditions vs. people with motor deficits.

As shown in Figure 6.32, it can be seen that there are no notable differences concerning the affordance analyzed. Both macro groups paid attention to looking for and observing the static emergency signs.

Considering the "NPC visualization" factor, people with disabilities highlighted these actors 95 times in their field of vision, compared to 91 times for players with good physical conditions.

After all, it should be noted that users such as visitors and medical staff viewed/interacted with the hazard many more times (96) than the visual minors+limping category (89).

| | Visitors+Medical Staff | Visual impairm.+Limping |
| --- | --- | --- |
| Npc | 91 | 95 |
| Hazard | 96 | 89 |
| Signage | 242 | 241 |

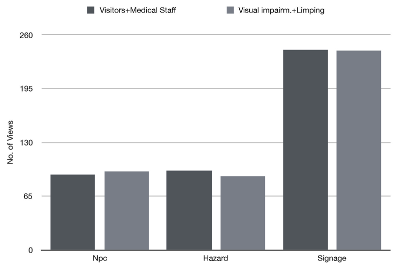



Figura 6.32: Macro groups Affordance (Visitors+Medial staff vs. Visual impairments+Limping).

Figure 6.33 shows the performance acted by the two macro groups and it is highlighted that the categories enjoying good health carried out a very high-performance test compared to the categories with visual and motor disabilities.
The category in good health had an average performance of around 80% unlike the Visual impairments and Limpings who finished the test with a final score of 72%.

| Performance Score in % | Visitors+Medical Staff | Visual impairments+Limping |
|---|---|---|
| | 100 | 100 |
| | 100 | 100 |
| | 0 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 0 | 3 |
| | 100 | 49 |
| | 0 | 0 |
| | 0 | 87 |
| | 76 | 100 |
| | 79 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 94 |
| | 100 | 0 |
| | 100 | 0 |
| | 100 | 100 |
| | 0 | 64 |
| | 68 | 0 |
| | 100 | 100 |
| | 0 | 100 |
| | 0 | 0 |
| | 76 | 100 |
| | 0 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 6 |
| | 100 | 100 |
| | 100 | 0 |
| | 100 | 0 |
| | 100 | 26 |
| | 100 | 0 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 36 | 100 |
| | 51 | 100 |
| | 45 | 100 |
| | 36 | 0 |
| | 88 | 100 |
| | 90 | 95 |
| | 100 | 5 |
| | 100 | 46 |
| | 100 | |
| | 100 | |
| | 100 | |
| | 100 | |
| | 62 | |
| | 87 | |
| | 100 | |
| | 100 | |
| | 100 | |
| | 68 | |
| **Average** | 79 | 72 |

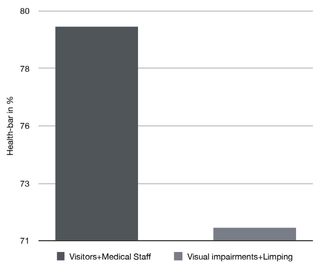



Figura 6.33: Macro groups Score(Visitors+Medial staff vs. Visual impairments+Limping).

### 6.0.7 Comparison of categories with good health conditions (Visitor vs. Medical Staff).

In this section, we try to compare the categories that enjoy good health conditions but that have differences in terms of knowledge of the environment.

The sample compares 30 visitor testers against 30 medical staff testers and the percentage generated by G*Power, which determines the strength of the final data, of 47% (See Figure 6.34).

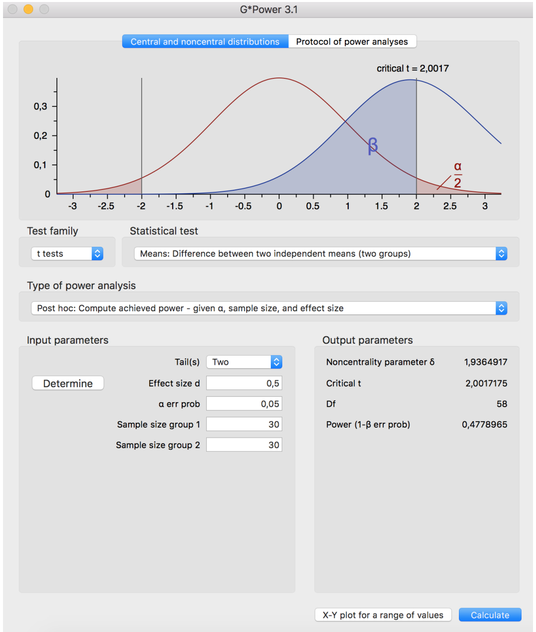



Figura 6.34: Reliability of visitor and medical staff categories.

Recall that the medical staff has a good knowledge of the built environment, unlike the visitor category.

It is denoted from Figure 6.35 that the medical staff displayed static emergency signage, hazard, and NPCs more times than the visitors.

This result could be due to the fact that the average staff looked for other ways to get to safety by having the starting point inside the hospital.

Unlike the medical staff, the visitor category implemented a different attitude, paying less attention to emergency signage.

| | Visitors | Medical Staff |
|---|---|---|
| Npc | 40 | 51 |
| Hazard | 43 | 53 |
| Signage | 120 | 146 |

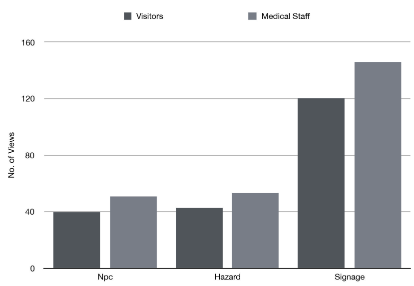



Figura 6.35: Comparison of visitor and medical staff Affordance.

Trying to find an answer to the right behavior implemented by the two categories, as in the previous case, a greater visualization of NPCs, Hazards and static emergency signs allowed the players to save themselves.
Figure 6.36 shows that the Medical Staff category managed to save itself with an average final life of 85% compared to 73% of visitors.

| Performance Score in % | Visitors | Medical Staff |
|---|---|---|
| | 100 | 0 |
| | 100 | 100 |
| | 0 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 0 | 100 |
| | 100 | 36 |
| | 0 | 51 |
| | 0 | 45 |
| | 76 | 36 |
| | 79 | 88 |
| | 100 | 90 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 0 | 62 |
| | 68 | 87 |
| | 100 | 100 |
| | 0 | 100 |
| | 0 | 100 |
| | 76 | 68 |
| **Average** | 73 | 85 |

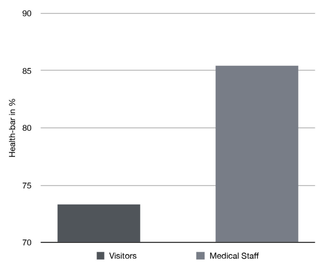



Figura 6.36: Visitor and Medical staff score.

This analysis shows that greater interaction with the environment and with a good knowledge of the environment could allow people to reach a safe place.

### 6.0.8 Comparison of categories with different physical disabilities (Visual impairment vs. Limping).

In this section, we try to compare the categories according to the physical disability they present, since both have partial knowledge of the environment.
The sample compares 25 visual impairment testers against 25 testers of the limping category and the percentage generated by G*Power, which determines the strength of the final data, is 41%, (See Figure 6.37).

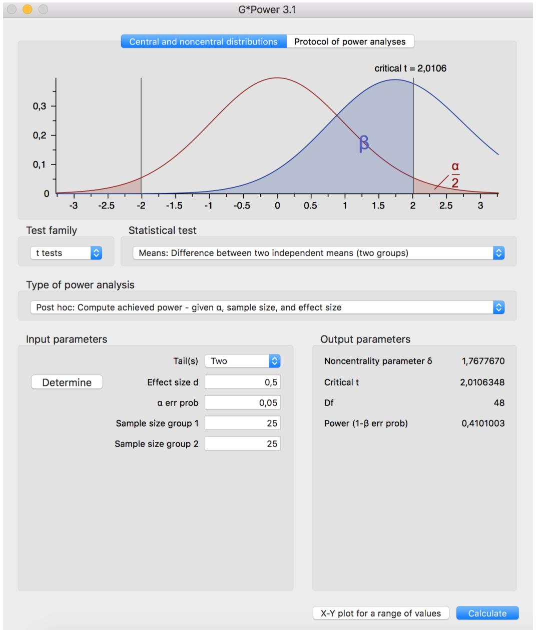



Figura 6.37: Reliability of visual impairment and limping categories.

Figure 6.38 shows that the limping category viewed the emergency signage fewer times than the visually impaired players.
In the end, there is no substantial difference between the two categories in terms of visualization of the elements constituting the affordance tool.

| | Visual impairm. | Limping |
|---|---|---|
| Npc | 43 | 52 |
| Hazard | 48 | 41 |
| Signage | 122 | 119 |

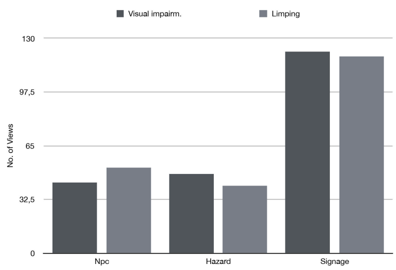



Figura 6.38: Comparison of visual impairment and limping Affordance.

An answer could be given to us by the final score which determines the performance performed by the players.
Figure 6.39 shows that the average life with which the limping concluded the test was 63% compared to 80%.

| Performance Score in % | Visual impairments | Limping |
|---|---|---|
| | 100 | 0 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 0 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 6 |
| | 100 | 100 |
| | 100 | 0 |
| | 3 | 0 |
| | 49 | 26 |
| | 0 | 0 |
| | 87 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 100 |
| | 94 | 0 |
| | 0 | 100 |
| | 0 | 95 |
| | 100 | 5 |
| | 64 | 46 |
| Average | 80 | 63 |

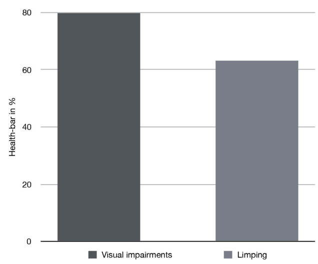



Figura 6.39: Visual impairment and Limping score.

This tool allows us to say that the slowness of the Limpings' movements most likely played a decisive role in the evacuation. The impossibility of running may have affected the ability to reach safety in a relatively short time.

## 6.1 Survey after drill

The following are the results collected from the surveys conducted by the testers after completing the evacuation test.

This survey gives us an overview of the learning power of simulation done through the use of virtual reality and the realistic implementation of this tool to improve physical evacuation drills.

Of the 110 tests collected 40% of the players were involved in single-hazard fire and flood scenarios. The remaining 20% in the multi-hazard scenario (See Figure 6.40).

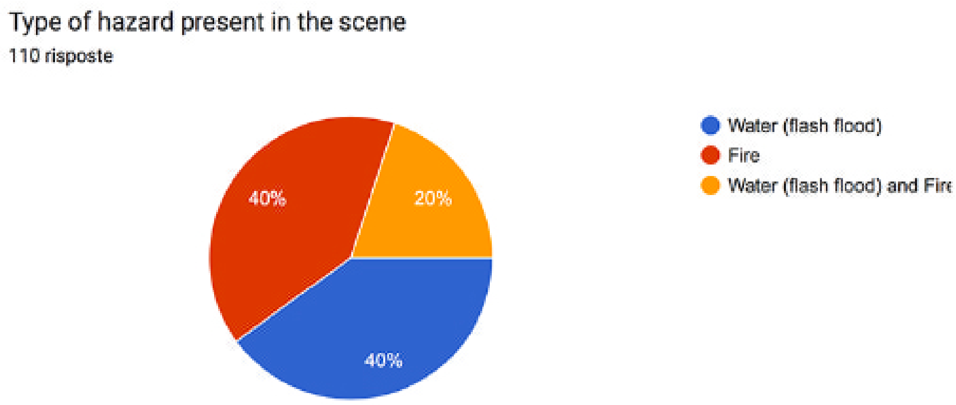



Figura 6.40: Type of hazard present in the scene.

Figure 6.41 records that nearly half of the total sample of testers, 45.5%, covered the "patient" category (Visual impairment and Limping), while 26.4% as visitors and the remaining 28.2% as the medical staff.
An anomaly is noted in that the testers were divided equally into 30 visitors and 30 medical staff. So it is believed that someone, in filling out the survey, made a mistake.

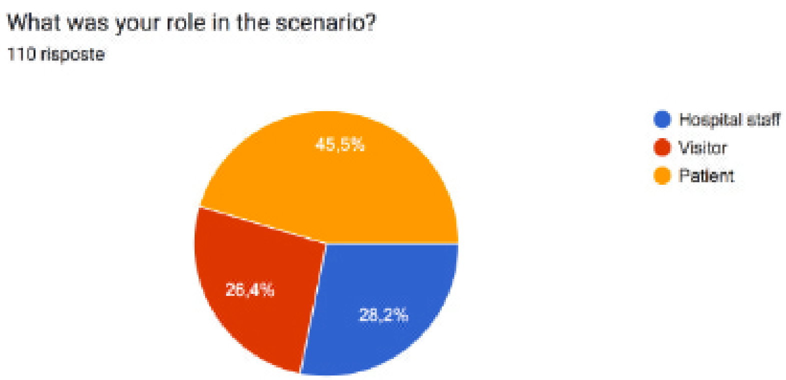



Figura 6.41: Type of role played by testers.

Similar to the roles played by the testers, Figure 6.42 shows the physical conditions of the participants. The categories Limping and Visual impairment (people with disabilities) are 22.7% each, accounting for 45.4% of the total sample. The remaining 54.5% held positions such as visitor and medical staff, i.e., with good health conditions.

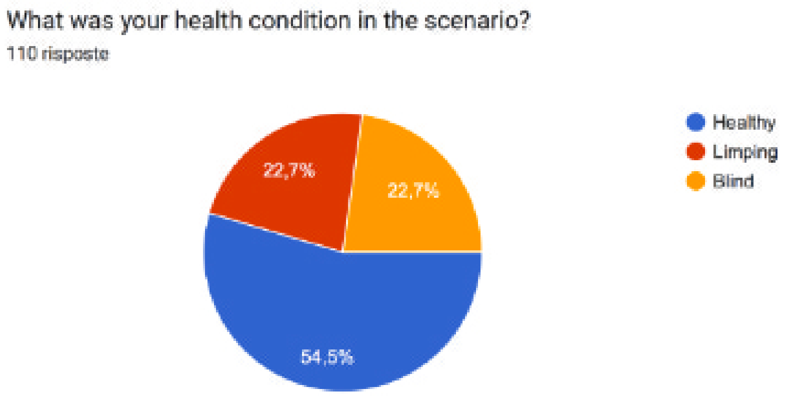



Figura 6.42: Testers' health conditions.

This initial analysis is followed by the actual evaluation of the results of the questions posed to the participants.

It is important to assess the participants' stress levels during evacuation. The result shown by Figure 6.43 notes that about half of the players (48.2%) experienced some level of stress.

This finding could stand to signify that the evacuation test accomplished through immersive virtual reality aroused significant emotions in people. A 30% of the participants, on the other hand, responded "neutral," while 11.8% of the testers confirmed a high level of stress experienced during the test.

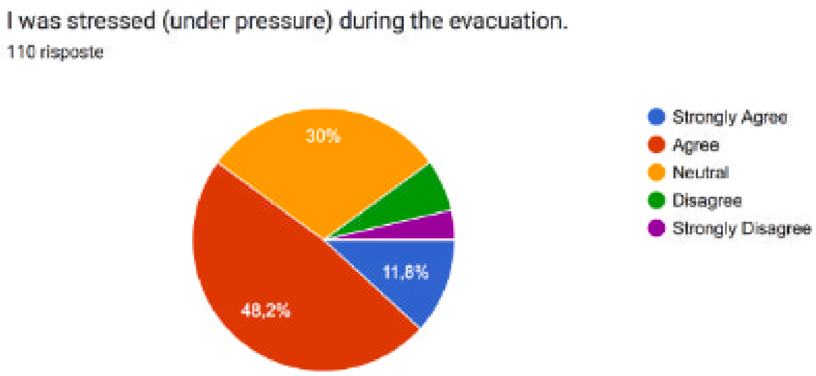



Figura 6.43: Participants' stress assessment

Related to anxiety and stress, it was proposed whether the user was concerned about being able to evacuate the building before the danger got too close.

The response shown in Figure 6.44 shows that 65.5% of the participants agreed to this statement while 10% strongly agreed. 17.3% were neutral to this.

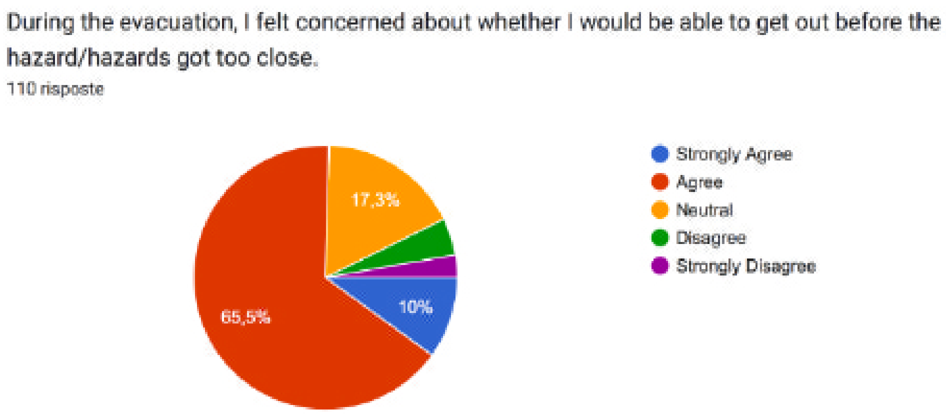



Figura 6.44: Assessment of player worry during evacuation.

Because NPCs were also present in the environment we asked users whether the behavior of other people in the environment, during the evacuation, was consistent with expectations.

Figure 6.45 shows that 56.3% (more than half of the players) strongly agreed or agreed with the type of behavior adopted by the NPCs. This finding is comforting in that the behaviors of NPCs were varied in the implementation process, not guaranteeing that everyone adopted the same behavior during evacuation.

28.2% described other people's behavior as "neutral," while 14.5% showed disapproval. In fact, some NPCs were running against the fire with the intent to evacuate the building anyway.

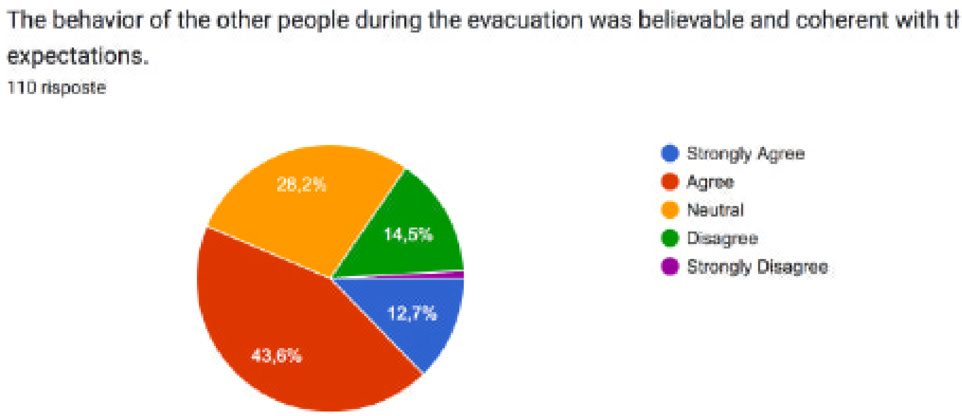



Figura 6.45: Player assessment in considering the behavior of NPCs.

Inherent to the behavior of NPCs, the tester is asked whether he or she was surprised to see what kind of exits people took during evacuation.
Consistent with the result in the previous paragraph, players expressed disagreement in being surprised by 39.1%, while 42.7% remained neutral (See Figure 6.46).

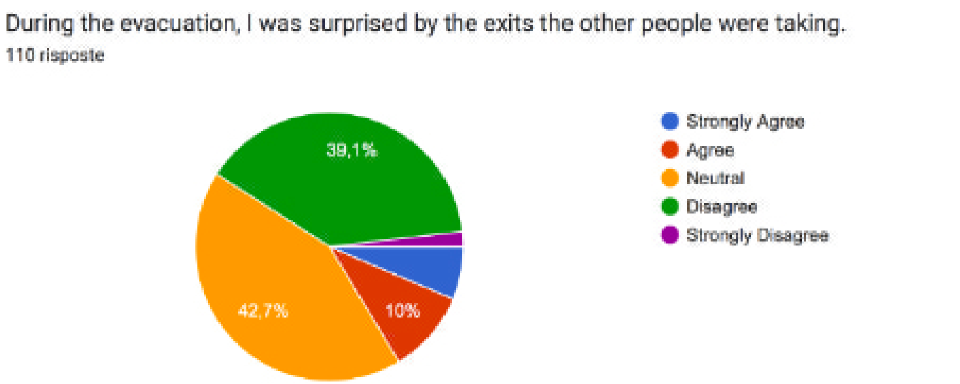



Figura 6.46: Player assessment in considering the exits took by NPCs.

Attention is now turned to the user's ability to relate to the context he was in.
We asked whether they had lost their sense of direction during the exercise.
Figure 6.47 shows that people during the evacuation felt strongly disoriented 11.8% or disoriented 42.7%, while a 30% remained neutral. Also reported is a 7.3% of users who disagreed with this statement. This could be because some of the testers were partly or well acquainted with the environment they were in ( e.g., patients (with

visual impairment, limping, and medical staff).

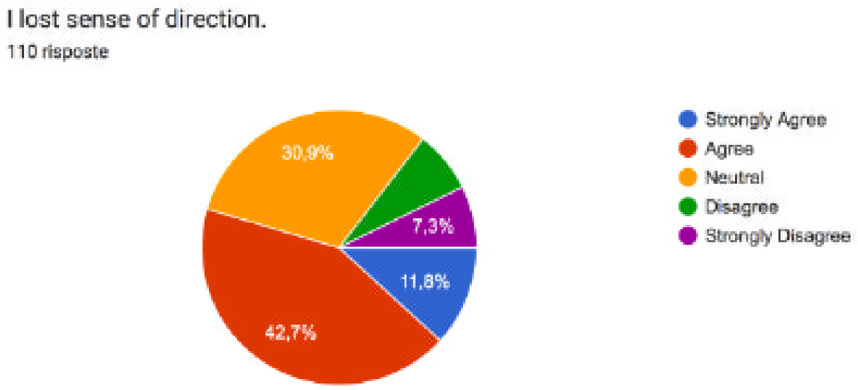



Figura 6.47: Evaluation of loss of player direction.

Next, we asked the participants what were the major difficulties they encountered during evacuation.

Figure 6.48 shows that 28% of the sample also found it difficult to evacuate the building because of the fires near the emergency routes and the main entrance.

The 26% of the testers did not detect much difficulty. This could be because in the integrated systems we had more information and therefore they found no problems during the escape. It is noted that 22% of the participants had difficulty in the evacuation because their movements were greatly affected by the disabilities (visual or motor) they had.

11% of the occupants reported a lack or poor presence of signage indicating the presence of stairs or elevators.

Still, 8% of the sample could not immediately understand the type of hazard involved in the test. The lack of hazard recognition is found in scenarios where the standard warning system was present.

9% of the players showed a problem in movement in the scene. This was because some testers had never had previous experience with immersive virtual reality. In addition, the 3% found it difficult to follow the NPCs during evacuation.

Finally, the 1% of testers stated that they had difficulty handling the opening of the doors present in the scene.

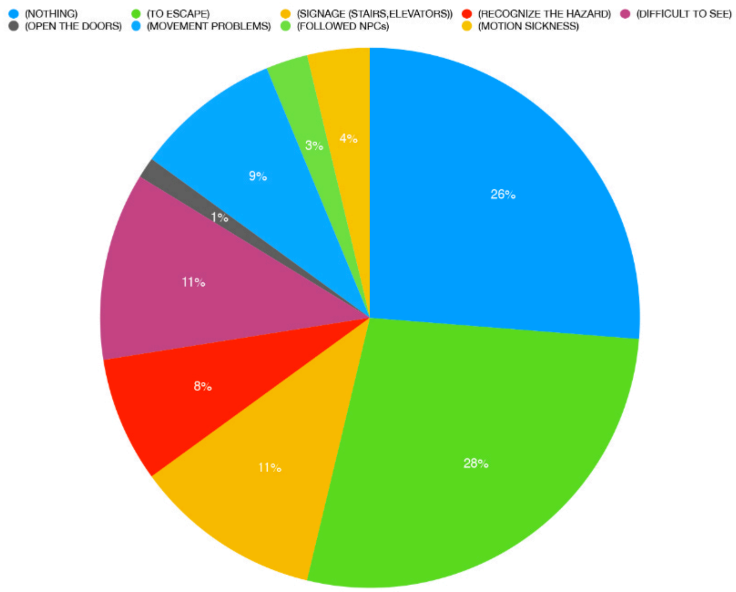



Figura 6.48: Difficulties found by player during the drill.

To further explore the issue of interaction between the player and the virtual environment, we asked the testers whether the movements made during the trial were natural.

Figure 6.49 shows that 65.5% of the participants found no great difficulty in handling the joysticks and thus the movements during the evacuation trial, while 8.2% found no difficulty at all.

The remaining 26.3% of the sample either remained neutral or had difficulty with movement during the test.

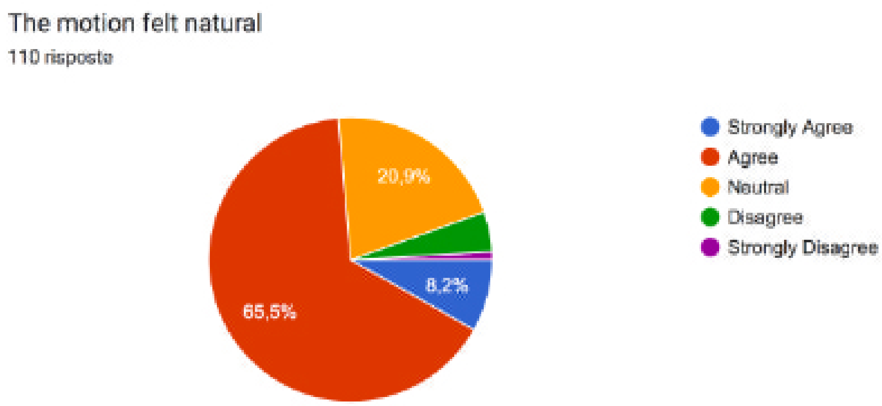



Figura 6.49: Motor difficulties noted by the players.

Considering the difficulties or otherwise that the players found in moving through the scene, we felt it only fair to ask whether they were caught by motion sickness during the simulation.
The answer shown in Figure 6.50 notes that 58% of the users did not experience any problems. Some of them 19% experienced dizziness, 10% nausea, 9% headache, and finally only 3% experienced stomachache.
This result is comforting since the rendering of the evacuation trial was set, due to a limitation set by default by the Head Mounted Display, at 72 FPS.

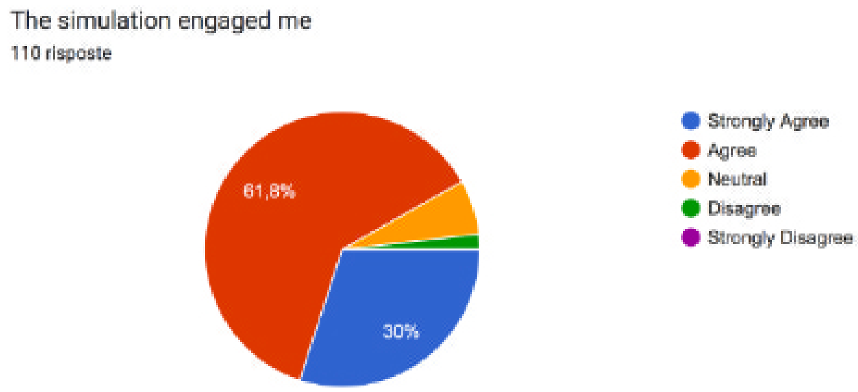



Figura 6.50: Motion sickness noted by the players.

After analyzing the movements and problems the participants experienced during the simulation, we asked whether the test had been interesting and whether they had felt engaged. The feedback was very positive 61.8% agreed that they felt an active part of the system, while 30% strongly agreed (See Figure 6.51).
In addition to involvement, we asked whether the players agreed that the technology used (immersive virtual reality) was useful for evacuation testing.
Again, Figure 6.52 shows that 76% strongly agreed and 20.9% agreed.
No player is found who disagreed with this statement.

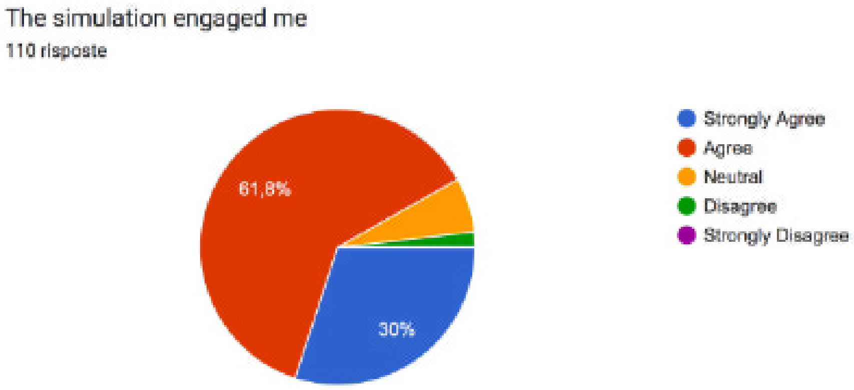



Figura 6.51: Engaging level of the player in the scene.

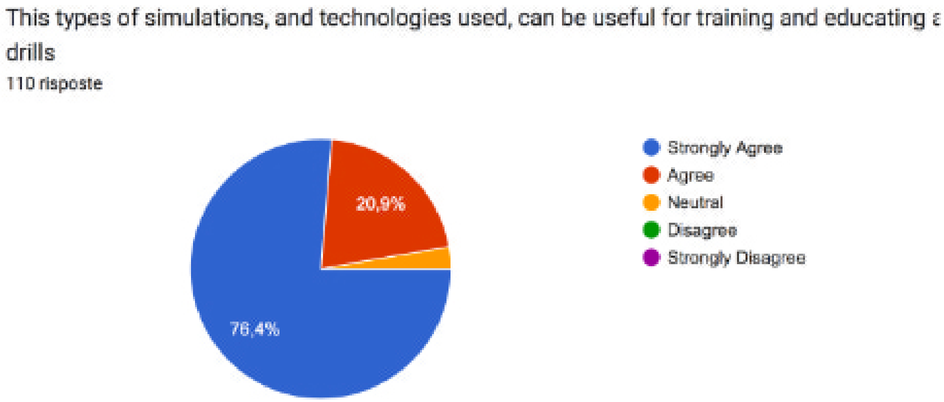



Figura 6.52: Assessment of interest in using the proposed technology for evacuation training.

Finally, we asked the volunteers for a technical/aesthetic view of the built environment and proposed to them.
Figure 6.53 highlights that 61.8% of the sample involved in the experiment considered the built environment well constructed and sometimes even semi-realistic, as reported by 24.5% of the respondents.
The remaining portion either did not comment or disagreed.

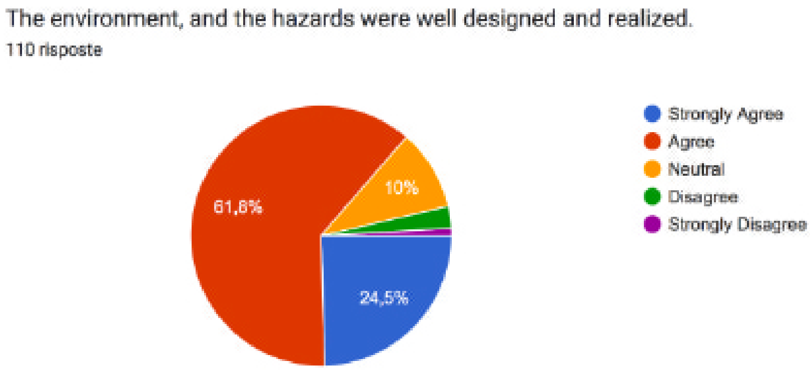



Figura 6.53: Evaluation of the liking of elements in the environment.

More detailed, it was asked which of the physical elements in the proposed environment they liked.
45% of volunteers responded that they were surprised to be in a well-constructed hospital environment, while 29% placed more attention on the good construction of the hazards (water, fire, and smoke).
A 22% of the users noted interest in the integrated emergency system proposed in the scenarios, while 3% were surprised to see NPCs in the environment (See Figure 6.54).

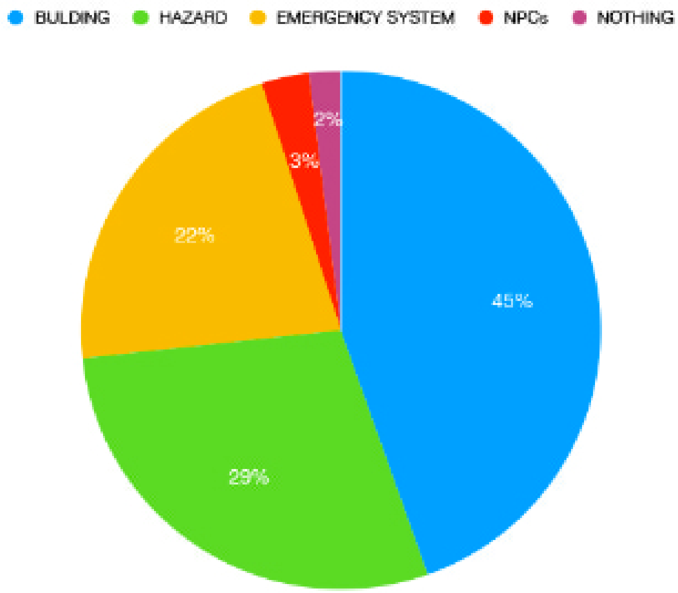



Figura 6.54: Evaluation of the liking of elements in the environment.

Of course, they were also asked what aspects of the environment they disliked, and from Figure 6.55, we find that 46% of the sample surveyed reported no anomalies or negative aspects in the scene.
24% paid attention to the malfunction of the doors.
In addition, 22% pointed out a lack of furniture within the built environment.

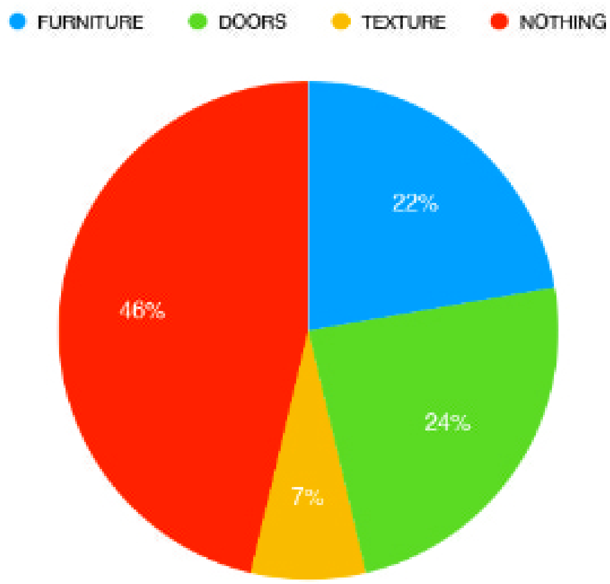



Figura 6.55: Evaluation of disliking the elements in the environment.

Attention was also paid to the interaction, especially the positive aspects the player had with the NPCs in the scene.
Figure 6.56 shows that 33% of the volunteers were pleased with the presence of other actors and 44% pleased with their movements. In fact, the implementation of NPCs involved different roles (doctors, nurses, visitors, and patients) with different physical conditions. This was decided precisely to represent the consistency of characters present in a hospital setting.
Finally, the 23% was not expressed.

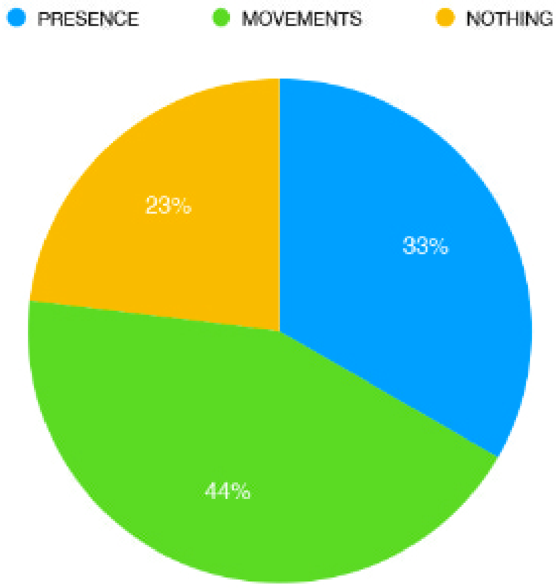



Figura 6.56: Evaluation of liking the NPCs in the environment.

The testers were asked what aspects of the other computerized actors (NPCs), present in the system, they did not like.
As shown in Figure ??, 32% did not express themselves, while 27% of testers noted that the NPCs weighed a problem, i.e., they could, in some cases, pass through doors and walls.
A 23% noted that NPCs adopted, during the evacuation, a not very consistent movement, while 17% of players pointed out the inability to interact with them.

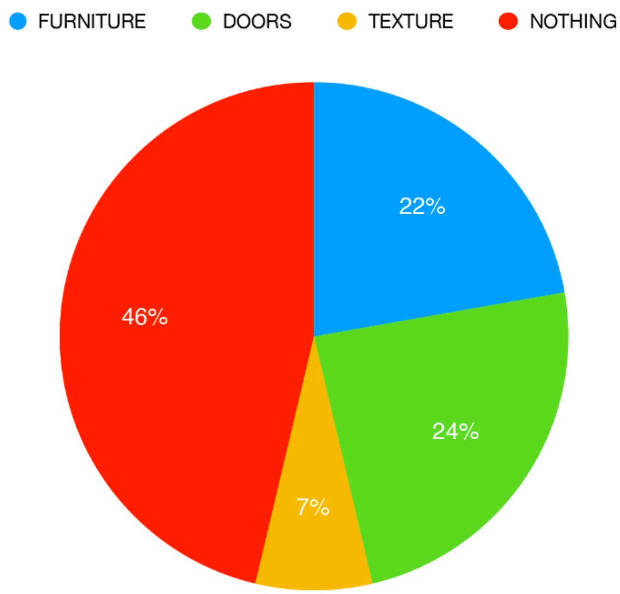



Figura 6.57: Evaluation of disliking the NPCs in the environment.

As a final question, we asked volunteers what aspects were missing in the scene that could be implemented or adjusted.
Figure 6.58 shows that 56% of the respondents did not express, while 22% adjusted the interaction that NPCs have with the physical elements of the built environment ( eliminating the possibility of walking through walls and doors).
11% of respondents felt it was important to make the environment more truthful through the implementation of furniture, and still another 11% to use more attractive textures.

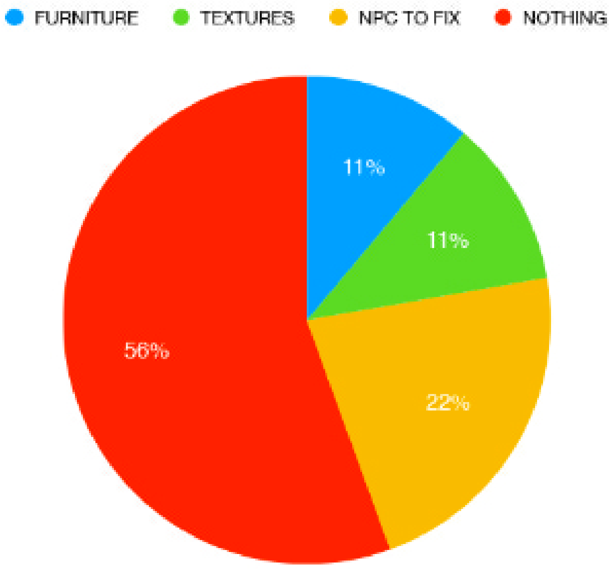



Figura 6.58: Evaluation of missing parts in the project.

# Capitolo 7

# Discussion

Through immersive virtual reality, this thesis research seeks to examine the effects of new driving systems while taking into account individual behaviors and personal physical and cognitive health.
More generally, such technology is considered useful for evacuation drills because physical drills can be affected by distortions and oversimplifications of real-world situations (e.g., oversimplifications of reaching safety/exiting the building, reaching a rendezvous point, and actual environmental conditions) [4, 7, 9, 10].
Moreover, with immersive virtual reality, trainings are often conducted outside normal working hours to minimize risks to occupants and costs to business continuity (in terms of monitoring devices/human resources and loss of service delivery) [6, 11].
An additional limitation is inconsistent and/or biased data collection during physical emergency exercises, often due to the lack of systematic and objective data collection methods [15].
Even though this work has some limits (essentially because of the simple size, especially for some kind of tests and sub-conditions of the sample) the results obtained from these studies, therefore, provide a limited understanding of the drills and the ability to compare them and evaluate whether the drills constitute a valid evacuation model [15].
In addition, previous work points to the limited evidence of lasting benefits in physical evacuation trials compared to trials done with VR, given the high contrast between test scenarios and the real world [4, 16, 17]. Given these peculiarities that prompted the thesis project to involve immersive virtual reality, a preliminary study of the existing scholarly literature was implemented to search for the strengths and

structure that papers have adopted in their case studies. From this analysis, some gaps immediately arose.

- The nonexistence of a framework law that united all the studies carried out so far;
- The development and study of multi hazard scenarios (thus the development of the tool);
- The development and study of scenarios considering people with different physical and cognitive characteristics as protagonists, studying which category is the most vulnerable;
- The development of scenarios that implement a comparison between different emergency systems applied in the scene, verifying which is the best.

Once framework was drafted that encapsulated all the elements characterizing an experiment of such importance, to make the structure of our simulator more reliable and truthful.

Attention is paid especially to the fact that the scholarly journals did not deal at all with the different roles that characters can play in a built environment. All too often, vulnerable and fragile groups (e.g., individuals with medical or physical problems [12, 13]) are not considered/involved in the tests, even though their engagement should be a priority action in view of their specific characteristics if a dangerous condition occurs [**?**].

With the use of this framework, we formalized scenarios dependent on four basic characteristics:

- The type of built environment considered;
- The type of hazard condition considered;
- The roles of the characters involved in the project;
- The type of emergency system applied in the scenario.

From this, the relevant 20 scenarios were defined, which was followed by the formalization of the methodological approach.

Having outlined the methodology, we implemented the simulator through the use of state-of-the-art, software that could allow us to carry out such a project, such as AutoCAD, Rhinoceros, and finally Unity 3D.

The latter software, through the various scripts added, allowed the collection of data from the 110 tests performed through a Head-Mounted Display (Oculus Quest 1).

The collected data were analyzed taking into consideration the written methodology that allowed a clear view of the performance performed by the players depending on the alert system employed and according to the different roles played.

Inherent to the comparison between the different alarm systems employed we paid attention to studying to study affordance, but in simplified terms, and the results coming from were corroborated, or not, by the performance calculated through the final life with which the players finished the exercise.

It is found that in the scene where the integrated warning system was present, users had fewer interactions with the constituent affordance elements (NPCs, Hazard, and Static Emergency Signs) than in the scenario where the standard emergency system was adopted. To this decrease, however, there is an improvement in user performance: a 94.32% of average user life in the integrated emergency system compared to 65.14% in the standard system.

Considering the comparison between the standard system and the integrated system for independent single-hazards, it can be seen that the integrated system allowed for a decrease in user-environment interactions in both the fire and flood scenarios. Moreover, as in the case cited above, this decrease was countered by an improvement in performance, i.e., more players were able to get to safety, recording a higher final life average.

That essentially means that the evacuees appear to regard the integrated systems more favorably, resulting in a reduction in the number of times they must reevaluate how to behave when utilizing the signage.

In terms of occupied areas and escape times, the integrated system was also better than the standard system.

Comparing the integrated emergency systems: alarm+voice in the flooding scenario and multi-hazard scenario, and dynamic signage (augmented reality) in the fire scenario, shows that the integrated system in the fire scenario performs better.

In addition, this system finds validation in the fact that users managed to finish the test with a higher average percentage of life than the same in the standard emergency systems (alarm only).

Looking instead at the comparison between the integrated systems, the system involving augmented reality performed the best.

Relative to the roles that were played by the testers, it is found that they all paid attention to looking for emergency signs.
A true statement considering how many times the player observed the emergency signs in his or her area of vision.
This behavior is consistent with the fact that one is in a hazardous condition and needs to evacuate the building.
Also from the comparison of different roles, the medical staff, while knowing the environment and enjoying good health conditions, was the category that had the most interactions with NPCs, Hazards, and static emergency signs, but performed better than the others.
Comparing people with good health conditions to patients (limping and visual impairments) denotes that the categories "visitors" and "medical staff" performed better than testers playing the roles with disabilities, as expected.
We expected that those with more environmental awareness would be more likely to safeguard themselves given the various responsibilities, depending on physical and cognitive conditions. In terms of the physical conditions, however, we anticipated that motor issues might extend the time needed for evacuation.
In fact, comparing the visitor and medical staff categories taking into consideration the variable "knowledge of the environment" reports that the medical staff had more interactions with the environment, but managed to get to safety more than the visitor category.
Comparing the different disabilities affecting the patients considered in the project denotes that those with visual impairments had more interactions with the environment, but managed to get to safety than those with limited motor skills.
Summarizing what has been said. The study of the different roles implemented in the project allowed the assumption to be valid that the more characters see/interact with the environment the more they have the ability to get to safety.
However, the thesis project has some limitations: - The low number of tests performed;
- The low quality of the proposed environment (missing furniture, missing signage, problems with NPCs, problems opening doors).
- No possibility of interaction between player and NPCs - No heat generators and no

anxiety sensors. - Rendering quality set at 72 FPS.

# Capitolo 8

# Conclusions and Future challenges

With the same emergency systems applied (standard vs. integrated), the integrated system wins over the standard system. In addition, the integrated system significantly reduces the interaction the user has with the environment, performing better.

Regarding roles, on the other hand, greater interaction with the environment ensures that the user can evacuate the building and reach a safe point, performing a superior performance.

In the case of roles, knowledge of the environment and health conditions play a key role. But among these two variables, the one that most affects performance is the physical condition that the user plays in the scene; especially if the player is afflicted with motor impairments. The result achieved offers a clear reading on possible future research.

However, these results could be improved by increasing the sample under investigation and consequently increasing the reliability of the final data.

By incorporating furniture, adding directional signage indicating the location of stairs and elevators in the constructed environment, and improving the realism of doors, one can also improve the quality of the virtual environment.

Fixing NPCs' behavior will also enable them to communicate with the player (for example: able to give information, or need help).

Use eye-tracking technology to determine what the player is most drawn to in the environment, or incorporate sensors that monitor the amount of fear during the experiment.

Finally, upgraded devices with improved rendering quality, like the Oculus quest 2 or Oculus quest pro, might be utilized in place of the virtual reality tool used in our project (Oculus quest 1).

In addition, an attempt could be made to integrate "de facto" technology into the environment that would allow all people, regardless of their physical condition, to be able to get to safety.

The most efficient technology found in our case study appears to be augmented reality and in this regard, one could try to realize such technology and implement it in the scene through the use of building engineering and information technology.

# Capitolo 9

# Annex A

| TESTER | AGE RANGE | BACKGROUND | GLASSES | Corridor **A** | | Corridor **B** | | Corridor **C** | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | DETECTION (meters) | CONFIDENCE (meters) | DETECTION | CONFIDENCE | DETECTION | CONFIDENCE |
| 1 | B | PHD STUDENT | I | 30 | 22,9 | 30 | 23 | 29,7 | 23,25 |
| 2 | B | PHD STUDENT | I | 30 | 22,5 | 30 | 22,9 | 30 | 22,8 |
| 3 | B | PHD STUDENT | O | 30 | 22,5 | 30 | 23 | 29,8 | 23 |
| 4 | C | PROFESSOR | O | 29,65 | 18,7 | 29,5 | 18,9 | 28,2 | 20,5 |
| 5 | C | EMPLOYEE | O | 29,7 | 21,8 | 30 | 21 | 30 | 21,5 |
| 6 | A | STUDENT | O | 29,95 | 22,5 | 30 | 23 | 30 | 23,1 |
| 7 | A | STUDENT | I | 30 | 22,8 | 30 | 23 | 29,3 | 22,9 |
| 8 | A | STUDENT | 0 | 29,75 | 21,5 | 30 | 22 | 30 | 22,5 |
| 9 | A | PHD | I | 29,95 | 22,9 | 30 | 20,9 | 30 | 21,5 |
| 10 | B | PHD | I | 30 | 22,9 | 30 | 23,1 | 30 | 22,9 |
| 11 | A | STUDENT | I | 30 | 23 | 29,8 | 23 | 29,8 | 23 |
| 12 | A | PHD STUDENT | O | 30 | 23,3 | 30 | 23,35 | 30 | 23 |
| 13 | C | EMPLOYEE | I | 29,65 | 22,1 | 29,9 | 21 | 30 | 20,5 |
| 14 | C | EMPLOYEE | O | 29,7 | 21,3 | 29,8 | 22 | 29,5 | 22 |
| 15 | B | PROFESSOR | O | 30 | 21,8 | 30 | 19 | 29,9 | 18,3 |
| 16 | B | PROFESSOR | O | 29,95 | 22 | 30 | 19,5 | 30 | 20 |
| 17 | C | PROFESSOR | O | 29,7 | 22,5 | 29,6 | 20 | 30 | 19,8 |
| 18 | A | STUDENT | I | 29,95 | 22,7 | 30 | 23 | 30 | 23 |
| 19 | B | EMPLOYEE | I | 29,95 | 22 | 30 | 21,7 | 30 | 21,5 |
| 20 | B | EMPLOYEE | O | 29,95 | 22 | 30 | 21,8 | 30 | 22,2 |
| 21 | A | PHD STUDENT | O | 30 | 23 | 30 | 23 | 29,9 | 22,9 |
| 22 | B | EMPLOYEE | I | 30 | 22,8 | 30 | 22,5 | 30 | 22,5 |
| 23 | B | PHD STUDENT | I | 30 | 21,3 | 29,8 | 19,5 | 30 | 19,7 |
| 24 | B | EMPLOYEE | I | 30 | 22,8 | 30 | 22 | 29,8 | 21,8 |
| 25 | A | STUDENT | O | 30 | 22,85 | 30 | 22,5 | 30 | 22,3 |
| 26 | C | PROFESSOR | O | 29,7 | 22,5 | 30 | 21,5 | 30 | 20,3 |
| 27 | C | EMPLOYEE | I | 29,95 | 21,5 | 30 | 19,2 | 30 | 19,4 |
| 28 | C | EMPLOYEE | O | 29,75 | 20 | 29,7 | 19,5 | 30 | 19,2 |
| 29 | B | PHD STUDENT | I | 29,8 | 21,5 | 30 | 19,5 | 30 | 19 |
| 30 | B | PROFESSOR | I | 30 | 21 | 30 | 22,6 | 30 | 22 |
| 31 | B | EMPLOYEE | O | 29,9 | 22 | 30 | 22 | 30 | 21,9 |
| 32 | B | EMPLOYEE | I | 29,95 | 22,2 | 30 | 22 | 29,8 | 22 |
| 33 | B | PHD STUDENT | O | 29,9 | 22 | 30 | 21,5 | 29,9 | 21 |
| 34 | A | STUDENT | I | 30 | 22 | 30 | 21,5 | 30 | 21,2 |
| 35 | A | STUDENT | I | 30 | 22,5 | 30 | 22 | 30 | 22,5 |
| 36 | A | STUDENT | O | 30 | 22,8 | 30 | 23 | 30 | 23 |
| | | | Average (meters) | 29,91111111 | 22,12361111 | 29,94722222 | 21,6375 | 29,87777778 | 21,60972222 |
| | | | Average dev (cm) | 35 | 460 | 40 | 445 | 180 | 490 |

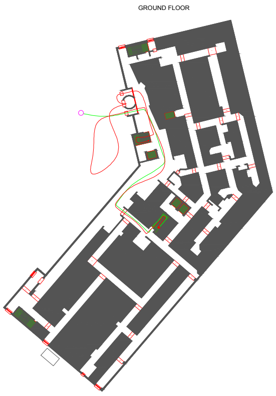
| Corridor A | Corridor B | Corridor C |
|---|---|---|
| H corrid: 3.2 m | H corrid: 3.2 m | H corrid: 3.2 m |
| W corrid: 2.44 m | W corrid: 3.6 m | W corrid: 2.44 m |
| L corrid: 30 m | L corrid: 30 m | L corrid: 30 m |
| dim. sign: 0.23 x 0.5 m | dim. sign: 0.23 x 0.5 m | dim. sign: 0.23 x 0.5 m |

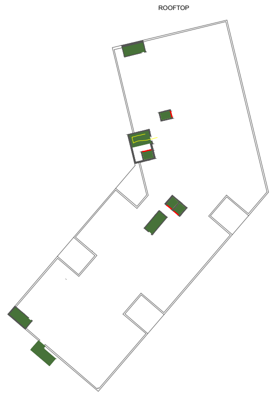
# Capitolo 10

# Annex B

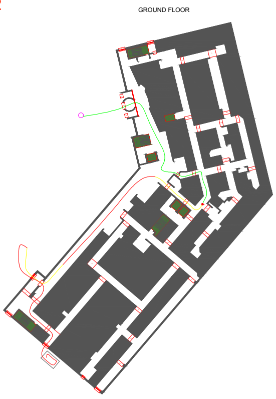
FLOOD-VISITOR-STANDARD SYSTEM

T1



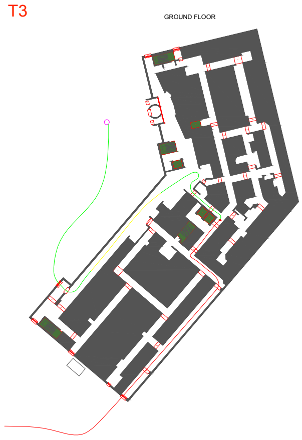




T2




FLOOD-VISITOR-STANDARD SYSTEM

T3

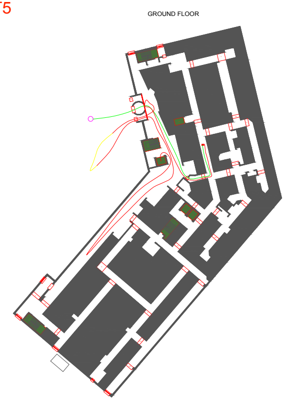




T4

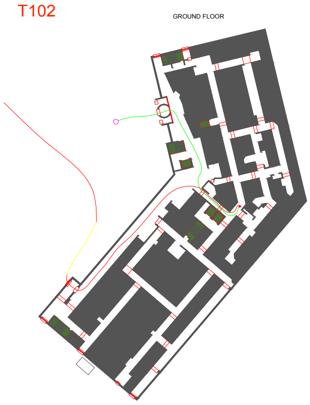

FLOOD-VISITOR-STANDARD SYSTEM

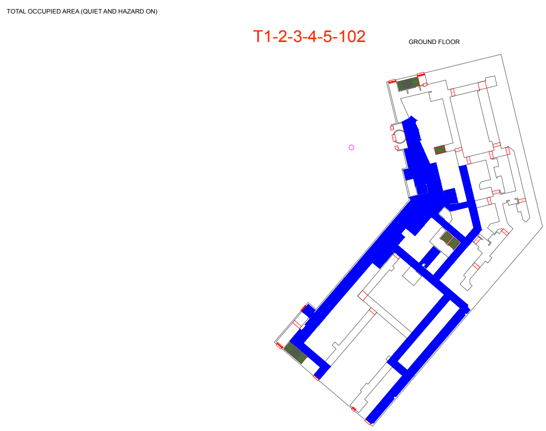
T5

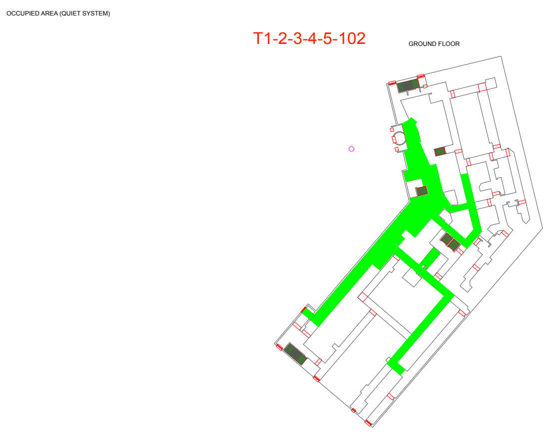


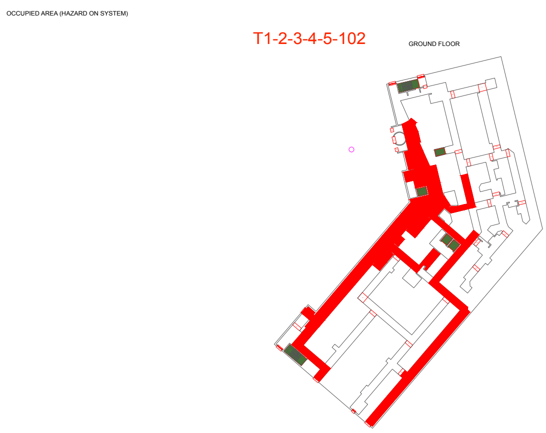


T102





TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T1-2-3-4-5-102
GROUND FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T1-2-3-4-5-102
GROUND FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T1-2-3-4-5-102
GROUND FLOOR

FLOOD-STAFF-STANDARD SYSTEM

T6



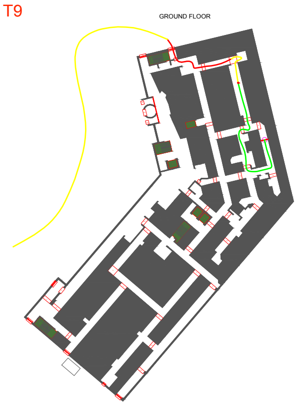
T7


FLOOD-STAFF-STANDARD SYSTEM

T8



T9

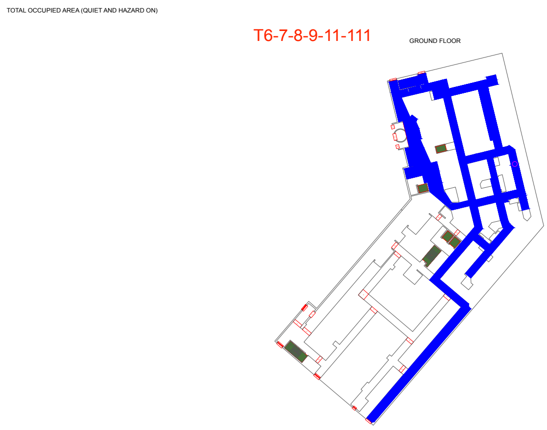


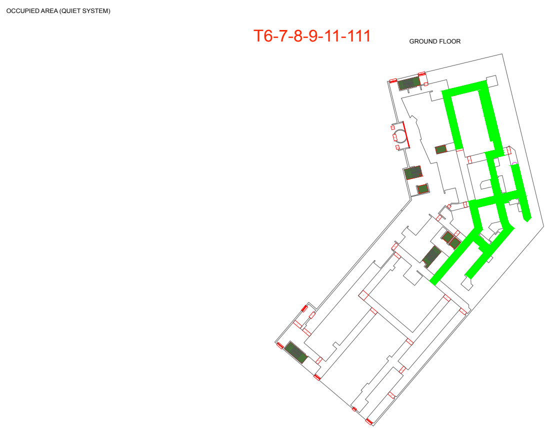

FLOOD-STAFF-STANDARD SYSTEM

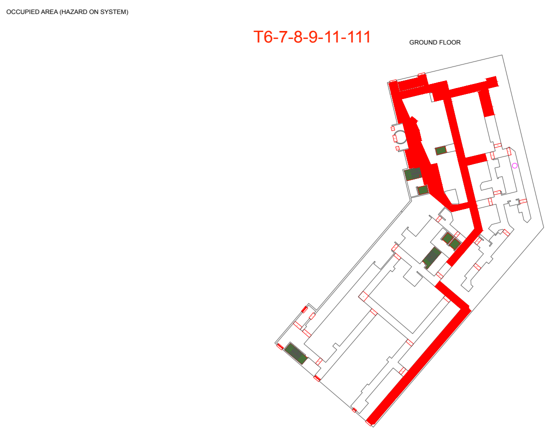
T11



T111

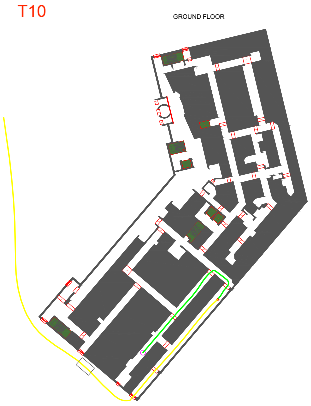


TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T6-7-8-9-11-111
GROUND FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T6-7-8-9-11-111
GROUND FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T6-7-8-9-11-111
GROUND FLOOR

FLOOD-VISUAL IMP.-STANDARD SYSTEM

T10



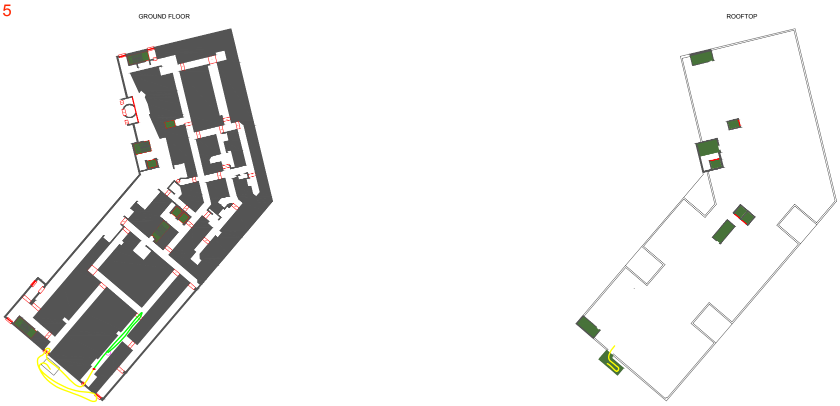


T13


FLOOD-VISUAL IMP.-STANDARD SYSTEM

T14


T15



FLOOD-VISUAL IMP.-STANDARD SYSTEM

T16

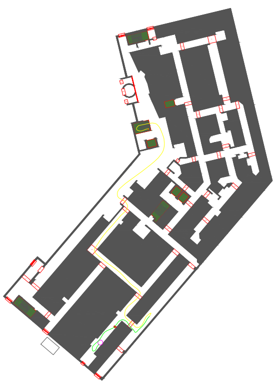

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T10-13-14-15-16
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T10-13-14-15-16
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T10-13-14-15-16
GROUND FLOOR
FIRST FLOOR

FLOOD-LIMPING-STANDARD SYSTEM

T12

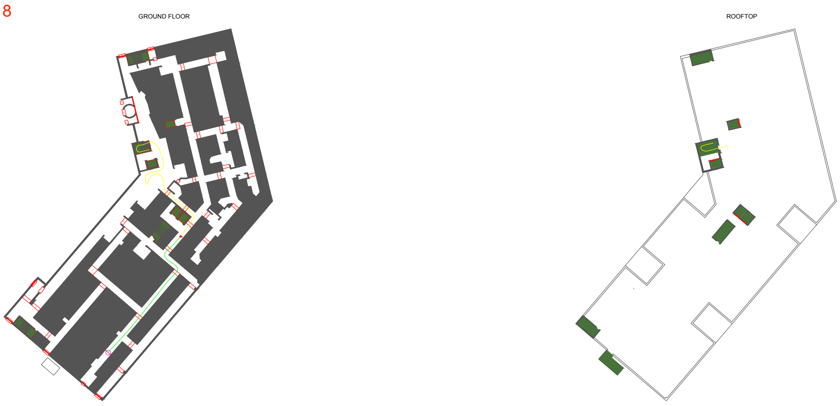




T17


FLOOD-LIMPING-STANDARD SYSTEM

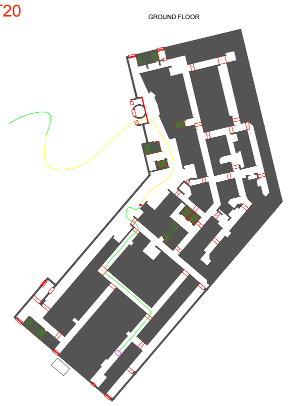
T18



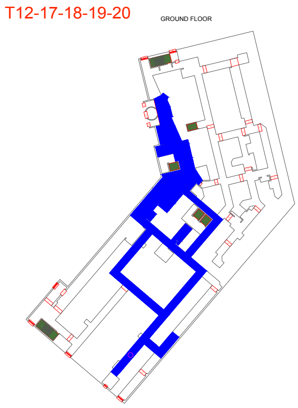

T19

FLOOD-LIMPING-STANDARD SYSTEM

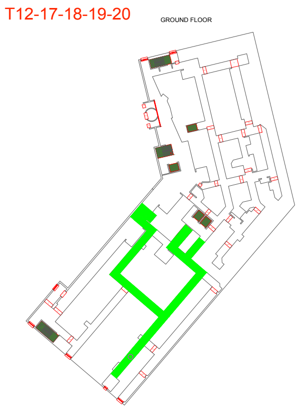
T20




TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)




OCCUPIED AREA (QUIET SYSTEM)




OCCUPIED AREA (HAZARD ON SYSTEM)

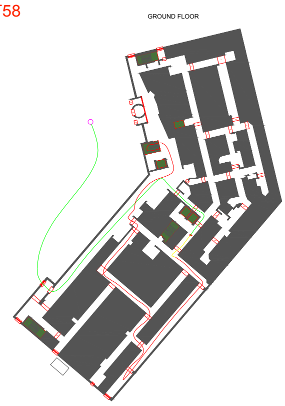
FLOOD-VISITOR-INTEGRATED SYSTEM

T56


T57

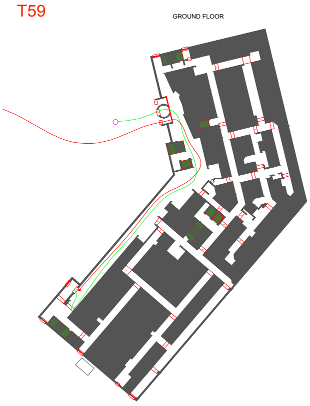
FLOOD-VISITOR-INTEGRATED SYSTEM

T58





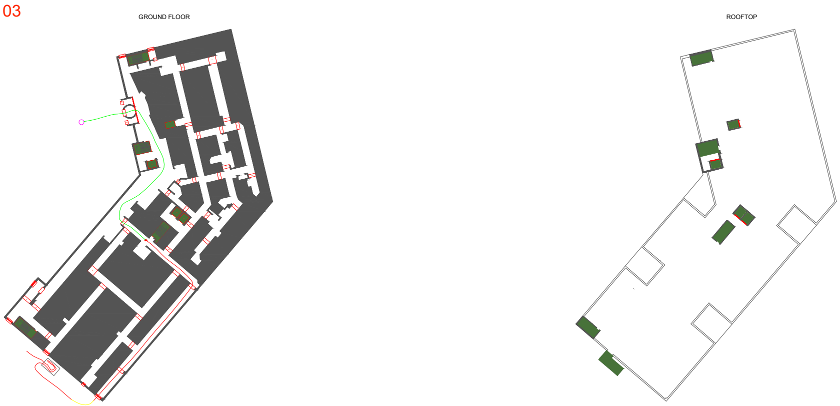
T59




FLOOD-VISITOR-INTEGRATED SYSTEM

T60


T103



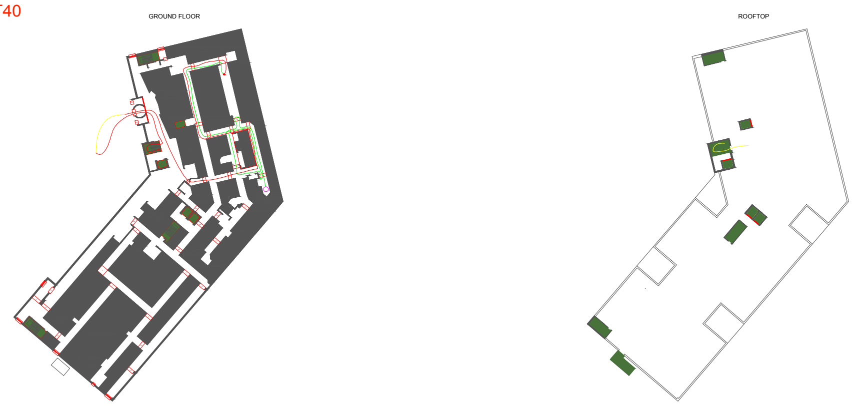
TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)


OCCUPIED AREA (QUIET SYSTEM)

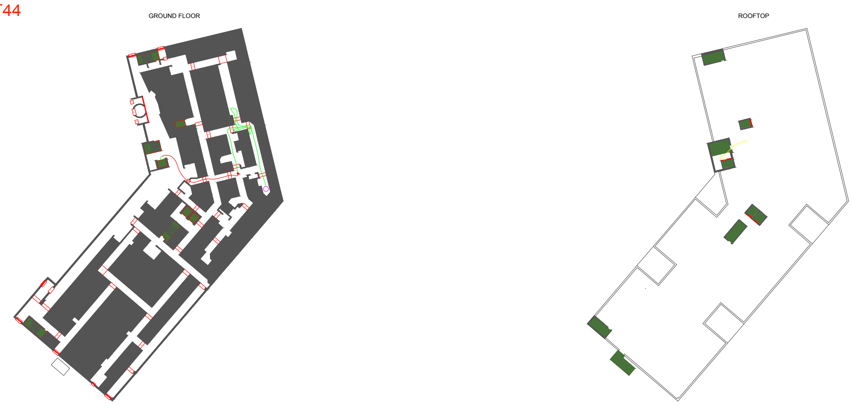

OCCUPIED AREA (HAZARD ON SYSTEM)

FLOOD-STAFF-INTEGRATED SYSTEM

T40




T44



FLOOD-STAFF-INTEGRATED SYSTEM

T45



T46

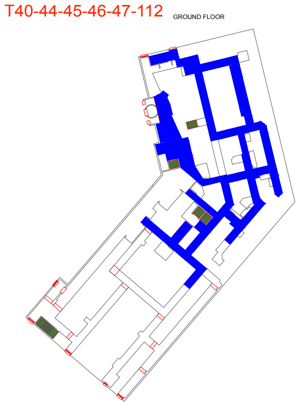

FLOOD-STAFF-INTEGRATED SYSTEM

T47

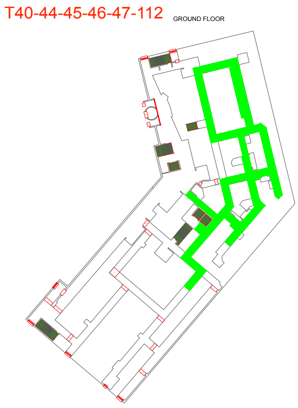


T112


TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)




OCCUPIED AREA (QUIET SYSTEM)




OCCUPIED AREA (HAZARD ON SYSTEM)

FLOOD-VISUAL IMP.-INTEGRATED SYSTEM

T21



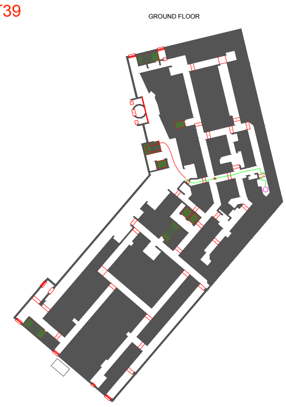
T22


FLOOD-VISUAL IMP.-INTEGRATED SYSTEM

T38



T39

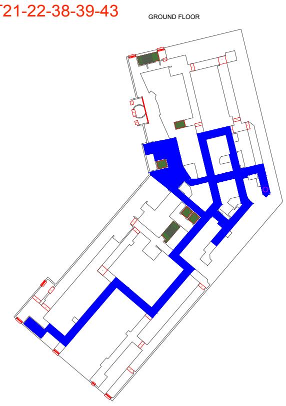



FLOOD-VISUAL IMP.-INTEGRATED SYSTEM

T43

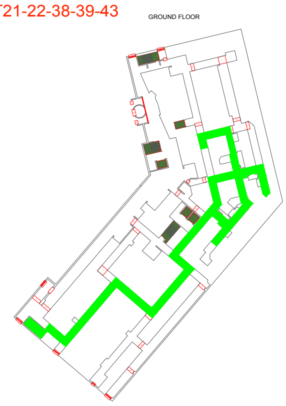

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)

T21-22-38-39-43



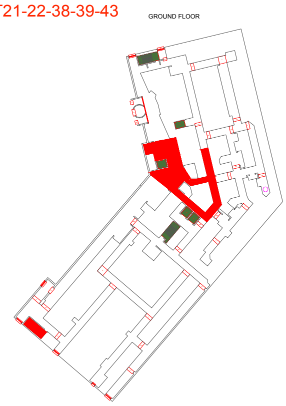

OCCUPIED AREA (QUIET SYSTEM)

T21-22-38-39-43




OCCUPIED AREA (HAZARD ON SYSTEM)

T21-22-38-39-43



FLOOD-LIMPING-INTEGRATED SYSTEM

T34



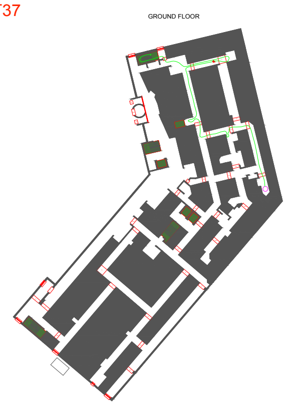
T35


FLOOD-LIMPING-INTEGRATED SYSTEM

T36



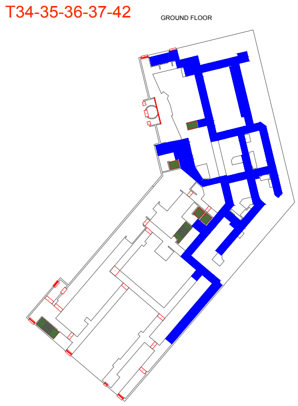
T37



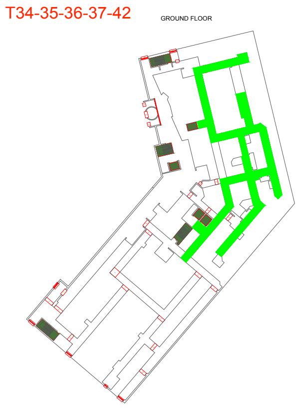

FLOOD-LIMPING-INTEGRATED SYSTEM

T42


TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)



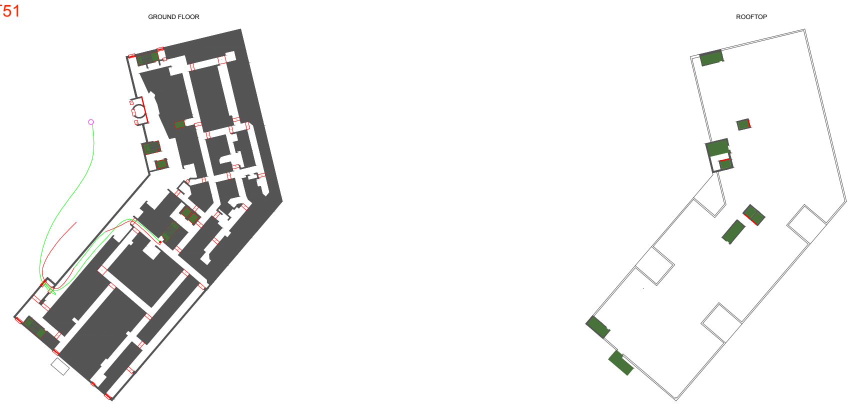

OCCUPIED AREA (QUIET SYSTEM)




OCCUPIED AREA (HAZARD ON SYSTEM)

FIRE-VISITOR-STANDARD SYSTEM

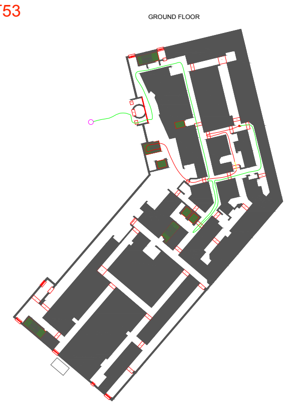
T51




T52

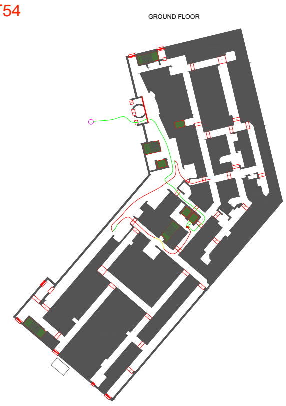
FIRE-VISITOR-STANDARD SYSTEM

T53





T54

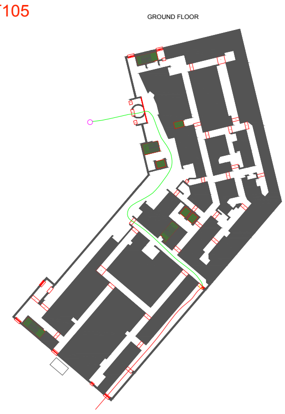



FIRE-VISITOR-STANDARD SYSTEM

T55



T105





TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T51-52-53-54-55-105
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T51-52-53-54-55-105
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T51-52-53-54-55-105
GROUND FLOOR
FIRST FLOOR

FIRE-STAFF-STANDARD SYSTEM

T48


T49

FIRE-STAFF-STANDARD SYSTEM

T50



T29


FIRE-STAFF-STANDARD SYSTEM

T41



T113



TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T29-41-48-49-50-113
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T29-41-48-49-50-113
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T29-41-48-49-50-113
GROUND FLOOR
FIRST FLOOR

FIRE-VISUAL IMP.-STANDARD SYSTEM

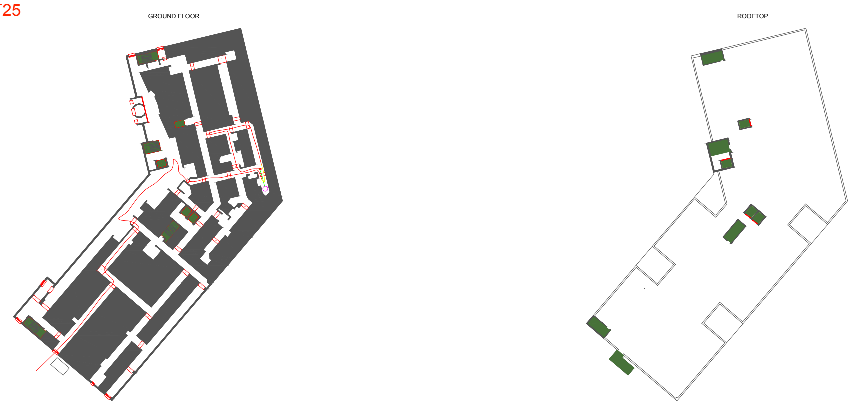
T23



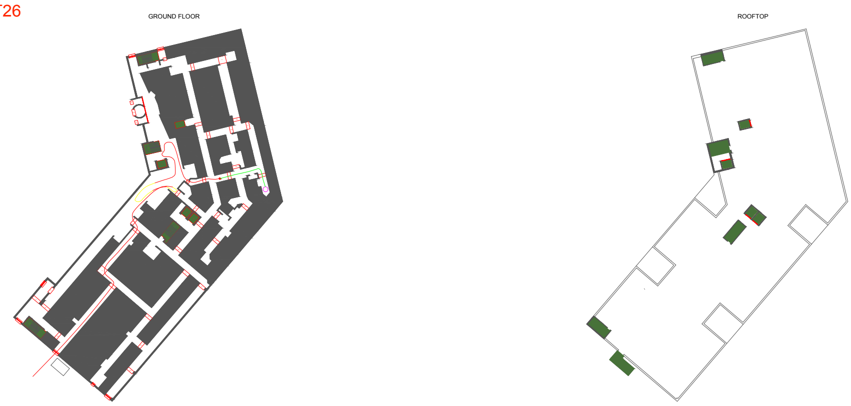
T24


FIRE-VISUAL IMP.-STANDARD SYSTEM

T25

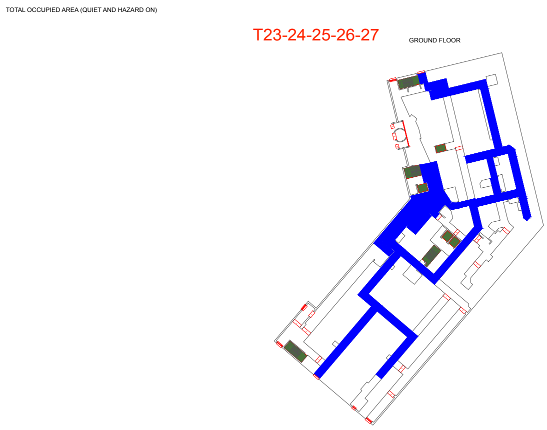


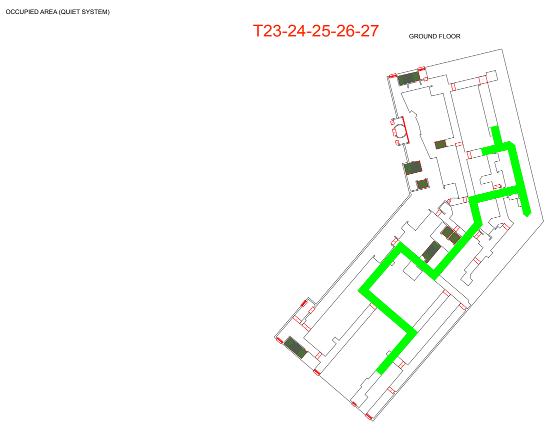

T26

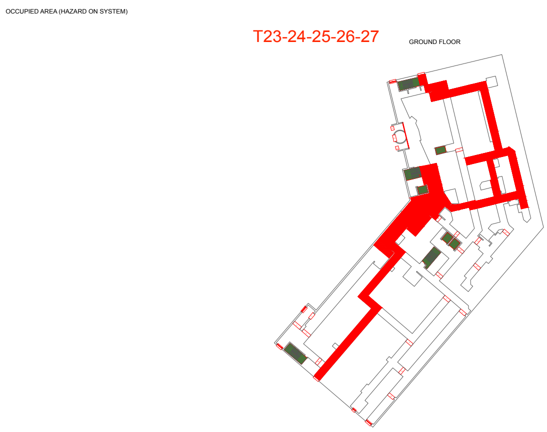


FIRE-VISUAL IMP.-STANDARD SYSTEM

T27

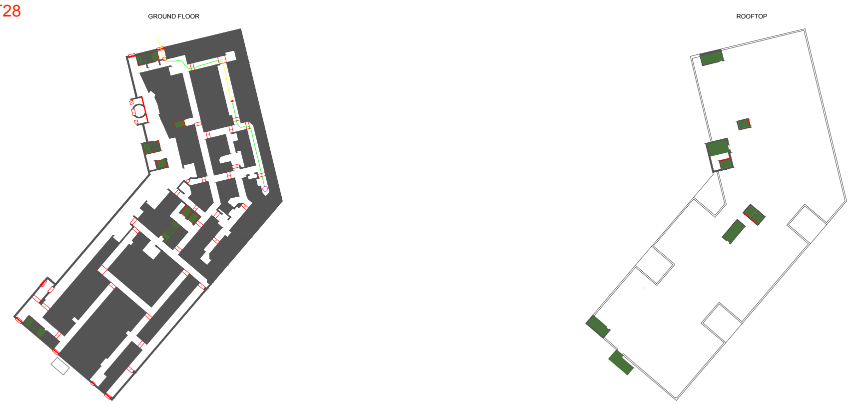


TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T23-24-25-26-27
GROUND FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T23-24-25-26-27
GROUND FLOOR

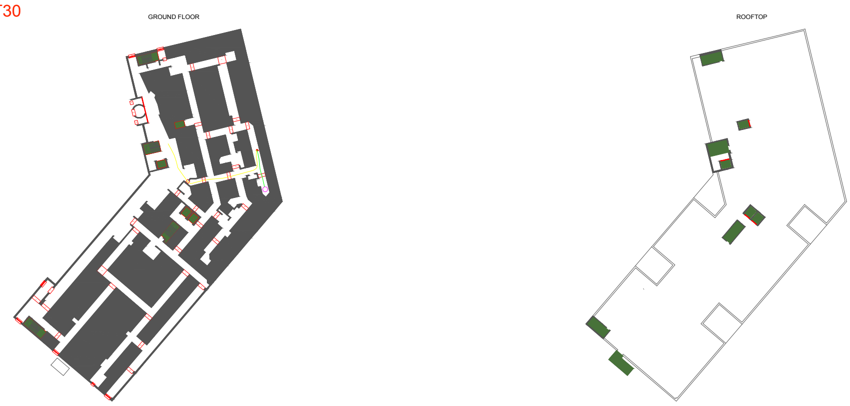

OCCUPIED AREA (HAZARD ON SYSTEM)
T23-24-25-26-27
GROUND FLOOR

FIRE-LIMPING-STANDARD SYSTEM

T28




T30



FIRE-LIMPING-STANDARD SYSTEM

T31

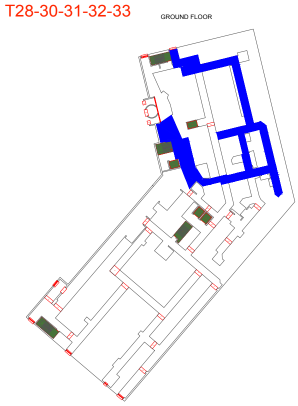


T32


FIRE-LIMPING-STANDARD SYSTEM

T33


TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)

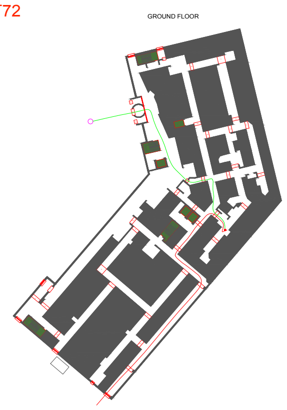



OCCUPIED AREA (QUIET SYSTEM)


OCCUPIED AREA (HAZARD ON SYSTEM)

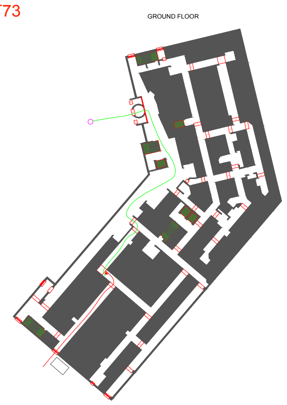
FIRE- VISITOR-INTEGRATED SYSTEM

T72



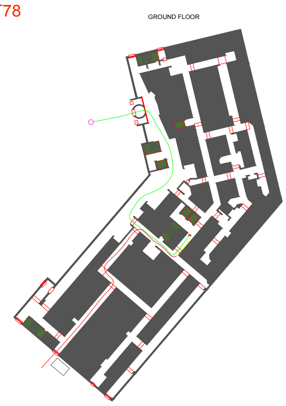


T73



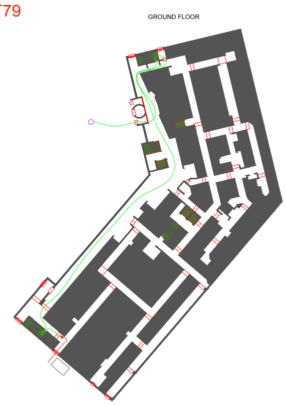

FIRE-VISITOR-INTEGRATED SYSTEM

T78





T79

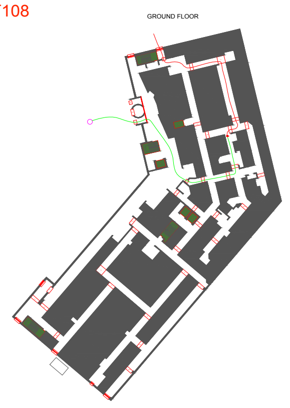



FIRE- VISITOR-INTEGRATED SYSTEM

T80

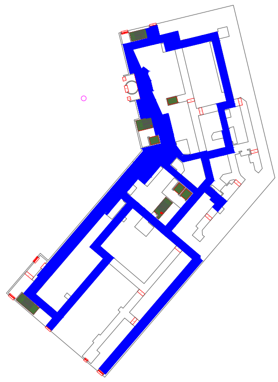


T108



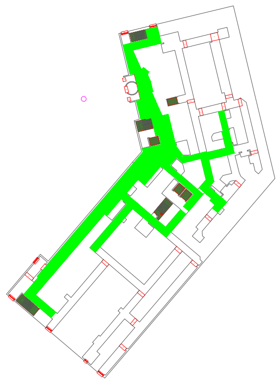

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)

T72-73-78-79-80-108 GROUND FLOOR



OCCUPIED AREA (QUIET SYSTEM)

T72-73-78-79-80-108 GROUND FLOOR



OCCUPIED AREA (HAZARD ON SYSTEM)

T72-73-78-79-80-108 GROUND FLOOR

FIRE- STAFF-INTEGRATED SYSTEM

T68



T69


FIRE- STAFF-INTEGRATED SYSTEM

T70



T71

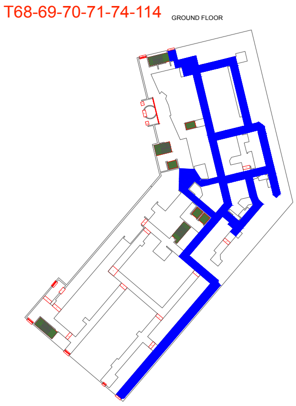

FIRE- STAFF-INTEGRATED SYSTEM

T74

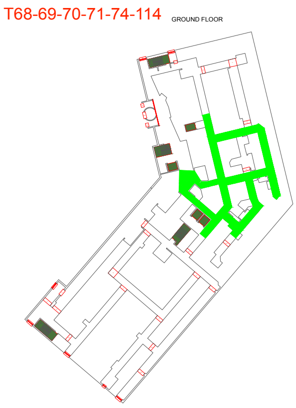


T114


TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)




OCCUPIED AREA (QUIET SYSTEM)




OCCUPIED AREA (HAZARD ON SYSTEM)

FIRE- VISUAL IMP.-INTEGRATED SYSTEM

T66



T67


FIRE- VISUAL IMP.-INTEGRATED SYSTEM

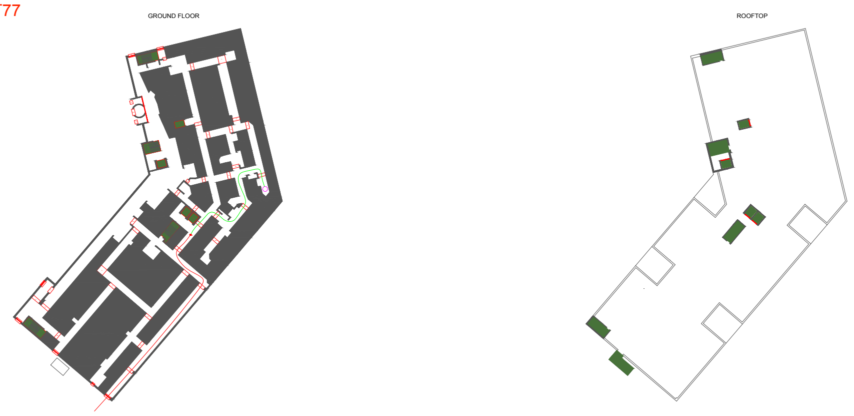
T75

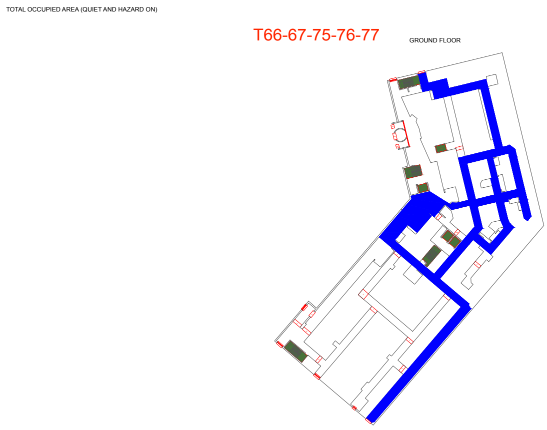


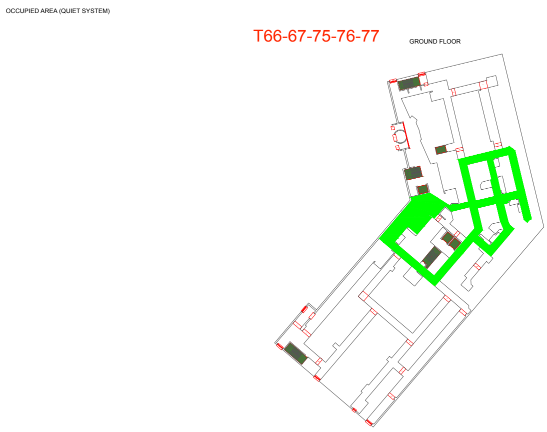
T76

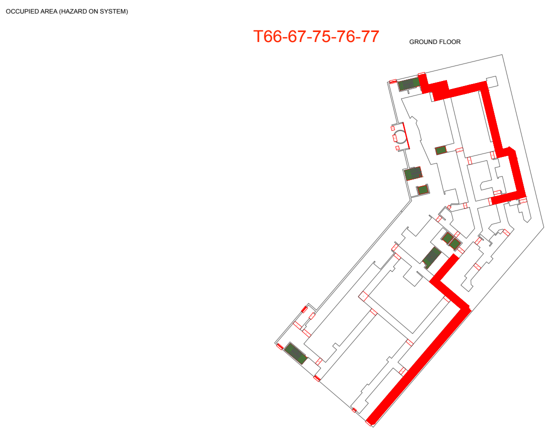

FIRE- VISUAL IMP.-INTEGRATED SYSTEM

T77



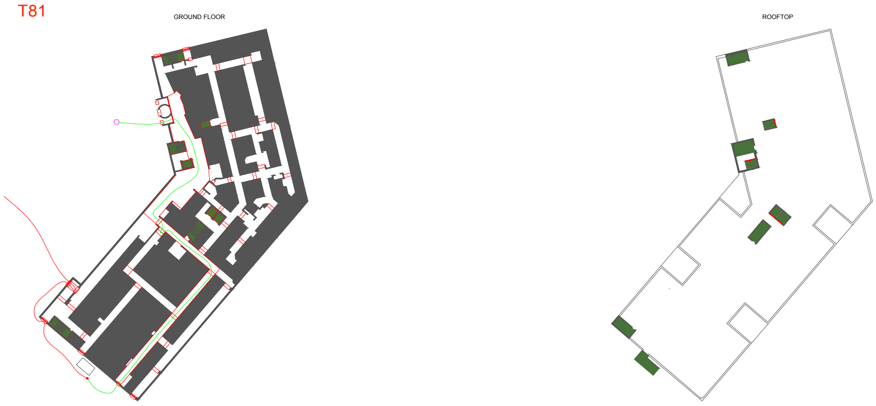

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T66-67-75-76-77
GROUND FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T66-67-75-76-77
GROUND FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T66-67-75-76-77
GROUND FLOOR

FLOOD+FIRE-VISITOR-INTEGRATED SYSTEM

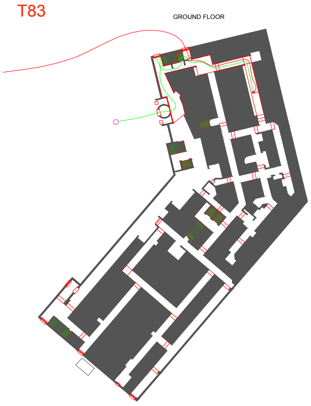
T81




T82

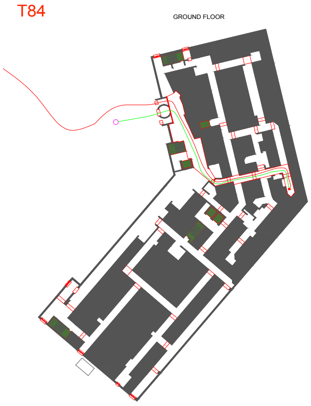
FLOOD+FIRE-VISITOR-INTEGRATED SYSTEM

T83



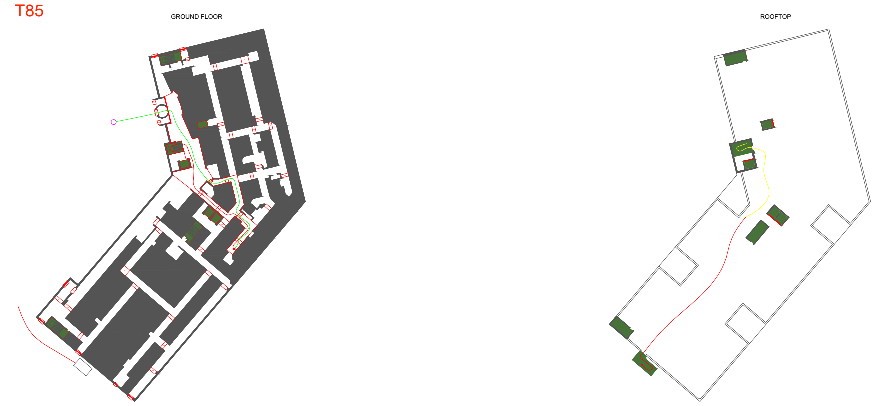


T84

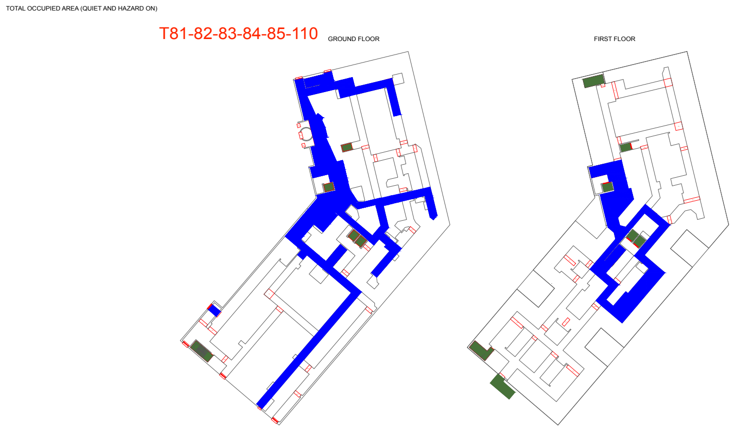



FLOOD+FIRE-VISITOR-INTEGRATED SYSTEM

T85




T110

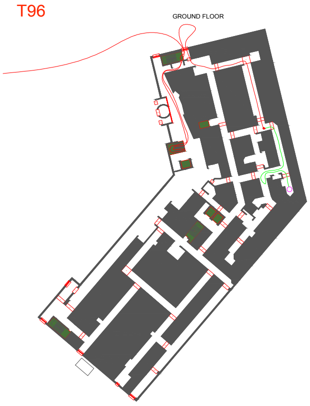

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T81-82-83-84-85-110
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T81-82-83-84-85-110
GROUND FLOOR
FIRST FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T81-82-83-84-85-110
GROUND FLOOR
FIRST FLOOR

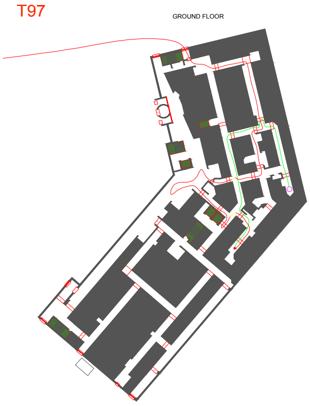
FLOOD+FIRE-STAFF-INTEGRATED SYSTEM

T96





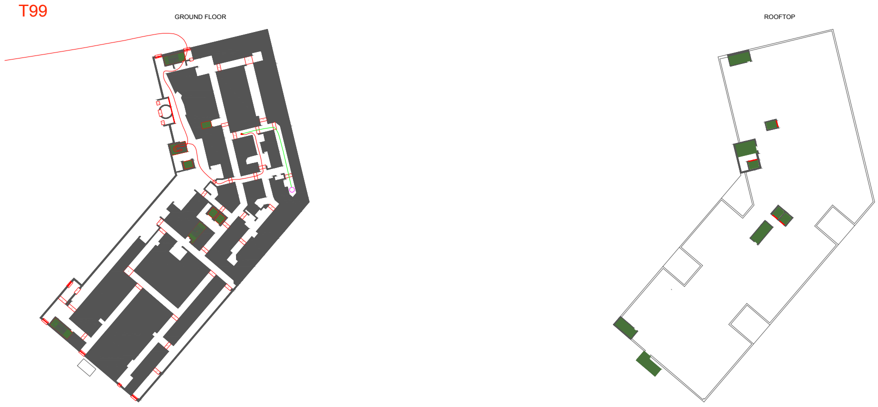
T97




FLOOD+FIRE-STAFF-INTEGRATED SYSTEM

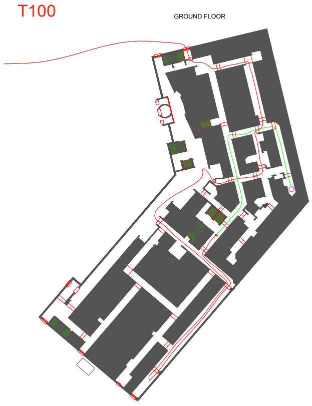
T98


T99



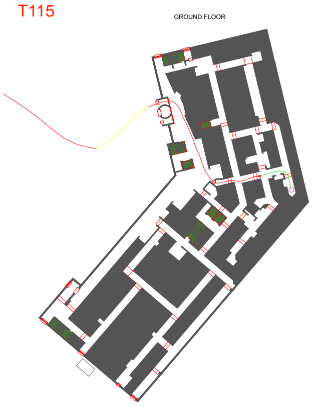
FLOOD+FIRE-STAFF-INTEGRATED SYSTEM

T100





T115



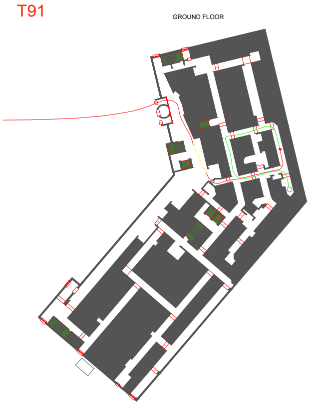

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)


OCCUPIED AREA (QUIET SYSTEM)


OCCUPIED AREA (HAZARD ON SYSTEM)

FLOOD+FIRE-VISUAL IMP.-INTEGRATED SYSTEM

T91

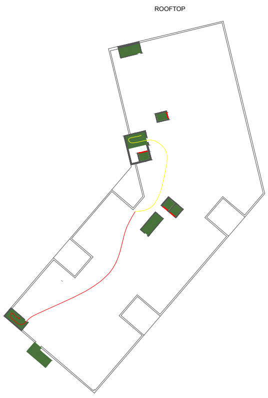




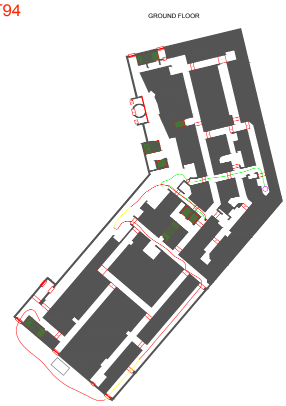
T92

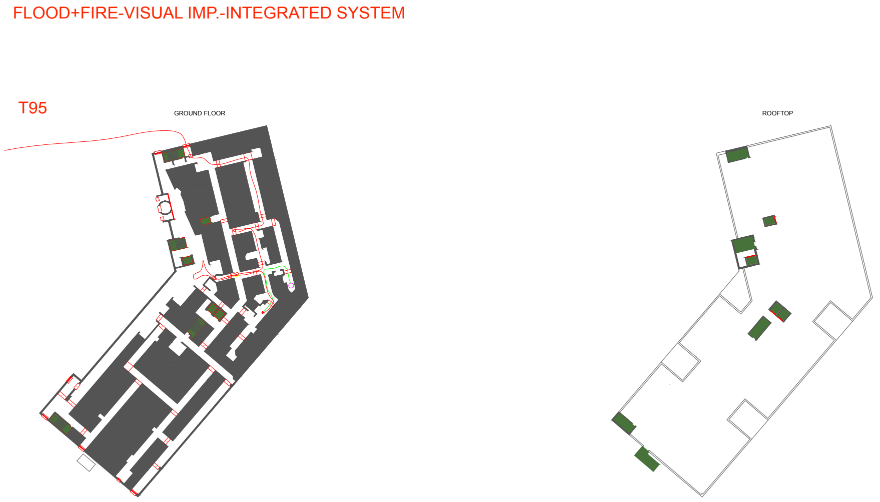

FLOOD+FIRE-VISUAL IMP.-INTEGRATED SYSTEM

T93

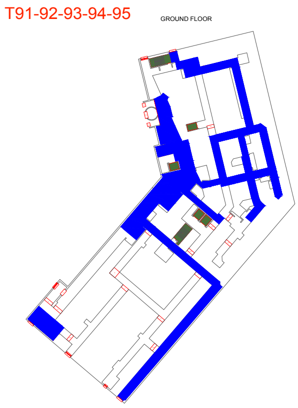




T94

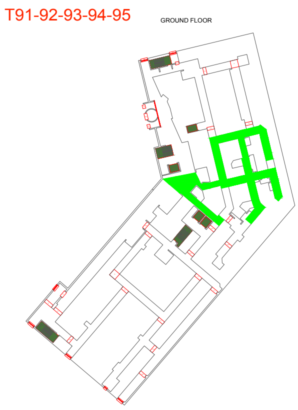




FLOOD+FIRE-VISUAL IMP.-INTEGRATED SYSTEM
T95
GROUND FLOOR
ROOFTOP

TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)



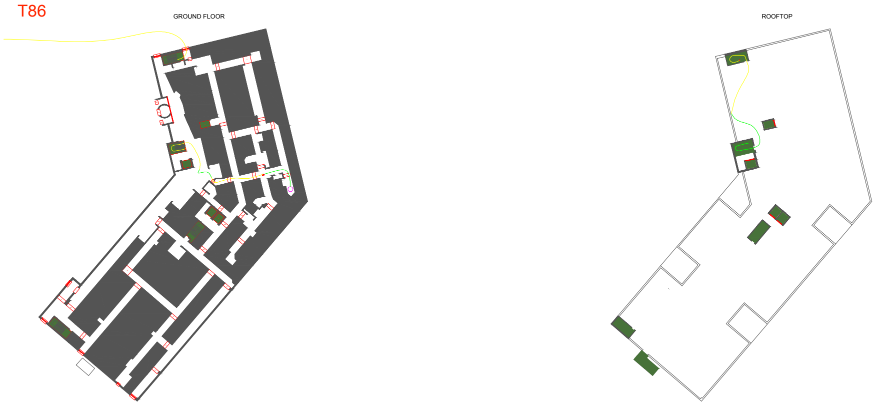

OCCUPIED AREA (QUIET SYSTEM)



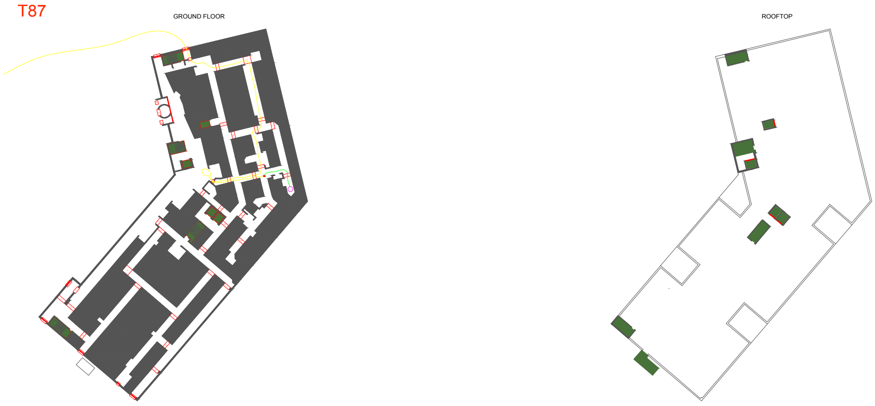

OCCUPIED AREA (HAZARD ON SYSTEM)

FLOOD+FIRE-LIMPING-INTEGRATED SYSTEM

T86

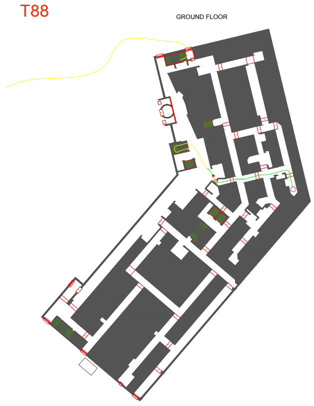


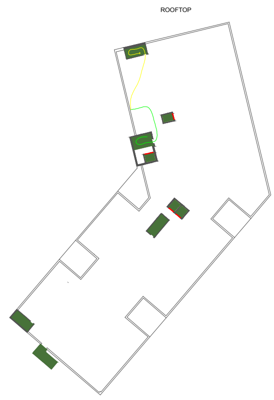

T87



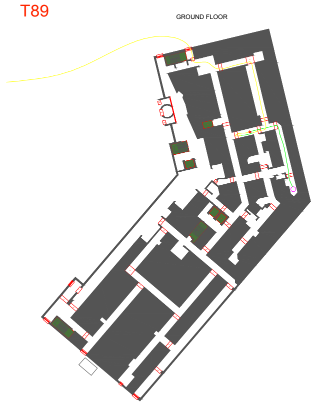
FLOOD+FIRE-LIMPING-INTEGRATED SYSTEM

T88



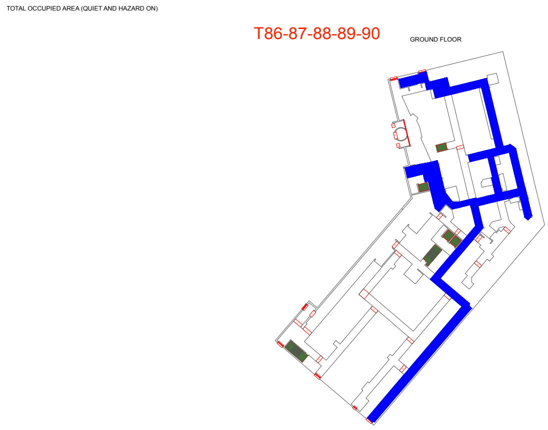



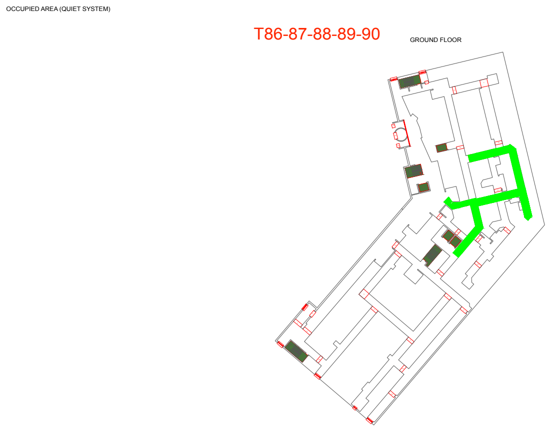

T89

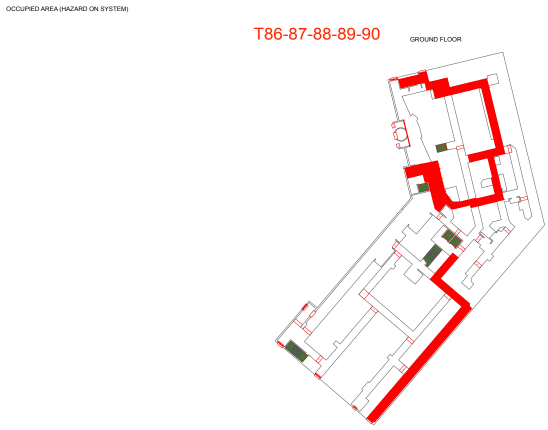



FLOOD+FIRE-LIMPING-INTEGRATED SYSTEM

T90



TOTAL OCCUPIED AREA (QUIET AND HAZARD ON)
T86-87-88-89-90
GROUND FLOOR


OCCUPIED AREA (QUIET SYSTEM)
T86-87-88-89-90
GROUND FLOOR


OCCUPIED AREA (HAZARD ON SYSTEM)
T86-87-88-89-90
GROUND FLOOR

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