Study and validation of modelling for planned evacuation in Compact Muon Solenoid (CMS)

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Abstract
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An unannounced evacuation drill was conducted in the CMS cavern which capture data from 10 occupants through questionnaires, observation and video recording. The drill highlighted the discrepancies between self-reported behaviours and actual action which implicates the need for cross-verification of data. Key findings include an average pre-evacuation time of 55s.

Also, simulated scenario analysis by changing the behavioural and design factors such as occupant load, distribution, usage of lifts and emergency devices were studied which were based on CMS drill data and past studies. The model revealed variability in evacuation time across different scenarios, with coefficients of variation ranging from 21% to 45%. The adjusted evacuation model validated against the CMS drill.

Future works could focus on standardizing data collection method to aim establishing a mutual database for evacuation data comparison between different background. Exploring non-intrusive technologies such as RFID could enhance data accuracy by avoiding influence by observers. Moreover, refinement of CMS evacuation models on behavioural and design factors is needed to investigate.

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STUDY AND VALIDATION OF MODELLING FOR PLANNED EVACUATION IN COMPACT MUON SOLENOID (CMS)

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May 2024

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International Master of Science in Fire Safety Engineering

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摘要

這篇論文研究了進行突擊疏散演習的記錄方法，以增强對CERN複合緲子電磁鐵（CMS）實驗洞穴内疏散行為和表現的理解。主要目的是驗證CMS地下疏散模擬模型在計劃疏散中的效果，並比較各種數據收集方法。

在CMS洞穴中進行了一次突擊疏散演習，通過問卷調查、觀察和視頻錄像收集了10名人員的數據。這次演習突顯了自報行為和實際行動之間的差異，這表明需要交叉驗證數據。關鍵發現包括平均預疏散時間為55秒。

此外，還對通過改變行為和設計因素如人員負荷、分佈、電梯和應急設備的使用進行模擬場景分析，這些分析基於CMS演習數據和過去的研究。模型揭示了不同場景下疏散時間的變異性，變異係數範圍從21%到45%。經過調整的疏散模型已對照CMS演習進行了驗證。

未來的工作應集中於標準化數據收集方法，以建立一個共同的數據庫，便於不同背景下的疏散數據比較。探索如RFID等非侵入性技術可以通過避免觀察者的影響來提高數據的準確性。需要進一步完善CMS疏散模型中的行為和設計因素進行深入研究。

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Chapter 1

Introduction and objectives

1.1 Introduction

The Compact Muon Solenoid (CMS) cavern at Point 5 of the European Organization for Nuclear Research (CERN) is part of Large Hadron Collider (LHC) which is located about 100 meters underground on the 1km to southwest of Cessy, a commune in France. The purpose of the facility is to conduct particle physics experiments via the CMS detector with 21.6 m long and diameter of 14.6 m. Its 3D model is shown in Figure 1.1. It locates in the cavern and can detect and can analyze the particles produced by high-energy proton-proton collisions. More than 17500 people from over 110 nationalities work in CERN to contribute the preparation and operation of the physics experiments. The fire safety strategy for the cavern is based on performance-based design due to its uniqueness and complexity. An effective evacuation strategy is one of the key elements in the design for ensuring that occupants can evacuate to a safe place before the environment becomes untenable. The evacuation could be triggered by fire, inert-gas leakage, false alarm and evacuation drill.

The fire safety engineering team typically assesses the safety of the building by comparing the available safe egress time (ASET) and the required safety egress time (RSET)[3]. ASET is the available time for occupants to evacuate a building safely before conditions become untenable due to the smoke, heat or fire which could be assessed with engineering calculation and fire scenario simulation. RSET is the duration for all occupants to evacuate a building to a safe place. The objective in the design is to ensure that ASET is greater than RSET [4] for reserving safety margin. In order words, the conditions within the building remained survivable for longer than it takes for all occupants to evacuate. RSET consists of 4 elements which are detection time, alarm time, pre-evacuation time and movement time, as illustrated in Figure 1.2. The detection

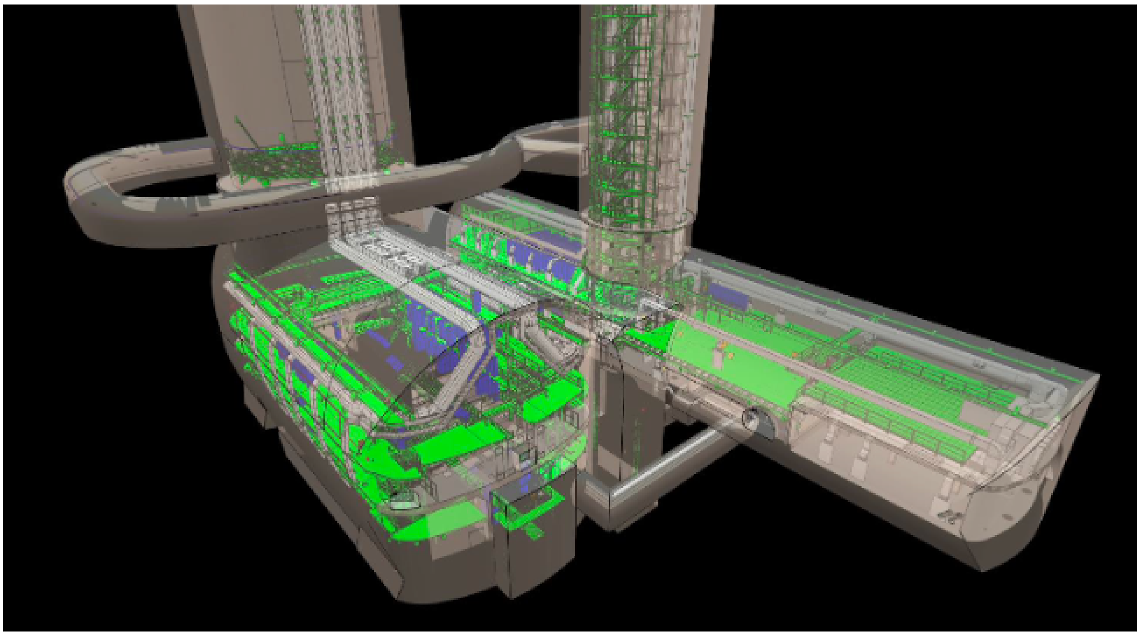


Figure 1.1: 3D model of Compact Muon Solenoid (CMS). Image taken from [1]

time is the time between the ignition of fire and fire detection either by an automatic system or a human. The alarm time is the time between the moment the fire is detected and the alarm is triggered or the fire is reported. Pre-evacuation time can be categorized into two parts (recognition time and response time) which could be included in the duration between receiving cues of fire and purposive movement towards safety [2]. Recognition time is the time interval from alarm activation to the moment when a person realizes that an evacuation is necessary. Response time is the period between the realization and movement towards safety, which includes actions like gathering belongings or firefighting. Movement time corresponds to the time required to travel from the current position to reach a safe place. The total evacuation time is the duration for all the occupants to reach a safe place after hearing the alarm.

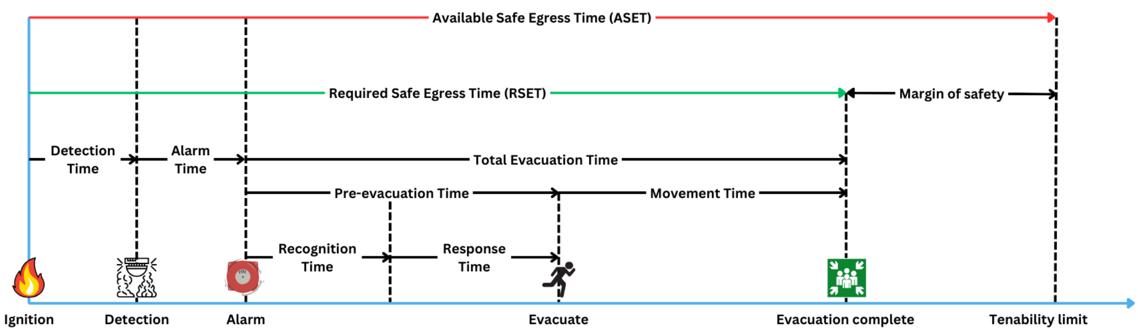


Figure 1.2: Evacuation timeline [2]

There are several ways to obtain RSET values such as hand calculations, evacuation measurements and evacuation simulations. One of the examples of hand calculations is the hydraulic modelling [5], which focuses on evacuees' physical movement by considering interaction between egress components and movement performance. In other words, it does not consider occupants' behaviour and individual pre-evacuation time. Since the settings of scenarios are based on variables such as occupant load and changing environmental conditions, results of evacuation time are generally distributed in a probabilistic approach [6]. In this context, evacuation modelling is a useful tool to estimate RSET value for evacuation situations as it can simulate different scenarios by independent variables which influence evacuation. These models help understanding evacuation performance which allowed fire engineers to evaluate safety measures [7]. In order to obtain data for development and validation of an evacuation model for CMS, it is necessary to review the available data and organize an evacuation drill in the target building to collect relevant data [8, 9, 10], but some evacuation data like pre-evacuation time distribution in underground research facilities are insufficient. Therefore, the evacuation drill would allow to record activities carried out at during the evacuation and select input data align with the organization. The collected data could be utilized to refine evacuation models, input data and examine human behaviour to contribute to future development of evacuation studies and improve the underground facilities' fire protection design.

In an evacuation drill, researchers can measure about occupant characteristics, pre-evacuation time, travelling distance, human behaviour, movement speed, exit choice and flowrate [11]. These data became critical inputs for modelling. Although there are many database and models for different premises such as tunnel, metro station and construction sites [12], [13], their direct applicability to underground research infrastructures like the CMS and ALICE cavern is limited [14], where ALICE is another large detector for physics experiment in CERN. The closest comparable evacuation scenario is detailed in [13], which examines the large-scale evacuation in complicated construction environment. Building an evacuation model for CERN facilities consists of numerous unique challenges including its special and complex structural and architectural features, limited spaces and passing through access safety devices [15]. Also, CMS occupants might need to equip with certain personal protective equipment such as helmet, self-rescue mask and must evacuate by using lift. Existing models may need dedicated validation to represent for this uniqueness of the infrastructure. This is necessary to investigate the evacuation in the CMS and other complex underground research infrastructure through evacuation modelling tools and study the effectiveness of the existing design solutions.

Researchers can use different tools to assess evacuation drills with different effectiveness and accuracy. Data collection methods are important for measurements and assessment of evacuation drill performance. One of the existing methods is to deploy observers during the evacuation and distribute questionnaire immediately after an evacuation drill [16, 11]. Some other data collection approachs are to use camera or even radio frequency identification (RFID) or global positioning system (GPS) technology to record occupant movement [17] but still there is a gap to identify a cost-effective method and evaluate its effectiveness [18]. Even virtual reality (VR) technology has been applied to collect evacuation behavioural data which provide a safe, cost-effective and customizable training environment [19]. VR evacuation drill allows for repeated practice of evacuation procedures in various scenarios includes life-threatening environment without disrupting building operations or posing safety risks. However, physical drills provide a more realistic environment that include the social interaction among evacuees, their physical limitations and unforeseen circumstances that VR evacuation may not show. This can lead to more valid data on how people behave during a real emergency. At the same time, it leads to a question on the cost-effectiveness of each method is and how their time need [18] which could be analyzed by counting the working hours employed to arrange and execute an evacuation drill.

1.2 Objectives

The primary objectives of this thesis are:

1. To develop and validate the evacuation model used for life safety assessments in CMS: enhance the accuracy and relevance of model.
2. To conduct an unannounced evacuation drill collaborating with the CMS Safety Officers and CERN Fire Safety Engineering team in order to obtain a dataset for refining evacuation model.
3. To evaluate and compare various evacuation data collection methods for drills for complex underground facilities like CMS.

1.3 Thesis layout

The thesis is divided into seven chapters. Chapter 1 introduced the research topic, objectives and layout. Chapter 2 provided background information on occupant characteristics, building features in the CMS caverns and evacuation procedures in CMS. Chapter 3 reviewed existing studies on human behaviour in evacuation, evacuation studies related to CMS, data collection methods used in previous evacuation research and evacuation modelling. Chapter 4 described the methodology for the evacuation drill, data collection and the evacuation modelling process and inputs. The chapter 5 and 6 presented the findings from evacuation drill and simulation respectively. Chapter 7 discussed the results and their significance. Chapter 8 provided the conclusion of the thesis and suggested future work. The appendices contained supplementary materials like a sample questionnaire, observation sheet, evacuation route in USC55 and UXC55.

Chapter 2

CMS background and description

2.1 Building characteristics

The CMS detector is hosted in an underground infrastructure connected with surface buildings SDX5 and SX5 (shown in Figure 2.1 by two lift shafts: PM54 and PM56. It can be divided into two parts the experimental cavern (UXC55) and the service cavern (USC55) (shown in Figure 2.2). The dimensions of both of the USC55 and UXC55 are shown in Table 2.1. The caverns are organized on multiple levels (W3, W2, W1, U0, U2, U3) and are interconnected via the UP55 tunnel on the W2 level and the UPX56 tunnel on the U0 level.

2.1.1 UXC55

In the UXC55, the detector is located in the center of the cavern across all 7 levels (from the lowest to highest level: W3 to U3) shown in Figure 2.3. The cavern is divided into four quadrants (far, near, plus and minus) for navigational and operational purposes as shown in Appendix A. Stairs on U2 level allow occupants to access the top of the detector.

2.1.2 USC55

The USC55 is adjacent to the USC55, including six floors (from the lowest to highest level: W2 to U3). The purpose uses of USC55 are for equipment rooms mainly located on U0 and U2 floors. In particular, the EN-CV room for the cooling system, the counting room for electrical systems and the gas room are located at U0 floor as shown in Appendix A. The machine room, the magnet area for storing cryogenic installations and another counting room are located at U2 floor. At the

Figure 2.1: CMS surface layout (orange line: route to assembly point)

time of the study, there was a construction site in the 2PACL-system room at U2 floor and in the mezzanine at U0 floor.

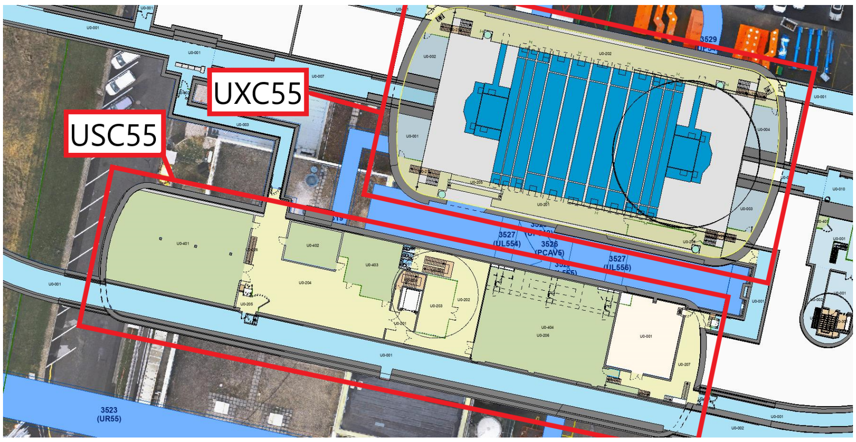


Figure 2.2: Layout in USC55 and UXC55 at U0 level

Building	**UXC55**	**USC55**
Length	83.6m	53.1m
Width	13.7m	24.3m
Height	13.3m	24.5m

Table 2.1: Dimension of USC55 and UXC55

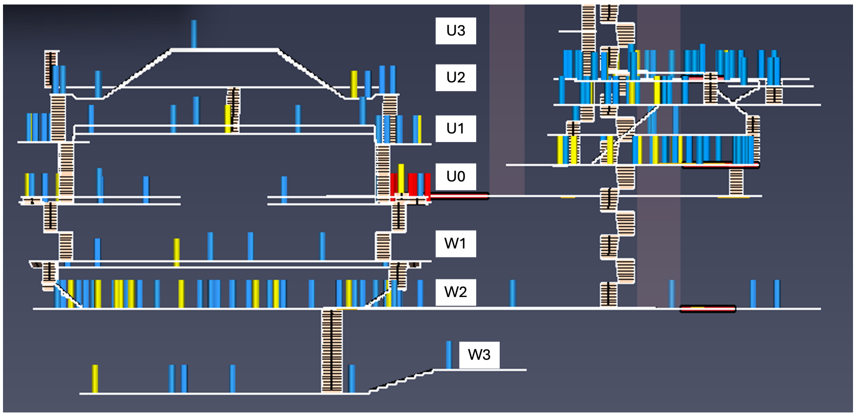


Figure 2.3: Cross section represented in the evacuation model Pathfinder (Left: UXC55; Right: USC55)

2.1.3 Lift shaft

The lift shafts, PM54 and PM56, connect the underground caverns to the surface and are equipped with staircases for exceptional uses including when the lifts are out of order.

The PM54 shift connects the USC55 cavern with building SDX5. The lift serves floor U2, U0 and W2 in USC55 and surface floor in SDX5. The capacity of PM54 lift is 39 persons which is 2.62m long, 1.85m wide and 2.70m high. The PM56 shaft is located in the building SDX5. The lift serves floor U0 and surface floor. The capacity of lift in PM56 is around 13 people. Their travel speed and time for opening and closing of doors are approximately 1.93m/s and 10s respectively. The lifts would operate normally during the activation of fire alarm.

2.1.4 Personnel Access Device (PAD) / Material Access Device (MAD)

PADs and MADs are part of the access safety system developed by CERN. These systems are designed to verify the identity of occupants and materials and ensure that only people with the requisite authorization to enter restricted areas including accelerators, experimental caverns and beam facilities. The PAD/MAD are equipped with interlocked door booths which effectively prevent unauthorized entry into these sensitive zones. Occupants are mandated to scan their RFID personal dosimeter at the PAD entry points, shown in Figure 2.4. The PAD has a biometric security device for verification by matching the access badge and the user's identity. Conversely, the MAD is secured with dual mechanical doors which is designed to operate sequentially. Normally, the duration of passing through PAD is 7s. In emergency scenarios, occupants can break a green emergency handle within the PAD/MAD to facilitate evacuation.

Additionally, the PAD and MAD systems have been installed at the surface entry points of PM54 and PM5. In the tunnel UP55 and UPX56 where connecting between USC55 and UXC55 cavern, only PAD is installed.

Figure 2.4: Personnel Access Device (PAD)

2.1.5 Fire hazards

The possible ignition sources in the CMS underground caverns are typically associated with operational activities and equipment malfunctions such as hot work and electrical failures. Maintenance activities including welding are commonly conducted during the Year-End Technical Stop (YETS) period. Regarding electrical failures, the extensive network of electrical cables and cabinets throughout the facility significantly contributes to the overall fuel load.

2.2 Occupant characteristics

2.2.1 Occupant classification

In the CMS cavern, there are mainly three types of occupant groups: technical workers, scientific engineering staff and visitors. They are assumed in age from 18 to 65 years and without any disability. Technical workers are engaged in hands-on activities such as installation and maintenance including tasks like welding. Members of the scientific engineering staff including scientists, engineers and safety officers focus on inspections and are less frequently present in the cavern. Visitors are only allowed in groups and must be guided by designated personnel to ensure adherence to safety protocols.

2.2.2 Safety requirements and training

Safety is one of the elements in the CMS cavern with stringent requirements to all occupants. All occupants have to wear helmets and safety shoes. Lone-worker rule is applied on CMS personnel which is a safety measurement to force worker working in group for avoiding worker working alone to minimize their risk by getting immediate assistance from co-workers. Additionally, all personnel before entering the CMS cavern must complete a series of safety training courses for every three years. This training is provided by both CERN's internal trainers and external experts covering a wide range of topics including the layout of the CMS underground caverns, the use of safety equipment, emergency evacuation procedures and awareness of potential hazards.

Evacuation drills are conducted regularly to ensure that all occupants can respond appropriately during an emergency. These drills are for testing the effectiveness of current safety measures and practice using to use evacuation routes.

2.2.3 Familiarity with the environment

It is assumed that both technical workers and scientific engineering staff have a high familiarity with the cavern's layout due to their regular presence and the recurrent safety training. In contrast, the visitors are not familiar with the facility, but they are guided by well-trained staff to visit the cavern.

2.2.4 Occupant load

The maximum number of people in the facilities could be up to 204 people, including 80 people from the UXC55, 100 people from the USC55 and 24 visitors.

In the routine operation, there are approximately 20 to 50 staff plus maximum of 24 visitors in both the service and experimental caverns.

2.3 Evacuation in CMS

In the CMS cavern, the primary evacuation method is through the use of elevators. If the evacuation alarm is activated, all occupants should exit the building via the nearest and safest route and all doors ought to be closed upon departure. In order words, total evacuation is applied. Occupants in UXC55 may utilize tunnel UP55 on level W2 to directly access the PM54 lift shaft or may choose tunnel UPX56 on level U0, which provide access to both the PM54 and PM56 lift shafts for egress to the surface floor, as shown in Figures 2.5 and 2.6. Meanwhile, occupants in USC55 can directly use the PM54 lift shaft on level U0 and U2 to reach the surface floor. The service floors of both of the PM54 and PM56 is mentioned in Section 2.1.3. All occupants in CMS have to evacuate to gather at the assembly point near the main gate. After arrived at the assembly point, occupants are required to stay until further instruction are provided by the Territorial Safety Officer (TSO) or Fire and Safety Rescue Service personnel. Stair evacuation is prohibited due to the demanding physical stamina because the caverns are located approximately 100m underground at level W3. Therefore, the staircases that connect the underground levels to the surface are designated exclusively for emergency use and required supervision from the fire brigade. Using staircase without fire service personnel is forbidden. In fact, CERN FSE team conducted an on-site inspection for the staircase that accompanied with local fire brigade.

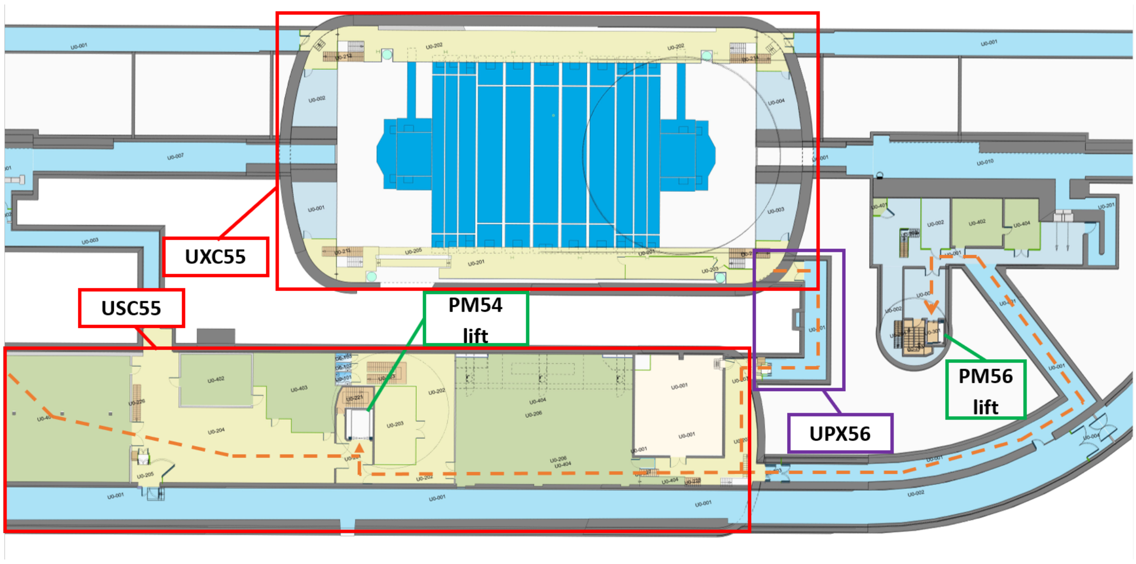


Figure 2.5: Evacuation route on level U0 (orange dash line: evacuation route to lift shaft)

2.3.1 Lift evacuation

During an evacuation, occupants have to access two lift shafts either PM54 or PM56. The lobbies of these lift shafts are pressurized to provide a safe and smoke-free place where occupants can be safely evacuated to the surface.

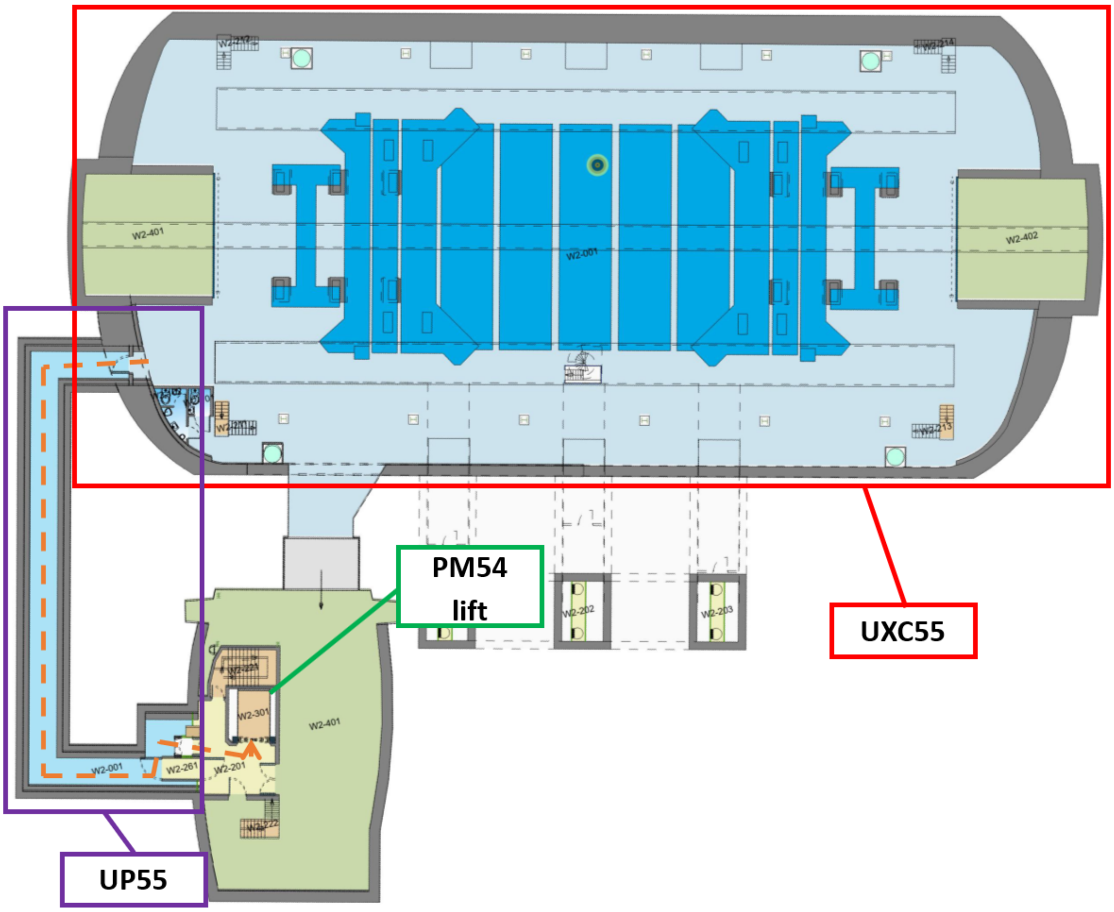


Figure 2.6: Evacuation route on level W2 (orange dash line: evacuation route to lift shaft)

Chapter 3

Literature review

This review examined the impact of human behavioural and environmental factors on evacuation efficiency in complex underground facilities, especially on the relationship between pre-evacuation time and RSET. The decision-making processes in emergency scenarios contribute to RSET significantly. Additionally, the review studied CMS occupant characteristics and data collection methods used in previous evacuation which could be suitable for underground research facilities. Finally, this chapter gave an overview of evacuation modelling. In summary, this literature review analyzed findings from various studies to identify key factors influencing evacuation. The goal was to establish a foundation for executing evacuation drill and developing an evacuation model for the CMS.

3.1 Human behaviour relevant to underground physics facilities

Understanding human behaviours during evacuations was important to predict and interpret evacuees' sequences of actions and their behaviours. This section reviewed existing researches on pre-evacuation behaviours concentrating on their decision making and actions directly to impact their evacuation.

3.1.1 Pre-evacuation time and decision-making

One of the most uncertain phases during an evacuation was the pre-evacuation period, where occupants interpreted emergency cues before taking action. The behaviour sequence model represented this process through three steps (interpret, prepare and act) [20]. It described the causation relationship of initial interpretations on the final actions taken by occupants and explained the thinking process and reaction after received cues or information about fire. At CERN, it was recommended that evacuees closed all doors and windows upon departure. Additionally, when an evacuation alarm was activated in the CMS facility, all occupants were required to evacuate. Nonetheless, construction activities such as welding and piping might be ongoing at the time of the alarm activation that could potentially influence workers' decisions regarding evacuation.

3.1.2 Influences on decision making

Researches showed that social influences, risk perception and individual factors heavily impacted evacuation decisions [21]. Social influence mean the effects of others' presence to individual behaviours including information sharing and groups evacuation. Risk perception involves interpretation and understanding of the threats during emergency. Individual factors include to personal characteristics such as evacuation experience and knowledge. Sime introduced the theory of affiliation who explored how people tend to go towards familiar people and places during an emergency [22]. An experiment in a virtual environment showed that participants were more likely to choose exits that they were familiar with especially when this behaviour was mirrored by virtual neighbours. The finding illustrated the importance of social influence and exit familiarity during evacuation [23]. Due to the lone-worker rule, workers in the CMS were required to operate in groups, which might encourage a collective response to evacuate together. On a typical working day, workers were expected to be present in the CMS suggesting that they were likely to have a degree of familiarity with its layout. Furthermore, many workers at CMS were contractors who frequently utilized the PM54 lift for travelling between the surface and the underground areas, as their resting and reporting areas were located near the SDX5 building, which were near the PM54 lift. Consequently, there was a foreseeable higher tendency for these workers to choose the PM54 lift as their primary evacuation route.

3.1.3 Risk perception and response

The theory of risk perception describes how people respond to emergencies. Sometimes people underestimated the urgency of escalating threats leading to delayed responses and extended pre-evacuation time [24, 25]. This underestimation could result in longer RSET. From there, it was predictable that there was a need of training to improve the awareness of fire risk and evacuation performance. To enhance safety awareness among CMS workers, they were required to complete specific safety courses, which included to identify the presence of hazards in CMS such as oxygen deficiency hazard and pass relevant quizzes prior to entering the CMS facility. However, the actual effectiveness of these safety courses and quizzes in increasing their safety awareness remained undetermined.

3.1.4 Training and Experience

Experience and training could affect how occupants react during an evacuation [26, 27]. Studies had shown that participants with emergency training or evacuation experience were better preparation to face an emergency and choose proper evacuation methods to shorter evacuation process. It highlighted the importance of regular drills and training sessions that could prepare occupants for emergency situations especially in complex environments like CMS. Additionally, in the event of an emergency at CMS, an emergency guide who has received adequate safety training would present at the scene to support the evacuation process. Occupants could highly depend on the emergency guide [25].

3.1.5 Conclusion

The existing literature on human behaviours in evacuation could be applied to complex facilities like CMS and it illustrated the complexity of the pre-evacuation period and its substantial factors on evacuation efficiency. The inherent uncertainties in human behaviours which were influenced by a wide range of factors including cognition, social dynamics and personal characteristics, representing challenges predicting evacuation [4]. However, there were databases and empirical studies which allowed researchers to capture and simulate the range of human responses to an emergency situation. Also, it was important to investigate scenarios such as tunnel and construction sites related to CMS evacuation to get a deeper understanding about CMS occupant characteristic and CMS facility design.

3.2 Factors of CMS evacuation

An underground physics research facilities study outlined that behavioural factors and design factors were the key factors to influence the evacuation process [28]. The behavioural factors contributed to two aspects (pre-evacuation time and movement time). The pre-evacuation period was affected by awareness to alarm procedures and occupants' familiarity with the emergency plan. The physical and psychological characteristics of occupants, familiarity with the facility and flow constraints impacted the movement time and evacuation routes. The design factors related to the egress components such as architectural features or structural components of the facility and environmental conditions such as presence of smoke, visibility and illumination system. By considering the characteristics of CMS (as mentioned in Chapter 2), along with behavioural and design factors, it could be predicted how the evacuation in CMS would function and a range of credible scenarios could be estimated. This could be beneficial for building a comprehensive and realistic evacuation model. Therefore, it is necessary to understand the impact of behavioural factors and design factors on evacuation [29].

3.2.1 Behavioural factors in CMS

This review summarized four human behaviour theories (Role-rule model, Affiliative model, Behaviour sequence model and social influence) illustrated through historical major fire incidents in underground facilities such as King's Cross station fire [25]. The diversity in features of underground systems may exert varying degrees of influence on occupants' responses but these foundational theories remained applicable across different settings. Specifically, this review predicted the potential parallel evacuation performance in occupant behaviours within CMS environments. This highlighted the importance of considering for the occupant load in CMS to contribute on pre-evacuation time and overall evacuation risk.

In an experiment involving a tunnel evacuation, participants were divided into groups of different sizes to assess dependency and information processing during evacuation. The findings suggested that individuals in smaller groups exhibit a dependency on participants with evacuation experience and ignored new information [30]. Conversely, evacuees in larger groups are more reliance on themselves. It demonstrated the impact of group size on decision-making and behaviours during evacuation. This study investigated the formation of groups during evacuation, revealing that while visual and verbal contact with occupants played a significant role but the dominant factors were the roles of pre-existing social bonds and shared activities or objectives prior to the activation of the alarm [31]. These observations were critical for anticipating behaviours in CMS evacuation as CMS implements lone-worker rule to force workers in group movement.

3.2.2 Design factors in CMS

Egress components and architectural features

A study on evacuation modelling in an irregular underground commercial building setting proposed a potential correlation between occupant load, exit usage and evacuation time [32]. It was observed that an increase in evacuation time could be attributed to a rise in the number of evacuees, which might lead to potential congestion and predefined utilization of exits. In the CMS, the structural complexity such as PAD/MAD access system, steep stairs and ladder could contribute to evacuation time or even considering as potential bottlenecks to occupants.

Environmental conditions and smoke management

The presence of smoke and psychological factors could adversely affect evacuation efficiency by impacting walking speed and physical capabilities [33]. Additionally, environmental factors such as architectural complexity and the effectiveness of wayfinding systems were considered in assessing overall evacuation performance. Moreover, the presence of smoke had been found to decrease walking speed and flow rates [34, 35], with reduced visibility occupants may need in certain circumstances extra assistance to evacuate efficiently [12, 36]. A relationship between walking speed and smoke conditions was proposed to understand mobility in such environments [37]. In the CMS, ventilation systems could keep evacuation routes in relatively smoke-free environment. Also, the emergency lighting system and the exit signs could guide occupants towards the exits.

Furthermore, the fractional effective dose (FED) concept had been introduced to evaluate the cumulative impact of irritating and/or toxic gases on the potential for incapacitation or mortality [38]. The duration for occupant to reach a smoke-free safe place became important. The strategic placement of exits emerged as a critical determinant of evacuation efficacy [39]. Mitigation strategies for avoiding the formation of bottlenecks included expanding exit widths, egress components or incorporating additional evacuation routes [40]. The wayfinding system in CMS might be important to the evacuation efficacy.

3.2.3 Lift evacuation in CMS

Lift Evacuation was a promising strategy to improve evacuation efficiency and increase survival rates in emergency situations [41], [42] as factors such as fatigue and disability significantly leveraged the advantages of lift evacuation over staircases especially in buildings with long stairwells or where ascending evacuation took place in underground facilities [43], [44], [45]. Also, a thesis outlined occupants might have higher willingness in actual scenario than in VR experiment to use lift for evacuation [46]. Furthermore, the study could illustrate the effectiveness of enhanced guidance and information systems in increasing both the willingness to use evacuation elevators and the acceptance of longer waiting times [47]. However, the effectiveness of lift evacuation was influenced by occupants' willingness and patience to wait for lifts, which correlated with the floor height that increases the likelihood of occupants to wait for lifts [48].

Despite these advantages, hesitancy of using lifts for evacuation persists due to conventional concept against lift use during fires [47]. Also, concerns about potential for fire and smoke spreading into lift shafts and the risk of sudden electrical failures during lift use were part of the hesitance. Nevertheless, occupants with prior experience in using lift systems were more likely to recognize and utilize lifts as a viable egress strategy during evacuation [49]. Lifts were the primary evacuation mean in CMS.

3.2.4 Conclusion

The review of both behavioural and design factors influencing evacuation indicate potential factors affecting the CMS evacuation. Both of the behavioural factors (pre-evacuation time, group evacuation dynamics, the effectiveness of wayfinding systems and occupants' familiarity with emergency procedures) and the design factors (the architecture of the facility, egress components, environmental conditions like smoke presence and the strategic use of lift evacuation) could significantly influence evacuation efficiency. Understanding these factors allowed research to consider their effect for evacuation in complex underground facilities when designing evacuation drills and modelling.

3.3 Data collection

By examining existing data collections during evacuation drills, researchers could obtain valuable insights into the strengths and weaknesses of various data collection methodologies employed in similar studies. This analysis aimed at identifying the methodologies that have demonstrated effective in addressing researchers' expectations and focuses on their applicability to the CMS at CERN. The objective was to identify methods that are effective, reliable and adaptable to the CERN's need.

3.3.1 Video recording

A recent study on an unannounced fire drill in at CERN office buildings was based on the strategic placement of video cameras in corridors and staircases to record the evacuation procedures which enabled to quantify in movement speed and pre-evacuation time [50]. The analysis yielded insight into pre-evacuation behaviours, the impact of carrying items and the effect of occupant density on walking speeds and social interactions particularly in group evacuations. This study demonstrated the benefits of utilizing video recording to capture evacuation details while also acknowledging its limitations which was restricted camera coverage. Consequently, researchers need to develop more sophisticated methods for monitoring evacuation. Furthermore, video footage offers objective data on occupant behaviours and movements which allowed validating other data collection methodologies such as questionnaires.

3.3.2 Questionnaire

Questionnaires could be treated as an effective tool for researchers to quantify data including people' pre-evacuation behaviour [11], which could be applied in the drill to collect direct information from evacuees. In another study, questionnaires were distributed to building occupants with assistance from local fire brigade to collect information [51]. The survey was strategically conducted within two weeks following a fire incident and aimed at identifying factors influencing occupants' behaviours during the pre-evacuation phase and to examine delays during the evacuation from the building. Interestingly, the working memory model stated that people' short-term memory had limited capacity [52], which might affect the reliability and validity of questionnaires. This could be investigate in the thesis.

3.3.3 Observation

Data on evacuation behaviours could be collected by observers including the times of key events [53]. Key timestamps during the evacuation process could also be collected such as the first and last person passing by designated points. However, the function of observers had inherent limitations in evaluating evacuations, as they could collect data only at designated locations, but it cannot capture the entire evacuation process. The designated locations for observation limited the scope of information gathering. Moreover, the presence of observers might affect occupants' behaviour. Accuracy and consistency of data from observers for post-drill analysis could be questionable because of possible variations in interpretation. These issues were significant in large-scale evacuation drills for buildings that required the deployment of numerous observers [54]. One current limitation in information collection was the reliance on observers stationed at specific locations in the initial phase of evacuation drill or during the whole evacuation drill. This method necessitated the training of personnel to ensure accurate and consistent observation techniques. Inconsistent terminology might be used to refer to similar variables or factors, thus contributing to issues in data collection and analysis across different studies [55].

3.4 Modelling

The selection of an evacuation model required careful consideration of its suitability and the representation of egress components and occupant interactions [56, 57, 58]. For the modelling evacuation in CMS experimental and service caverns, a simulation tool with modelling lift transport capability was essential. Pathfinder was able to simulate people movement in steering model in with continuous model [59], which tested through its verification and validation (V & V). These tests assessed its functionalities and predictive capabilities such as scenarios in evacuation via elevator in evacuation in complex underground physics research facilities [14]. Pathfinder was an evacuation simulation software that allowed to predict evacuation according to two alternative models (steering model and SFPE model). Over 60 evacuation softwares were reviewed with their features and modelling methods [60]. Pathfinder was one of the popular used simulation tool among fire safety engineers for simulating evacuation because of its user-friendly interface and ease of use.

Also, evacuation studies about complex environment such as tunnels and buildings by utilizing Pathfinder proved its adequacy to model complex structures [61, 40, 62, 63, 64]. Additionally, Pathfinder could import data from Building Information Modelling (BIM) and Fire Dynamics Simulator (FDS), allowing users to quickly build an evacuation model and combining it with fire model data including temperature, smoke density and toxicity. Besides, Pathfinder had been chosen for its ability to incorporate FDS toxicity data to compute occupants' fractional effective dose (FED) which affected their safe condition [65, 66].

The integration of these systems through a BIM-based approach harnessed the strengths of both Pathfinder and Pyrosim [67]. This synergy provided a detailed 3D view to easily identify visually potential congestion points during evacuation, thereby elevating the visual realism and evacuation simulations. Moreover, this approach streamlined the modelling process, eliminating unnecessary duplication of effort and fostering collaboration across design, construction and maintenance teams [68]. By leveraging the combined capabilities of BIM, Pathfinder and Pyrosim, an idea was proposed to export fire and evacuation modelling outcome to BIM to enhance the information amount and overcome the limitation of the current BIM which was without fire safety engineering information [69]. The CMS stakeholders could achieve a more effective and efficient simulation process to ensure better preparedness for emergency evacuation.

Some simulation tools such as buildingEXODUS and MassMotion were utilized in modelling evacuation in underground facility or construction sites [70, 71]. However, these tools were not considered for the current study because Pathfinder was used in past relevant studies for the experimental caverns at CERN. In order to maintain the consistency and comparability with previous studies, Pathfinder was selected to use.

3.4.1 Conclusion

The Pathfinder was selected as simulation tool for evacuation in the CMS caverns because it was capable to model lift transport, commonly use and was able to integrate FDS toxicity data to compute the FED for occupants. Also, it had been adopted to use in previous CERN experimental caverns where was similar with CMS cavern to enable researchers to continue the relevant studies.

Chapter 4

Methodology

This chapter detailed the approach undertaken to gather evacuation data from the CMS site. An unannounced evacuation drill was conducted to simulate an emergency scenario. This drill facilitated the observation of responses from CMS occupants including technical workers, such as technicians and contractors, and members of the scientific engineering staff, including researchers, engineers and students. The methodology was structured into three main phases: data collection, parameter input and results, as illustrated in Figure 4.1.

4.1 Evacuation drill

The evacuation drill was planned and executed within the underground facilities of USC55 and UXC55 on the 6th February 2024. Conducting the drill during the Year-End Technical Stop (YETS), a period that allows technical departments and contractors to provide maintenance, repairing and upgrading services to the LHC equipment which minimized operational disruptions. Due to safety reasons, the drill purposely excluded the presence of visitors in CMS.

4.1.1 Participant and notification

Approximately 50 occupants were expected to participate to the drill. The participants for the drill consisted of technical and scientific staff along with contractor personnel which reflected the typical occupancy composition during operational periods and were not specifically selected for participation. Participants were not notified prior the drill to avoid influencing their reactions and behaviours. Total evacuation was implemented as normal emergency plan.

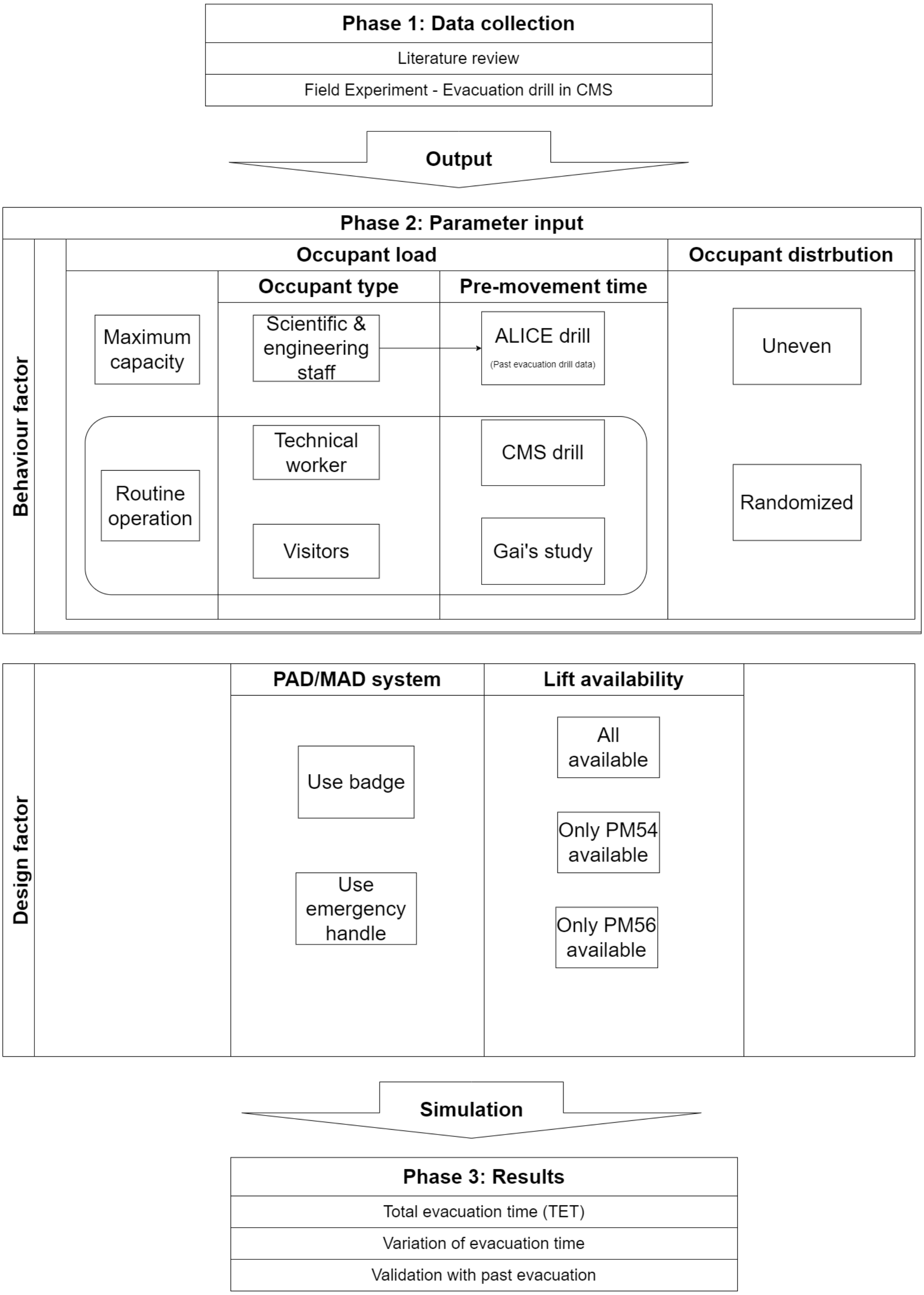


Figure 4.1: Workflow of evacuation model construction

4.2 Data collection

Data were collected through three methods: questionnaires, observations and video recordings. Each method was designed to record their evacuation timestamp, collect information about responses and their rationale.

4.2.1 Designing questionnaire

Introduction and objective of questionnaire

The post-evacuation questionnaire aimed to collect a wide range of information including the audibility of alarm, pre-evacuation activities, evacuation route and their background. Each question was tailor-made for the targeted building. Respondents would answer the questions based on their perception, memory and judgement. Therefore, researchers could have a better understanding about the rationale behind occupants' decisions making. The questionnaire was distributed immediately after the drill at the assembly point.

Preparation for designing questionnaire

In preparation for designing a questionnaire that effectively collected data on actions taken during an evacuation and the decision-making rationales of participants, a review for relevant literature was conducted. Three types of resources were consulted:

- Past CMS evacuation reports: These reports provided by CMS safety officer gave insights into previous evacuation procedures, number of evacuees and outcomes especially thanks to the comments in the reports, as illustrated in Table 4.1. Notably, the reports included comments which highlighted as a recurring issue: occupants failing to break the emergency handles for rapid evacuation.
- Evacuation studies related with questionnaires [55, 54, 72, 73]: The review helped identify commonly used metrics and methods in evacuation studies such as measuring the initial location of occupants and the activities performed in pre-evacuation period which provided ideas about the content and format of the questionnaire.
- Books on questionnaire design [74]: The books offered insights on formulating questions, confirming expectation and assumption of using open-end/ close-end questions, ways to measure attitudes and techniques for designing questions that would allow the authors to collect responses in a measurable way.

This literature review was useful to develop a questionnaire that addresses the needs of the study on evacuation.

Date	Evacuation type	Reason	Starting time	Ending time	Evacua-tion time	No. of occupants	No. of people in UXC	No. of people in USC	Remark
03/02/2012	Announced	Drill	13:45	14:04	00:19	77	33	34	12 of 34 occupants in USC are simulated visitors
26/04/2013	Announced	Drill	12:18	12:48	00:30	226	80	100	Two simulated visitor groups (Each group: 12 visitors with 1 guide)
11/01/2017	Announced	Drill	11:45	12:10	00:25	180	80	100	The ending time was according to Safety Guards to declare empty for underground cavern. 24 of them are simulated visitor.
22/01/2019	Unannounced	Drill	14:04	14:39	00:35	80	Not mention	Not mention	
29/11/2021	False alarm	Dust	07:59	08:04	00:05	4	4	0	The ending time was based on the alarm ending time
23/08/2022	Emergency	ODH	18:20	18:22	00:02	2	0	2	Not reach assembly point
21/01/2023	Emergency	Fire due to electrical failure	13:43	13:47	00:04	4	3	1	Not reach assembly point
06/03/2023	Unannounced	Drill	09:56	10:10	00:14	33	Not mention	Not mention	
09/08/2023	Unannounced	Drill	14:33	14:41	00:08	20	Not mention	Not mention	
06/02/2024	Unannounced	Drill	15:18	15:28	00:10	48	5	5	The other 38 occupants might from other buildings and surface.

Table 4.1: Summary of CMS evacuation

Content of questionnaire

In the questionnaire, there were a total of 24 questions including 1 question that asked occupants to draw their evacuation route on floor plans as shown in Appendix A. The questionnaire was designed in English, then translated to French, Spanish and Russian for fulfilling assumption to CMS workers' background. The questionnaire was divided into 3 sections (occupant characteristic, pre-evacuation phase and evacuation phase). The questionnaire was developed based on past studies and evacuation reports in CMS. The questionnaires were approved by CERN FSE team and CMS Safety team.

In the section 1 of questionnaire, the first question aimed to locate occupants when they heard the alarm. Question 2 to 7 mainly focus on asking occupants' pre-evacuation activities such as the sequence of actions before the start of the evacuation, estimation of the pre-evacuation time and factors related to exit choices. In section 2 (question 8 to 20), respondents were asked about the factors affecting their travel speed, obstacles during evacuation, their feelings, exit choice and lift evacuation. In the question 20, they were asked to draw their evacuation path on the corresponding floor plans. Section 3 (question 21 to 24), this section was designed to collect occupants' background including past evacuation experience, history of attending safety training courses and their routine location in CMS.

4.2.2 Observation

A team of 21 observers recruited by CERN's FSE team and CMS Safety team was strategically positioned throughout the site to cover all main exits, corridors and workplaces. The observers were instructed on evacuation procedures and their primary role was to document evacuation behaviours with a particular focus on pre-evacuation activities and difficulties during the movement phase. Observation sheets were distributed to observers to report evacuation details like human behaviours, delays in the evacuation and occupant characteristics. The distribution of observers could be consulted in Table 4.2. Before the drill, observers attended a meeting to familiarize with their position, responsibilities and were briefed on the importance of non-intrusive observation to minimize their influence on the participants' natural responses. After the drill, a meeting was held with all the observers for reporting the observation and comment on the drill.

Designing observation sheet

The observation sheet sample could be found in the Appendix B. The content of observation sheet was similar with the questionnaire which allowed researcher to crosscheck the responses

Observer #	Location		Camera
	Building	Floor	
1	UXC55	W2	GOXTREME® BLACK HAWK+
2	UXC55	U0	GOXTREME® BLACK HAWK+
3	USC55	U2	GOXTREME® BLACK HAWK+
4	UXC55	W2	GOXTREME® BLACK HAWK+
5	USC55	U2	GOXTREME® BLACK HAWK+
6	UXC55	U2	GOXTREME® BLACK HAWK+
7	USC55	U0	GOXTREME® BLACK HAWK+
8	UL56	U0	GOXTREME® BLACK HAWK+
9	USC55	P	GOXTREME® BLACK HAWK+
10	Point5	Assembly point	GOXTREME® BLACK HAWK+
11	USC55	U0	GOXTREME® BLACK HAWK+
12	UXC55	U1	GoPro HERO11
13	UXC55	U1	GoPro HERO11
14	CMS Control Room	Surface	N/A
15	PM54	Surface	N/A
16	SD5	Surface	N/A
17	SDX55	Surface	N/A
18	USC55	U0	N/A
19	UPR57	Surface	N/A

Table 4.2: Locations of the cameras and observers

from questionnaire. To formulate the observation sheet, a review was conducted for learning from scientific studies and observation sheets from previous evacuations in CMS [55, 54, 72, 73].There were 4 sections about background information on the building, events in the pre-evacuation phase, events in evacuation period and post-evacuation phase. There were total of 29 items that needed to observed, 4 related to the building background, 12 related to pre-evacuation phase, 9 related to evacuation phase and 4 related to occupant's characteristics.

The observation sheet was designed to record data during the evacuation drill. Its structure facilitates the cross-checking with responses from the questionnaire to enhance the validation of data.

In total, the observation sheet contained 29 items that covered a range of variables for analyzing of evacuation and participant behaviours.

4.2.3 Video analysis

Camera recordings was a practical and objective tool in the evaluation and analysis of evacuation drills. It recorded the entire evacuation process allowing researchers to conduct a complete post-evacuation analysis namely recording key timestamps. Also, it helped to identify human behaviour patterns such as the flow of people, social influence, usage of lift and congestion points particularly effective in low-density scenarios because it allowed for clearer visibility of individual behaviours and interactions to minimize overlap and congestion. Moreover, the video recordings from different angles could offer reviewers the possibility to crosscheck data collected with other methods such as questionnaires and observation sheets. Also, the footage could be reviewed multiple times to extract additional information if needed. It minimized the chance of influencing occupant behaviour. There were 2 sources for the video footages which were from CMS surveillance system and action camera hold by observers. The timestamp of all the video footages from CMS surveillance system and mini cameras were synchronized with CMS surveillance system.

Action camera

Observer role and strategy

Observers equipped with helmet-mounted or handheld cameras, were instructed to follow occupants discretely to avoid disturbance occupants' decisions and behaviours. They were asked to follow occupants from their designated location until arrived at the assembly point. Their original designated position could refer to Table 4.2. A briefing meeting prior to the drill emphasized the importance of non-intrusive observation to avoid biased data. In order to minimize the potential influence of cameras during the drill, observers were instructed to blend into the environment as much as possible.

Action camera placement and specifications

For this drill, 13 action cameras were utilized. Table 4.2 showed the locations of the cameras and observers. The cameras were strategically placed and carried by observers to maximize coverage of evacuation routes and common areas. The placement of camera and observers was on-site visits and experience from past evacuations.

The evacuation drill was recorded in two brands of mini-cameras: GOXTREME® BLACK HAWK+ and a GoPro HERO11. Both cameras captured footage in 1080p resolution. The GOXTREME® BLACK HAWK+ used a 60fps frame rate, while the GoPro HERO11 used a 25fps frame rate.

Surveillance cameras

The surveillance camera system deployed for the evacuation drill comprised a total of 52 surveillance cameras covering the CMS cavern and its egress routes.

Camera Specifications and Placement

The surveillance system included cameras of varying angles strategically installed across two main areas: USC55 (11 cameras from U0 to U2 floor) and UXC55 (24 cameras from W2 to U3 floor). These cameras were recording at 1080p. The cameras featured wide-angle lenses and were checked prior to the drill to ensure the operation of the camera. Also, a site visit was conducted to adjust camera' angle towards exits and areas with higher occupancy.

Data analysis by video review

The video footage collected during the evacuation drill was analyzed to understand evacuation behaviours especially focusing on pre-evacuation timestamp and usage patterns of exits and lifts. This analysis provided quantitative and qualitative data on participant actions during the evacuation drill.

Analytical Techniques

The analysis involved manual reviews. Each frames from each camera was extracted at every seconds to analyze movement timestamp.

Behaviour categorization

The timestamp of evacuees' RSET would be defined by the following conditions:

- Pre-evacuation time: from the activation of the alarm to the beginning of physical evacuation heading to an exit without returning back.
- Evacuation time: from the time when people started moving towards exit to the moment they reached the lift lobby
- Waiting time for lift: from the time when people opened the lift-lobby door to the time when the lift door opened at underground floor.
- Lift travelling time: from the time when the lift door opened at the underground floor to the time when the lift door opened at surface floor.

Integration with Other Data

To enhance the reliability of findings, video data were checked with observation sheets and questionnaire responses. This approach helped validate the data obtained from different sources and provided a multifaceted view of the evacuation process.

Ethical Considerations Ethical guidelines were strictly adhered to throughout the video review process [75, 76]. All participants were informed about the video recording after the drill which outlined how the data would be used and the measures in place to ensure privacy. Identifiable information was anonymized in the analysis phase and access to video data was restricted to the research team.

4.3 Modelling setting

In this study, the Pathfinder version 2023.2.0826 and 2023.3.1206 were used to develop the evacuation model [66]. The model built upon a previous CERN internal study also conducted with Pathfinder to ensure continuity in the simulation methodology. The inputs of parameters including delay time and time for passing through PAD/MAD were extracted from the CMS drill.

4.3.1 Model development

The geometry for the simulation was imported from a BIM model. Minor modifications were made to simplify the geometry and increase its applicability. The changes included the addition of floors and stairs on top of the detector to simulate the bridge above the detector. Additionally, the road between buildings and the assembly point was sketched based on snapshots from CERN Geographic

Information System (GIS). Also, part of the model such as the route toward PX54 shaft and surface buildings were sketched based on DWG file. The end point of the evacuation simulation was for all occupants to reach a designated assembly point which aligns with the evacuation in reality.

The parameters for the simulation model were derived from a literature review including evacuation analysis related to the CMS facility and direct measurements taken during evacuation drills.

Unimpeded walking speed of occupants

The model applied the unimpeded walking speed of occupants during tunnel evacuations in smoke-filled environments as worst-case scenario although the ventilation system could remove smoke to prevent smoke accumulated in egress routes during the evacuation. This parameter was derived from data collected from the tunnel evacuation experiment [12], which was 1.2m/s $\pm$ 0.3 [0.6-2.4]. The normal distribution profile was assumed.

Setting of elevator

The settings for elevators PM54 and PM56 in the model include two operational parameters which were travelling speed and door operation time. These inputs were based on direct measurements. The average travelling speed was 1.93m/s and the door operation time for both opening and closing was 5s.

4.3.2 Variable of model setting

CMS occupant load and distribution

The estimation of occupant load and distribution was derived from a study [65] which analyzed two years of access records and a maximum capacity of CMS facility.

CMS occupant load and distribution from [65]

A study had provided insights into the occupant number and distribution which were critical factors in defining parameters for evacuation simulations in CMS [65]. By utilizing a 90th percentile distribution based on two years of access records, the study determined a representative number of occupants for simulation purposes for a total of 62 occupants. This included 28 occupants in the experimental cavern, 22 in the service cavern and 12 visitors. The CMS occupant load and distribution could be used in the simulation scenario.

CMS occupant load and distribution in maximum capacity

Location		Scenario P1 & P2	Scenario P3 & P4
Building	**Floor/ Room**	**Number of occupants**	
UXC55	U3	7	2
	U2	9	4
	U1	16	9
	W1	33	9
	W3	15	4
USC55	S4-Area	75	26
	mezzanine	37	8

Table 4.3: Occupant distribution of predefined distribution scenarios

The simulation considered the maximum capacity scenario of the CMS, based on CERN's official documentation. The maximum capacity of CMS was 180 people excluding visitors, 100 in building USC55 and 80 in building UXC55. This scenario could provide insight in the most conservative case for testing full-load condition.

CMS occupant distribution

The simulation explored the predefined and randomized occupant distribution in CMS. Four scenarios (as shown in 4.2) were investigated:

- Predefined Distribution

  Occupants were positioned on specific levels (W3, W1, U1-3 in UXC55 and S4-Area, mezzanine in USC55), as illustrated in Table 4.3 requiring them to utilize stairs before reaching the elevator lobby. The predefined scenarios aimed at evaluating the influence of increased travel distances on evacuation efficiency.

- Randomized Distribution

  Occupants were randomly assigned to all levels within UXC and USC buildings. This scenario served as a baseline for comparison in different occupant distribution.

Delay time setting for each occupant group

The identification of occupant characteristics was fundamental for the development of evacuation simulations as these characteristics affected evacuees' responses during an evacuation. Subsequently, it influenced their evacuation time, performance and movement patterns. A database about pre-evacuation behaviours among diverse occupant groups and across different countries had been established, serving as an input parameter for simulation purposes [77].

	CMS drill	**ALICE drill**	**Construction site** [13]
Delay time (s)	116 ± 24 [93-148]	161 ± 28 [116-191]	117 ± 29 [65-193]

Table 4.4: Delay time settings for different occupant group

Furthermore, studies had indicated that log-normal and log-logistic distributions represent the variability in pre-evacuation time [2] which gave an insight of the setting of pre-evacuation time in the model. The delay time data were extracted from CMS evacuation drill, previous evacuation drill in ALICE caverns in CERN and a previous evacuation study in construction site which were expressed in log-normal distribution. They were summarized in Table 4.4.

Delay time setting for each occupant group from experimental data

The delay time was for predicting occupants in pre-evacuation time, which was divided into two components (detection time and pre-evacuation time). Detection time was computed using the FDS model according to the critical fire scenario among the CMS previous fire scenario study, which was assumed 60s. Pre-evacuation time was collected from evacuation drills conducted at the CMS and ALICE caverns and a study [65].

Based on the routine activities in the CMS cavern, there were 3 types of occupants as described in Section 2.2.1. In the development of the evacuation model, occupant types were defined by specific roles and duties. Their pre-evacuation time was based on the feature of the corresponding evacuation drills. The pre-evacuation time for technical workers were defined from data collected in the CMS evacuation drill, as most of the evacuees of the drill belonged to this group. In contrast, the pre-evacuation time for scientific and engineering staff were obtained from the ALICE evacuation drill, since most of the data were collected from control officers who aligned with the staff's operational roles. For visitors, the pre-evacuation time were also sourced from the ALICE drill data as the assumption that visitors would be guided by CERN staff who were scientific and engineering staff. This approach ensured that the simulation reflected realistic behaviour patterns based on the specific experiences and roles of different occupant groups.

Delay time setting from construction site study [13]

The CMS evacuation study had analyzed the pre-evacuation time in defining parameters for evacuation simulations in the CMS at CERN [65]. The pre-evacuation time for the worker group based on the construction site study [13]. For the guided visitor group, the pre-evacuation time parameters were initially established based on the recommendations of PD 7974-6 [78]. However, as aforementioned Section 4.3.2, the pre-evacuation time for occupant group of scientific engineering staff had been adjusted to data obtained from the previous ALICE drill. Therefore, the simulation settings were closely aligned with observed data from evacuation drill.

	Emergency handle	Badge
Congestion time (s)	0	9 ± 1 [7-17]

Table 4.5: Congestion time settings in PAD/MAD

Study in CERN office building

An unannounced evacuation drill was conducted in some of CERN office buildings to examine occupants' pre-evacuation time and walking speeds in staircases and corridors [50]. The study measured the average walking speeds which were 1.17 m/s ± 0.32 m/s in the corridor of Building 1 and 1.28 m/s ± 0.31 m/s in the corridor of Building 2. The average walking speed on stairs was recorded as 0.88 m/s ± 0.19 m/s for building 1 and 0.88 m/s ± 0.12 m/s for building 2. These findings were consistent with the SFPE hydraulic model [79]. This drill contributed data on the occupants' movement speed during evacuations and pre-evacuation time which was lower than data from the exist literature.

For the pre-evacuation time, the pre-evacuation time in building 1 was 29.3 s ± 22.9 s while in building 2 was 34.8 s ± 20.3 s. The interquartile range for building 1 spans from 15 to 37 s indicating the most common pre-evacuation time while in building 2 were from 19 to 46 s. 95% of occupants in building 1 evacuated within 65 s while 64 s in building 2.

Congestion time of passing PAD/MAD system

In the past evacuation drills, it was noted that occupants tend to use their badges instead of the emergency handle when passing through the PAD/MAD system. It resulted in congestion which increased the TET. To simulate these scenarios, the congestion time of PAD/MAD were set to model both the use of badges and emergency handles and based on data collected from the evacuation drill, as illustrated in Table 4.5.

Lift availability in CMS

In the CMS facility, the availability of lifts could be disrupted due to fire and smoke spread to the access door in UPX56 or UP55 tunnel to block the access to the PM54 or PM56 lift shaft which might restrict occupants to access the primary escape routes and significantly affect the evacuation efficiency. To consider this problem, 3 scenarios were simulated: both PM54 and PM56 lifts available, only PM54 lift available and only PM56 lift available. The scenario with both lifts available represents normal operations let occupants to utilize both lift. The scenarios of only one lift available was set by only enabling one of the lifts during simulation. Each scenario considered different lift capacity, referring to Section 2.1.3.

4.3.3 Scenarios

22 scenarios were simulated based on two factors (behavioural factors and design factors). The summary of corresponding scenarios was shown in the Table 4.2. To test the effect of uncertainty, each scenario was simulated 100 times. However, a systematic approach to analyzing variability in the model involved employing convergence criteria, which provided a method for assessing the impacts of different simulation parameters. The naming system for the scenarios was based on their settings. For example, scenarios beginning with "M" represent maximum occupant load settings. Scenarios starting with "D" indicated that the pre-evacuation time was based on the CMS drill. Scenarios starting with "GAI" indicate that the pre-evacuation time was based on the study by Gai et al. [65]. Lastly, scenarios starting with "P" represented occupant distribution based on predefined conditions, as illustrated in Section 4.3.2.

The development of quantitative methods for evaluating behavioural uncertainty in modelling remains a nascent field, with existing practices often relying on the qualitative judgements of model users due to a lack of standardized criteria. A novel approach, employing convergence criteria derived from functional analysis, offers a systematic way to analyze variability in model predictions and determine the optimal number of scenario runs based on predefined acceptance criteria, thus enhancing the reliability and precision of behavioural simulations.

Scenario	Occupant number (people in UXC+ people in USC + visitor = total # of occupants)	Occupant type & Delay time (s)	Method of accessing PAD/MAD & Congestion time (s)	Lift selection	Occupant distribution
M1	80+100+12=192	Technical workers: 116 ± 24 [93-148] + Scientific & engineering staff and visitor group: 161 ± 28 [116-191]	Emergency handle: 0	All lifts available	Randomized
M2				Only PM54 available	
M3				Only PM56 available	
M4			Badge: 9 ± 1 [7-17]	All lifts available	
M5				Only PM54 available	
M6				Only PM56 available	
D1	28+22+12=62	Technical workers: 116 ± 24 [93-148] + visitor group: 161 ± 28 [116-191]	Emergency handle: 0	All lifts available	
D2				Only PM54 available	
D3				Only PM56 available	
D4			Badge: 9 ± 1 [7-17]	All lifts available	
D5				Only PM54 available	
D6				Only PM56 available	
GAI1		Technical workers and visitor group: 117 ± 29 [65-193]	Emergency handle: 0	All lifts available	
GAI2				Only PM54 available	
GAI3				Only PM56 available	
GAI4			Badge: 9 ± 1 [7-17]	All lifts available	
GAI5				Only PM54 available	
GAI6				Only PM56 available	
P1	80+100+12=192	Technical workers: 116 ± 24 [93-148] + Scientific & engineering staff and visitor group: 161 ± 28 [116-191]	Emergency handle: 0	All lifts available	Predefined
P2			Badge: 9 ± 1 [7-17]		
P3	28+22+12=62	Technical workers: 116 ± 24 [93-148] + visitor group: 161 ± 28 [116-191]	Emergency handle: 0		
P4			Badge: 9 ± 1 [7-17]		

Figure 4.2: Summary of simulation scenarios

Chapter 5

Results of evacuation drill

The unannounced evacuation drill was conducted on 6th February 2024 aiming to collect evacuation data about CMS facility to facilitate calibrating CMS underground simulation model by simulate emergency evacuation from CMS. The focus of this chapter was to report the evacuation performance, behaviours and responses of the CMS occupants.

5.1 Data collection

Three types of data collection methods were used including questionnaire, observation and video recording. The evacuation drill was carried during the Year-End Technical Stop (YETS) to minimize operational disruption.

The HSE Unit fire safety engineering team and CMS Safety Office deployed a total number of 65 cameras and 21 observers located strategically in CMS due to ensure full coverage to record the drill. As a result, approximately 100GB of video footage were obtained.

Although 14 questionnaires were received, 10 respondents originated from CMS and the other 4 respondents from other parts of the underground facility which were out of the study scope. Therefore, all the below data analysis were based on the responses from the 10 CMS occupants, corresponding to response rate of 100%. Analysis was conducted using 19 observation sheets received from 21 observers, along with the report provided during the debriefing session.

5.2 Description of evacuation drill

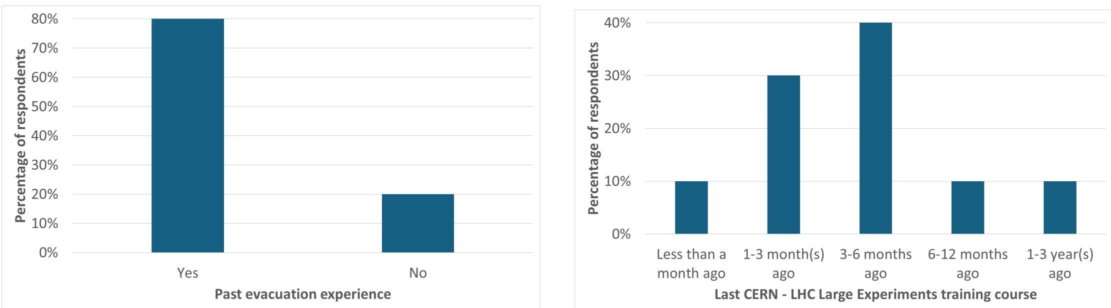
The unannounced evacuation drill was conducted on 6th February 2024 within the CMS facility (USC55 and UXC55) at CERN. The evacuation started at 15:18 with the activation of an alarm by a manual push button located in UXC55 and finished at 15:28. The total time of the evacuation drill was 10 minutes.

5.2.1 Participants in evcuation drill

A total of 48 occupants participated in the drill without prior notification or warning but only 10 of them started the evacuation in the CMS caverns (USC55 and UXC55) and the rest of 38 occupants located at the surface level when the alarm activation that were out of the scope of the data collection. Those 10 evacuees were all male contracted technical workers without any physical impairment. The source of video capture for occupants during pre-evacuation phase was mainly from CMS surveillance system. There were 4 occupant groups (1 from UXC55 level X6, 2 from USC55 level -2, 1 from USC55 level -1). All occupants reported in questionnaire that they could hear the alarm clearly and it was also the 1st clue for them to evacuate.

5.2.2 Evacuation background of occupants

The details of occupants' evacuation background was illustrated in Figure 5.1. 90% occupants attended the training course within the past year, indicating that there is a high probability that they remained familiar with evacuation procedures. Also, 80% of occupants had experience in evacuation which could be interpreted that they were familiar with standard emergency procedure.



(a) (b)

Figure 5.1: Evacuation background of respondents

5.2.3 Evacuation performance

The evacuation performance of the 10 CMS occupants was summarized in Table 5.1 and 5.2 which was derived from analysis of the video footage. The data included pre-evacuation time, movement to lift lobby time and total evacuation time. The method of defining pre-evacuation time, lift waiting time could be referred to Section 4.2.3. The time difference between the arrival of the first and last occupant at the PAD on the surface was 2m53s. The average duration of pre-evacuation time and movement time was 55 seconds and 1m37s respectively. 60% of occupants started their evacuation within 45s, as shown in Figure 5.2. The mean values of the RSET and the time taken to reach the surface floor were 2m32s and 4m59s respectively. According to the survey results, 70% of the occupants reported that they evacuated within 30s after hearing the alarm. Meanwhile, only 20% of respondents indicated that they required 1 to 4 minutes to begin their evacuation, as shown in Figure 5.3.

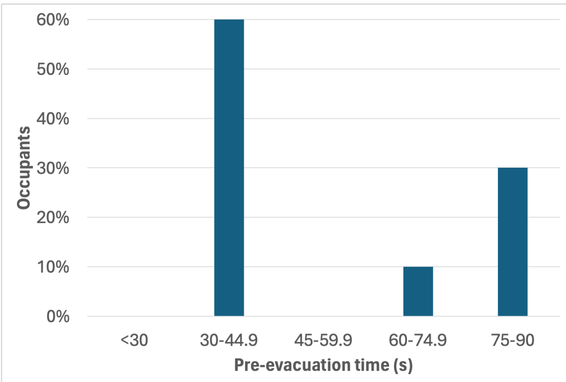


Figure 5.2: Pre-evcauation time distribution

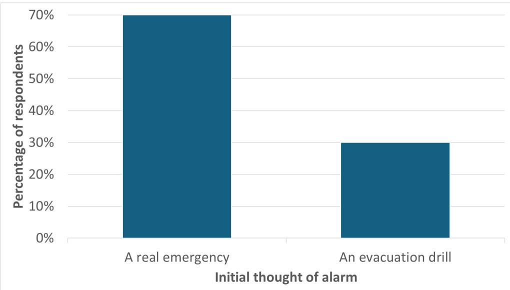
Item(s)	Average	Min	Max
Pre-evacuation time	00:00:55	00:00:32	00:01:28
Movement time	00:01:37	00:00:11	00:03:02
RSET (from original position to lift lobby)	00:02:32	00:01:20	00:03:59
Waiting time for lift	00:00:48	00:00:00	00:02:11
Lift travelling time	00:01:42	00:01:17	00:02:02
Total time to reach surface	00:04:59	00:03:23	00:06:36

Table 5.1: Summary of evacuation phase

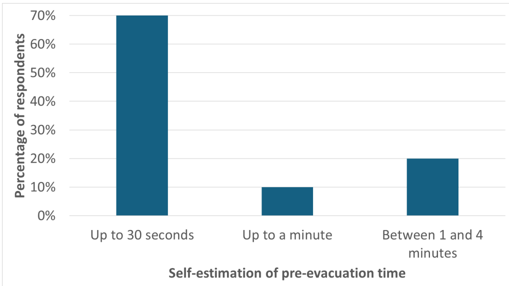
5.3 Pre-evacuation period

After the alarm activation and before starting evacuation, the behaviours among the 10 occupants in CMS were observed and reported as illustrated in Table 5.3 and Figure 5.4, 5.7, 5.5 and 5.6. From the Table 5.1, the activities during the pre-evacuation phase did not delay their evacuation significantly. There were significant difference between self-reported and analysis from observation.

The observation was according to video footage and observers. For example, there was five more the self-reported "Conducted work-related duties" behaviour than the observed work-related behaviours. One of the possible reason could be there was a blind spot on the crane on UXC55 level X6 where was the initial position of the occupants in UXC55, their behaviours could not be observed. Also, there was a significant difference between the self-reported and from the observation on "Encouraged others to evacuate" because this behaviour usually happened in the very initial phase of the evacuation. At that moment, observers had not located occupants. However, some conversation behaviours were captured by the surveillance camera system but the cameras were without audio recording function due to privacy protection. Therefore, the content of occupants' conversation could not be determined. The talking behaviour would be categorized as "Started conversation with colleagues" to maintain neutral judgement on the nature of their conversation, as shown in Table 5.3. The "Encouraged others to evacuate" behaviours reflected their group behaviour which aligned with the affiliation theory indicating that they influenced each other behaviours. The number of self-reported "Dressed up" behaviours was 2 less than from observation.



(a)



(b)

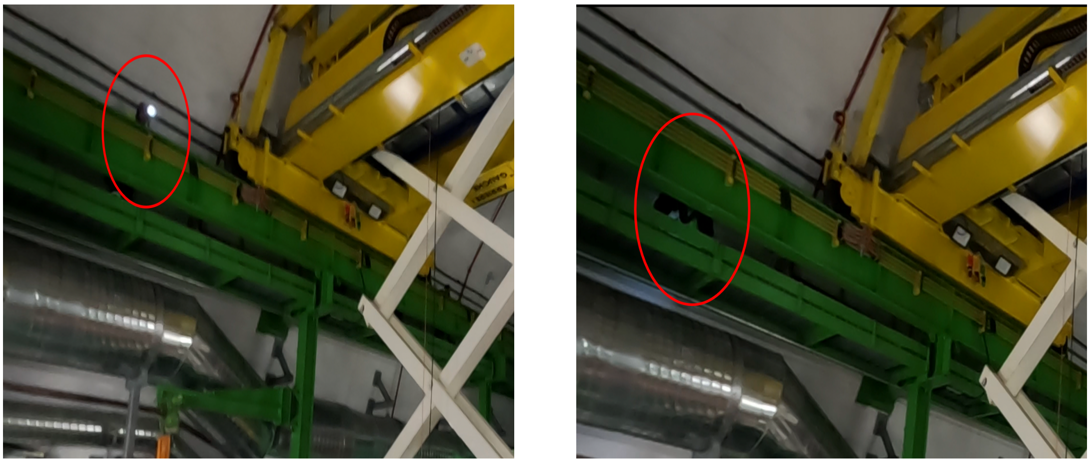
Figure 5.3: Clue of evacuation and self-estimated pre-evacuation time

5.3.1 Occupants on UXC55 level X6

After the activation of alarm, one of the workers came out from crane and stood on the mezzanine to look around for about 3s, as illustrated in Figure 5.4(a). After checking around, he dressed up and packed his belongings within 6s before evacuation, as shown in Figure 5.4(b).

5.3.2 Occupants in USC55 level -2 mezzanine

There were two workers who were conducting welding works before the alarm, shown in Figure 5.5 (a). After triggered the alarm, the workers stopped welding and started looking around and conversation for approximately 13s but the content of the conversation was unknown, shown in Figure 5.5 (b). Then, they started to put down their equipment and took their belongings to dress up, shown in Figure 5.5 (c). After that, they walked to staircases but one of the workers returned to



(a) A worker is looking around on UXC55 X6

(b) A working was dressing

Figure 5.4: Workers on UXC55 X6 during pre-evacuation phase

put the tools on the ground into to a box and took his jacket and shut down a machine, illustrated in Figure 5.5 (d) and (e). These series of movements caused around 37s then they started to evacuate.

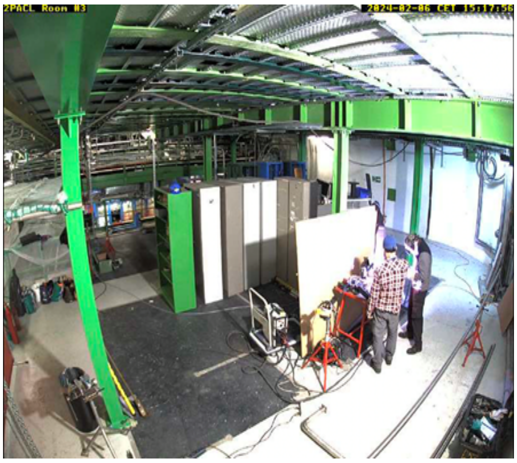
5.3.3 Occupants in USC55 level -1 2PACL-system room

Before the alarm, two workers were conducting welding and pipe works in the 2PACL-system room, shown in Figure 5.6 (a). After the alarm, they put down and shut down the equipment. They went to the staircase to inform the other two workers in mezzanine to evacuate before their evacuation (see in Figure 5.6 (b).

5.4 Evacuation phase

5.4.1 Evacuation route

The evacuation routes for the four occupant groups were shown in Appendix C and D. Based on the data collected from the questionnaire and observation, evacuees were asked about their initial position when the alarm activation but there was a maximum of three occupants that were able to accurately identify their initial location. For evacuation route choice, 100% of the evacuees chose to use PM54 lift for egress with none choosing the PM56 lift. It could be explained by their routine as they have to report to CMS control office where was near PM54 before entering CMS cavern and their resting room was also close PM54. From these two reasons, using PM54 lift might be more familiar than using PM56. Also, the factors of evacuation route selection was mainly influenced by the following factors: occupants' knowledge of the closest exit (80%), the way they came in



(a) Welding activity before the alarm activation

(b) Discussing after heard the alarm

(c) Putting down equipment

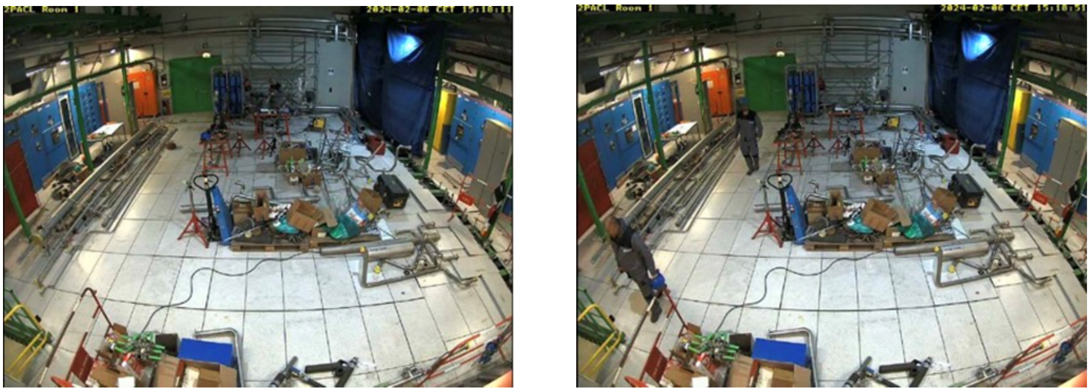
(d) One in dressing; one in returning back

(e) Shutting down machine

Figure 5.5: Workers in USC55 level -2 mezzanine during pre-evacuation phase

(70%) and the way they are familiar with (70%), as shown in Figure 5.7. However, it revealed that occupants in UXC55 missed to use the UPX56 tunnel, which was a shorter egress route. There was a discrepancy between perceived and actual closest exits. However, a confusing exit sign on visitor platform on UXC55 X3 was found in video analysis (see in Figure 5.8), it might mislead occupants to miss the closest exit.

From Question 9 of the questionnaire, five respondents indicated that ”waiting for the next lift” was a factor that delayed their evacuation. However, video analysis revealed that waiting



(a) Piping and welding activity before triggering alarm (b) Informing to workers in mezzanine

Figure 5.6: Workers in USC55 2PACL-system room during pre-evacuation phase

for a subsequent lift did not occur, as the lift was never full or overloaded. This suggested that respondents may have misinterpreted the survey option as waiting for the lift in general, rather than due to overcrowding. Additionally, four occupants reported no factors that slowed their evacuation. Thus, it could be concluded that the majority of occupants (90%) encountered no obstacles during evacuation. In Question 20, respondents were requested to illustrate their egress routes on floor plans. Only eight individuals attempted to respond to this question, and of these attempts, a maximum of three respondents provided an accurate depiction of their evacuation route.

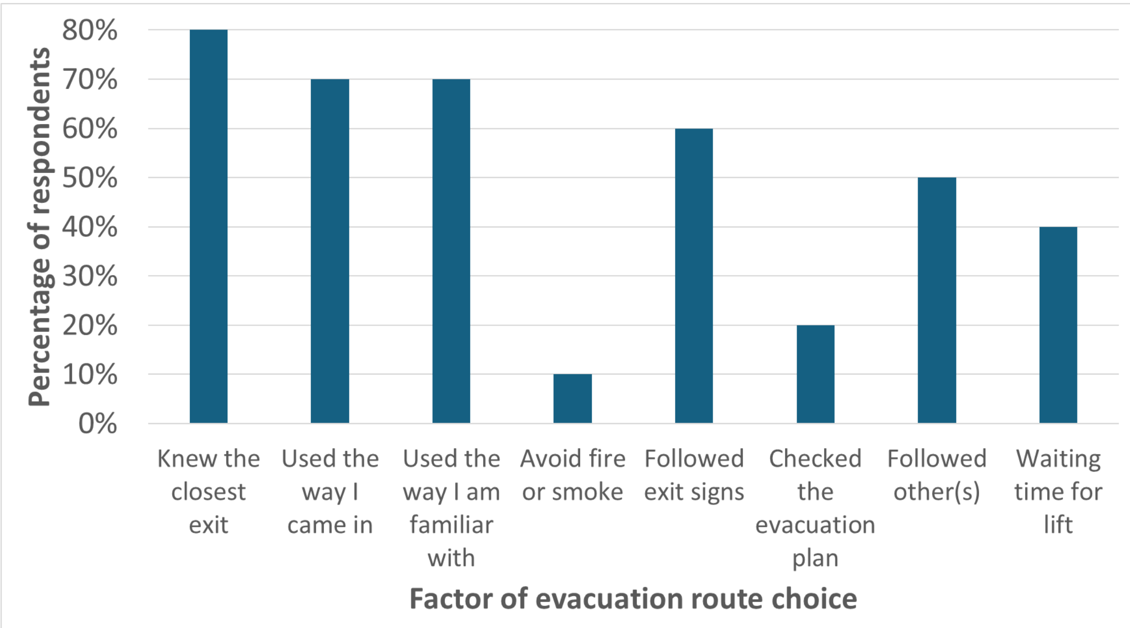


Figure 5.7: Factor of evacuation route choice

Figure 5.8: Emergency exit sign near visitor platform

5.4.2 Emergency guide on UXC55 level X4

All of the occupants on UXC55 level X6 evacuated to UP55 tunnel on level X1 for taking PM54 lift. During the evacuation, when the workers reached the X5 platform, an emergency guide on the X4 mezzanine showed up and involved to instruct them to evacuate, as shown in Figure 5.9. From the observation, it was hard to judge if the emergency guide help the evacuation process.

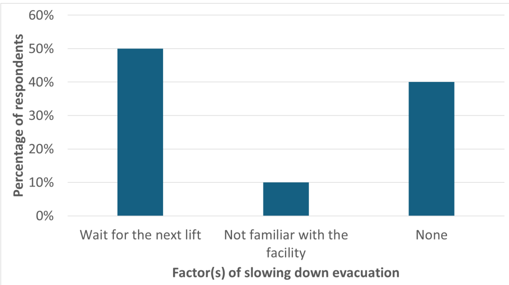
Figure 5.9: Presence of emergency guide

5.4.3 Carrying objects

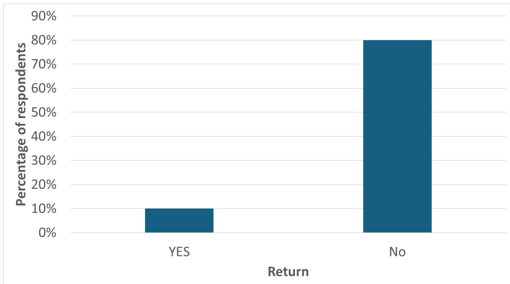
In the responses from questionnaire, only 2 evacuees reported not carrying any objects. This observation was consistent with the video footage. However, the number of self-reported of carried "Jacket" and "Self-rescue mask(s)" was less than in the observation, shown as Table 5.4. The reasons of this observation was unclear, but one of the causes could be that the weight of jacket and self-rescue mask might be lighter than their bag or backpack. Therefore, they could ignore to report it.

5.4.4 Congestion during evacuation

The congestion points were identified where queueing situations occurred which were observed at the PAD/MAD gate located on level X1 in UXC55 and on the surface floor in SDX5 but 40% of respondents reported that they did not encounter any factors to slow down their evacuation, as illustrated in Figure 5.10. Also, from the video footage, one of the occupants in UXC55 had to stop to sort his belongings, who held his jacket and backpack in hand before climbed ladder to descend from level X5 to X4, shown in Figure 5.11. Moreover, 50% of occupants claimed that "Wait for the next lift" was the factor to delay their evacuation, but both of PM54 and PM56 lift have never been full or overloaded.



(a)



(b)

Figure 5.10: (a) factors of slowing down evacuation (b) turn back during evacuation

Figure 5.11: An occupant stopped to sort his belongings

PAD/MAD on level X1 in UXC55

All occupants from UXC55 level X6 were directed to exit via the PM54 lift. They were required to pass through the PAD located in UP55 tunnel. Instead of utilizing the emergency handle, each occupants used the badge. The evacuees were divided into two groups due to the time difference of delay evacuation. A group of two people took approximately 18s to clear the PAD; the another group of three occupants required 31s to pass through the same PAD. In average, everyone used 9.8s to pass through the gate.

PAD/MAD in R-202 in SDX5

The 1st batch of occupants to reach the surface PAD/MAD consisted of occupants from Room U0-403 along with two groups from USC55 who merged while using the PM54 lift to the surface. After arrived at the PAD/MAD, they required a total of 43s to pass the PAD by using their badges. The average time in this group was 8.6s per person.

The 2nd batch of occupants to reach the surface PAD/MAD comprised five occupants from UXC55 level X6. The 1st batch of occupants had already left before the 2nd batch arrived the PAD/MAD, so there was no interaction between these two groups. Despite encountering a counterflow scenario with no observable influence, shown in Figure 5.12. On average, they also used 8.7s per person to pass through the PAD by badging.

Lift holding

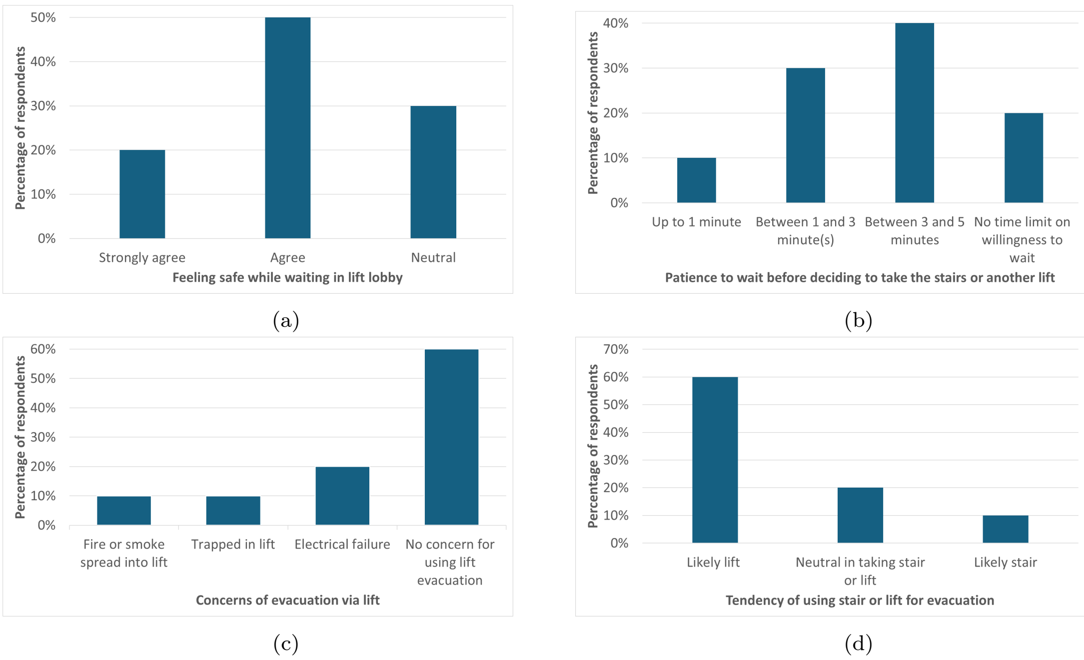
Occupants from 2PACL-system room arrived to PM54 lift shaft. After they entered the lift, they hold the lift for two occupants from mezzanine for about 10s, seen in Figure 5.13. This action showed group behaviour to wait for other to evacuate in a group.

Figure 5.12: Counterflow on surface

Figure 5.13: Holding lift in PM54

5.4.5 Lift evacuation

Seventy of occupants felt safe to wait for lift in the pressurized lift lobby, shown in Figure 5.14. However, 40% of the occupants expressed to have concerns about lift evacuation including ”Fire or smoke spread into the lift”, ”Trapped in the lift” and ”Electrical failure”. These concerns would contribute to their tendency to use alternative egress such as other lift and staircases. Consequently, the possibility of using stair during evacuation is higher. Indeed, they had not shown any hesitation to use the lift during evacuation drill. Also, a majority (60% of occupants) preferred to use the lift when evacuating. Meanwhile, 20% of the respondents remained neutral implying no strong preference between using the stairs or the lift, showing a potential for them to use staircases. Therefore, there could be up to 30% of occupants to use staircase possibly during evacuation. Moreover, 80% of occupants had a willingness to wait for up to 5 minutes before considering alternative evacuation methods, they might have higher tendency to take stairs or other lift shaft after waiting lift for 5 minutes. It could violate the protocol of CMS evacuation.



(a) (b) (c) (d)

Figure 5.14: Occupants' feeling about lift evacuation

Occupant	Building	Floor	Room	Alarm	Begin movement	Pre-evacuation time	Arrival time in lift lobby	Movement time	RSET (from original position to lift lobby)	Lift arrival	Waiting time for lift	Arrival time at surface	Lift travelling time	Total time to reach surface
1	UXC55	X6	Crane	15:18:17	15:18:49	00:00:32	15:20:40	00:01:51	00:02:23	15:22:51	00:02:11	15:24:53	00:02:02	00:06:36
2	UXC55	X6	Crane	15:18:17	15:18:50	00:00:33	15:20:57	00:02:07	00:02:40	15:22:51	00:01:54	15:24:53	00:02:02	00:06:36
3	UXC55	X6	Crane	15:18:17	15:18:56	00:00:39	15:21:50	00:02:54	00:03:33	15:22:51	00:01:01	15:24:53	00:02:02	00:06:36
4	UXC55	X6	Crane	15:18:17	15:18:58	00:00:41	15:22:00	00:03:02	00:03:43	15:22:51	00:00:51	15:24:53	00:02:02	00:06:36
5	UXC55	X6	Crane	15:18:17	15:19:44	00:01:27	15:22:16	00:02:32	00:03:59	15:22:51	00:00:35	15:24:53	00:02:02	00:06:36
6	USC55	-1	2PACL-System (Old Control Room)	15:18:17	15:18:56	00:00:39	15:19:47	00:00:51	00:01:30	15:20:23	00:00:36	15:21:40	00:01:17	00:03:23
7	USC55	-1	2PACL-System (Old Control Room)	15:18:17	15:18:57	00:00:40	15:19:49	00:00:52	00:01:32	15:20:23	00:00:34	15:21:40	00:01:17	00:03:23
8	USC55	-2	Mezzanine (Old Laser Barrack)	15:18:17	15:19:37	00:01:20	15:20:35	00:00:58	00:02:18	15:20:23	00:00:00	15:21:40	00:01:17	00:03:23
9	USC55	-2	Mezzanine (Old Laser Barrack)	15:18:17	15:19:45	00:01:28	15:20:36	00:00:51	00:02:19	15:20:23	00:00:00	15:21:40	00:01:17	00:03:23
10	USC55	-2	U0-403	15:18:17	15:19:26	00:01:09	15:19:37	00:00:11	00:01:20	15:19:59	00:00:22	15:21:40	00:01:41	00:03:23

Table 5.2: Evacuation data of 10 CMS occupants

Behaviours	No. of occupant(s) observed	No. of occupant(s) reported from questionnaire	Remarks
Conducted work-related duties	4	9	In the video footage, this behaviour included putting down working gear, shutdown of machine and packing tools into storage box.
Dressed up such as jackets and safety helmet	4	2	
Sought for more information	1	2	
Gathered belongings	0	2	
Encouraged others to evacuate	N/A	10	
Discussed emergency with other(s)	N/A	3	
Started conversation with colleagues	4	N/A	Observed in video without audio

Table 5.3: Behaviours in pre-evacuation phase

Carried object(s)	No. of occupant(s) observed in video analysis	No. of occupant(s) reported from questionnaire	Remarks
Self-rescue mask(s)	5	3	One of the occupants carried 2 masks
Bag(s)/ Back-pack(s)	3	3	
Work tool(s)/ Equipment	3	1	2 occupants were wearing full-body harnesses; an occupant brought his working gloves with his evacuation
Jacket	5	1	
Nothing	2	2	

Table 5.4: Carried object(s) during evacuation

Chapter 6

Results of simulation

The longest evacuation time among the 22 scenarios was scenario M6, averagely 2544s (≈42.4min). In contrast, the scenario D1 had the shortest evacuation time, averagely 838s (≈14min).

The simulation results of 22 scenarios, refer to 4.3.3, illustrated in Figure 6.1. The evaluation of the result focused on the variation and total evacuation time. For examining the variation, the coefficient of variation (CV) was used which indicated the relative variability in the same dataset and allowed us to compare the degree of variation to other datasets. The hypothesis for the evaluation was that higher CV means the higher effect of the independent variables namely behaviour and design factors contributing to the variability of total evacuation time. The lowest CV value was the scenario GAI2, 21%, while the scenario M3 had the highest CV value, 45%. Over 86% of scenarios' CV value are below 35%.

6.1 Behavioural factors

6.1.1 Delay time effect

The different delay time setting in simulation were compared in various evacuation scenarios. The delay time for scenario D1, D2, D3, D4, D5 and D6 were obtained from evacuation drills conducted at the CMS and ALICE facilities. The evacuation data from ALICE cavern was extracted from previous drill. In contrast, the delay time for scenario GAI1, GAI2, GAI3, GAI4, GAI5 and GAI6 were extracted from literature [13]. Analysis of evacuation time and its variation across these two data sets did not yield any observable correlation or discernible trend, precluding the drawing of definitive conclusions. The delay time effect between evacuation drill data and the literature data was minimal in terms of maximum evacuation time and the variation which might imply that

Scenario	Coefficient of variation (CV) of TET
M1	31%
M2	34%
M3	45%
M4	34%
M5	33%
M6	43%
D1	25%
D2	22%
D3	31%
D4	30%
D5	25%
D6	33%
GAI1	25%
GAI2	21%
GAI3	32%
GAI4	29%
GAI5	23%
GAI6	35%
P1	31%
P2	40%
P3	22%
P4	25%

Table 6.1: Coefficient of variation of TET of 22 scenarios

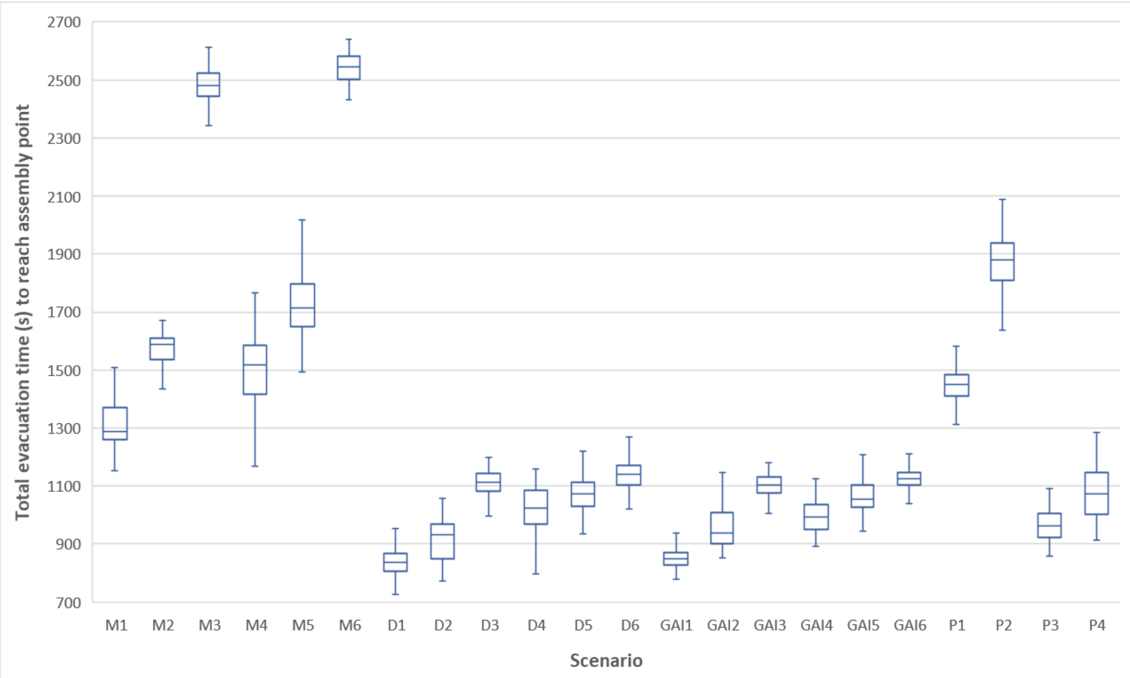


Figure 6.1: Total evacuation time

validation of the literature data to CMS evacuation. However, for scenario D1 vs GAI1, D2 vs GAI2 and D3 vs GAI3, the p-values from the Mann-Whitney U test were found $\prec 0.05$ which implied they are statistical differences in delay time under using emergency handle in PAD/MAD. Conversely, scenario D4 vs GAI4, D5 vs GAI5 and D6 vs GAI6 showed p-values $\succ 0.05$ unveiling no

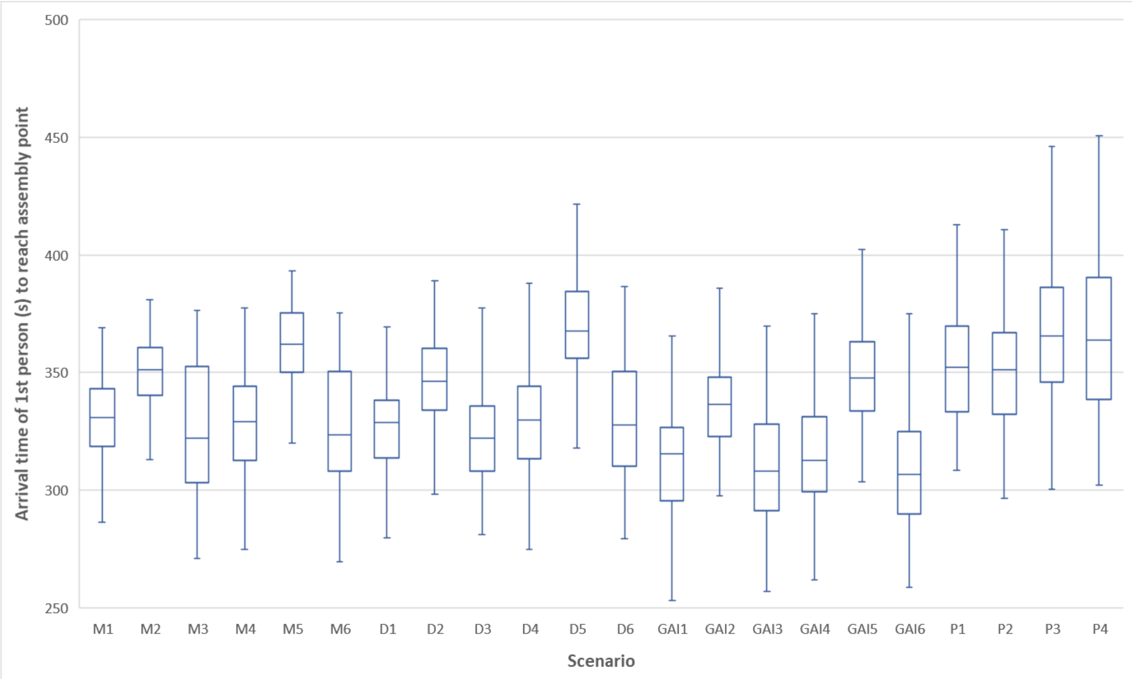


Figure 6.2: Evacuation time of 1st occupant (s)

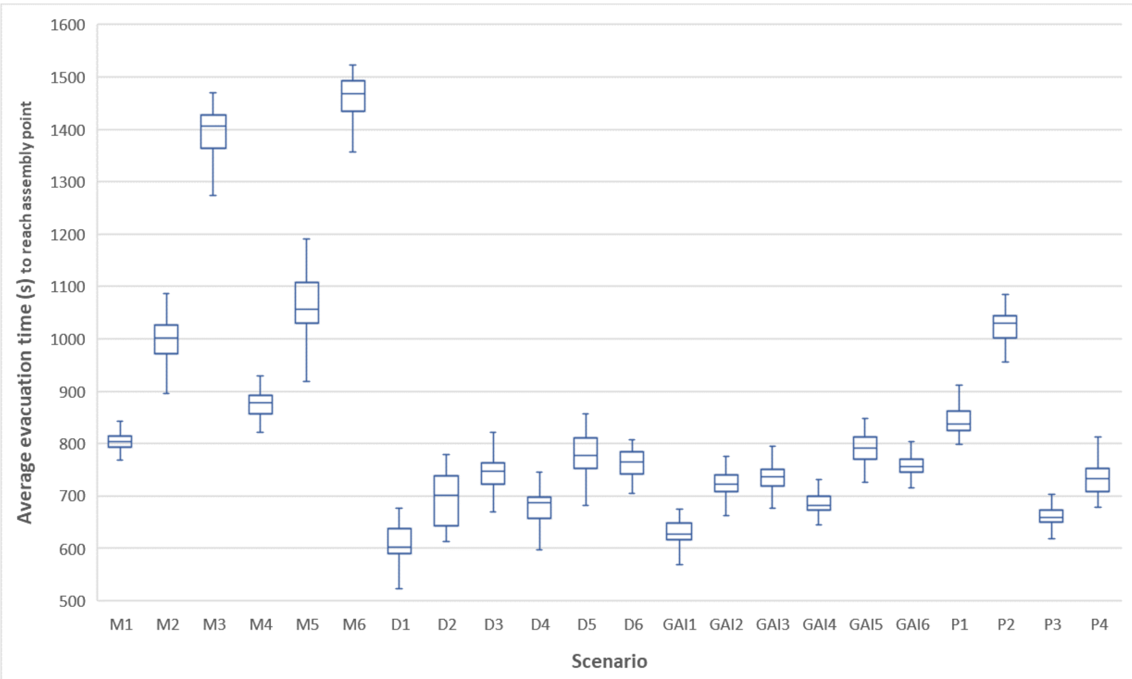


Figure 6.3: Average evacuation time

significant difference in delay times using badge in PAD/MAD. The divergence of the evacuation time may be compensated due to the congestion of PAD/MAD. The significant differences in delay time for the 3 scenario pairs in using emergency handle emphasized the influence of delay time under this condition. The non-significant difference in the using badge scenarios underline the delay time was less importance to evacuation time. This discrepancy pointed to the potential influence of variable namely method of passing PAD/MAD to evacuation time.

6.1.2 Occupant load

The impact of occupant load on evacuation time was examined by comparing scenarios with maximum load (192 people) and routine operational load (62 people). By observing the Figure 6.1, the range of TET for all scenarios with 62 occupants were from 725s (≈12min) to 1300s (≈22min). The relative difference between the highest and lowest TET was 80%. The evacuation time for scenario M1-M6 which were with maximum occupant load has at least 30% longer than the normal operation occupant load (scenario D1-D6). In terms of the evacuation time distribution, the scenarios with maximum load was more diverse and their CV were greater than the normal occupant load scenarios by at least 4%. These two observation might not only highlight a positive relationship between occupant load and evacuation time, which was consistent with the findings of [80] but also showed that this factor prolonged the evacuation time especially on evacuees who start evacuation on later stage.

6.1.3 Occupant distribution

By comparing scenario P1-P4, the scenarios with predefined occupant distribution tended to have longer evacuation time than scenarios with randomized occupant distribution, shown in Figure 6.4. For example, by comparing scenario M1 and P1, the average TET in scenario M1 was smaller than in scenario P1 by 164s (≈13%). However, the effect of occupant distribution to lighter occupant load scenarios with having PAD/MAD congestion problem was small. For instance, the average TET of scenario D4 and P4 was 1024s (≈17min) and 1071s (≈18min) respectively. It might indicate that the uneven occupant distribution was less important when the scenarios were small number of occupant and heavy congestion.

6.2 Design factors

6.2.1 Emergency handle vs badge in passing PAD/MAD

The simulated TET of scenarios between using an emergency handle and a badge to pass through PAD/MAD in the CMS facility were compared. Generally, the TET in scenarios of using badge was longer than in using emergency handle. The congestion effect could be significant under light occupant load scenarios with both PM54 and PM56 lift available. Thus, the average TET in scenario D1, 837s (≈14min) was 22% less than scenario D4, 1024s (17min). For limited lift availability scenario, the difference of TET was no greater than 15%. It may indicate that the access method of PAD/MAD could be the constraint of horizontal evacuation. Meanwhile, lift is

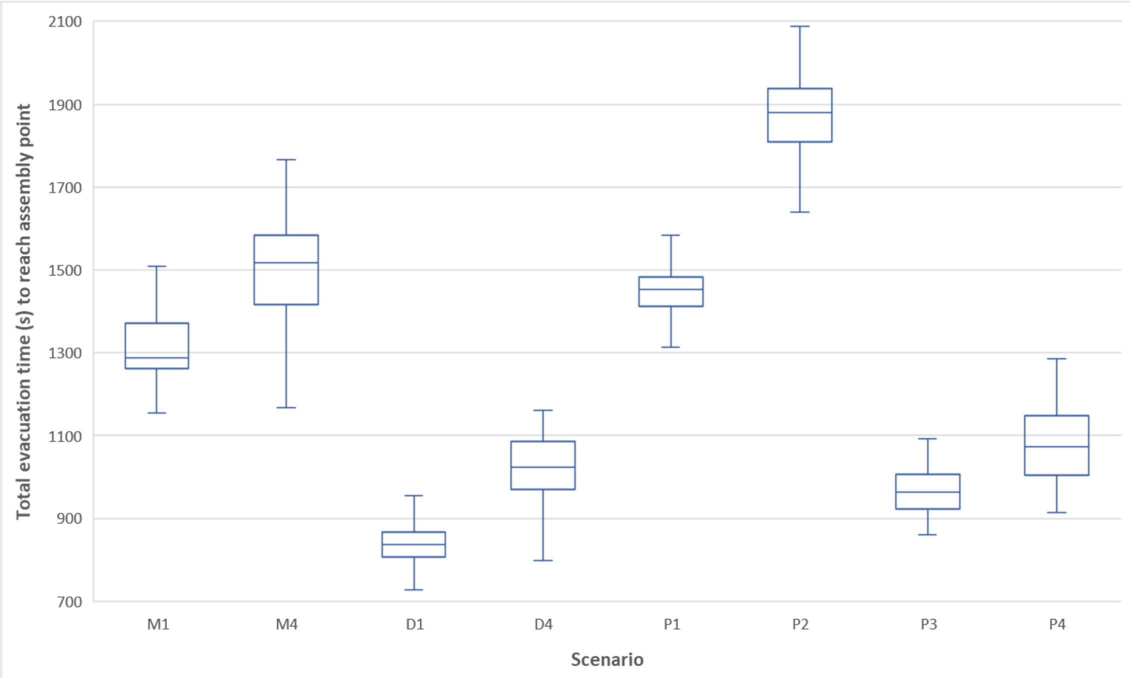


Figure 6.4: TET of predefined and randomized scenarios

still an important factor for the vertical evacuation.

6.2.2 Lift availability

The effect of lift availability on evacuation time could be significant, especially on full-loaded scenarios. By comparing with scenario M3 and scenario M6 with others, they were the top two longest TET scenarios which were higher than scenario M1 and scenario M4 by near 93% and 64%. In contrast, the lift availability might be less important in routine occupant load scenarios as the TET difference in these scenarios was maximum 264s (≈5min).

6.3 Validation of evacuation model

Validation was the step validating simulation model to ensure its applicability to realistic scenarios. This section presented the methodology and results of the validation for CMS evacuation model by comparing of simulated evacuation time with the actual evacuation time recorded during two separate CMS evacuation drills, referring to Table 4.1. The goal was to establish whether the experimental data falls within the confidence interval derived from the simulation to confirm the reliability of the model.

6.3.1 Validation methodology

The validation process was to compare the simulated evacuation time with the data obtained from evacuation drill reports. For each drill, the confidence interval for the simulated evacuation time was calculated at a 95% confidence level [4].

6.3.2 Evacuation drill on 6th February 2024

The recorded evacuation time for 10 CMS evacuees from underground was about 600s (10 mins). The modelling of the drill was constructed based on the data measured including pre-evacuation time, occupant load, their distribution and exit choice, as illustrated in Table 6.2. The simulation of evacuation time is 633s ± 24.5 [361.5 - 788.1]. The range of 95% confidence interval of simulated evacuation time was from 628 to 638s which indicate that the evacuation drill time was out confidence interval but the simulated average TET was close to the evacuation drill within 5.5% error.

Parameter	**Input**
Occuapnts in UXC55	5
Occuapnts in USC55	5
Pre-evacuation time (s)	116 ± 24 [93-148]
Access method of PAD/MAD	Badge
Congestion time in PAD/MAD (s)	9 ± 1 [7-17]
Walking speed (m/s)	1.2m/s ± 0.3 [0.6-2.4]

Table 6.2: Input of CMS drill modelling on 6th February 2024

6.3.3 Evacuation drill on 3rd February 2012

The evacuation data of the drill was 1281s which was extracted from badge records at the assembly point. The drill model was constructed based on the announced drill data including pre-evacuation time, occupant load, occupant distribution, and exit choices, as illustrated in Table 6.3. In the simulation model, evacuation time was 728s ± 35 [710 - 845] and the 95% confidence interval of simulation was from 721 to 735. To compare with occupants' evacuation time, 4 out of 76 occupants finished their evacuation within the 95% CI. In total, there was a 76% discrepancy between the average TET derived from the model and that observed during the evacuation drill.

This error may be contributed from three main factors. Firstly, the simulation data extracted from an evacuation drill conducted on 6th February 2024 that involved only 10 occupants, which was insufficient for scenarios to simulate 76 occupants. Secondly, the drill report on 3rd February 2012 was ambiguous about the access methods for PAD/MAD led to simulation settings largely based on observers' comment in report. Lastly, the usage and the times of lift door open during

Parameter	Input
Occuapnts in UXC55	33
Occuapnts in USC55	34
Pre-evacuation time (s)	0
Access method of PAD/MAD	Emergency handle
Congestion time in PAD/MAD (s)	0
Walking speed (m/s)	1.2m/s $\pm$ 0.3 [0.6-2.4]

Table 6.3: Input of CMS drill modelling on 3rd February 2012

the drill was unpredictable.

Chapter 7

Discussion

7.1 Reporting evacuation

The evaluation of evacuation suffered from inconsistent reporting [55]. The lack of standardized reporting complicated the comparison between different evacuation reports which undermined the development of more effective evacuation procedures. In order to address this issue, a structured and systematic reporting template for both planned and unplanned evacuations was suggested [81]. The template aimed to include the evacuation process, challenges faced and the organizational content that enhanced the quality of data collection. On the other hands, the prediction of human behaviours was one of the important points for understanding and considering human factors before evacuation and during movement [55]. This recommendation to incorporate human behaviours into the evacuation report stemmed from the need to address existing gaps in the model. Enhancing the observation of human behaviour during evacuations through diverse data collection methods was important that could improved the predictive accuracy of evacuation models and contributed to the design of safer buildings. Consequently, this session focused on reviewing the data collection methods employed in the evacuation drill.

7.1.1 Questionnaire design

To collect data in qualitative and quantitative manner from CMS evacuees directly about their evacuation performance, behaviours, factors of decision-making and background, a questionnaire was designed which consists of 24 questions, one of the question was required respondents to draw their egress route. The response rate declined slightly after the 15th question, as illustrated in Figure 7.1. In spite of this trend, the overall completion rate remained at 94.2% indicating the acceptance of the CMS occupants to a questionnaire containing 24 questions. The explanation of the declined answer rate after was unclear. Also, the question 22 had a significantly low response rate at only 20% which asked participants to recall the timing of their last evacuation. Another explanation for the low response rate in this question could be a loss of interest or patience among respondents, which aligns with study findings suggesting that shortening a lengthy questionnaire could increase response rates [82]. Despite 80% of evacuees having past evacuation experience shown in question 21, many of them might not be able to recall the duration.

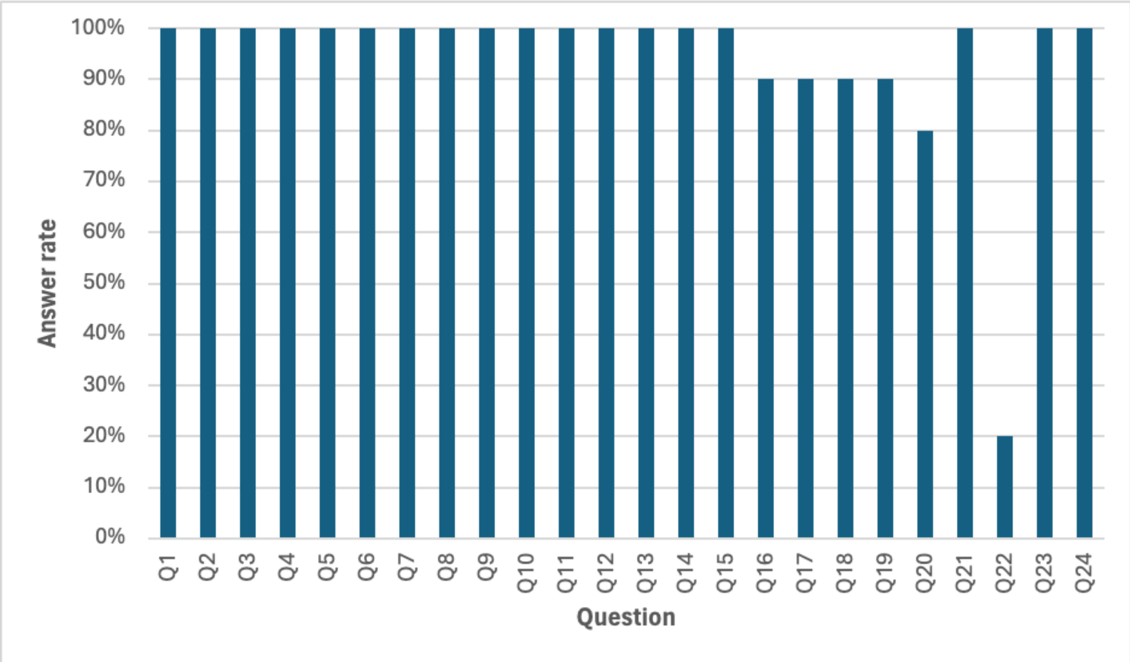


Figure 7.1: Answer rate

Length and complexity of questionnaire design

The optimal length and complexity of evacuation surveys remained a subject of debate due to the variability in occupant capability. This study utilized a 24-question survey. The response rate was consistent at 100% up to question 15. Notably, questions 21, 23 and 24 also maintained a 100% response rate. Therefore, it might give us insight about optimal length which could be 15 questions to achieve a 100% response rate. However, further investigation is still needed to determine the ideal survey length. Regarding question complexity, some participants selected choices for pre-evacuation actions rather than ranking them in sequence as instructed. Additionally, the task of drawing an egress route on a floor plan has only 30% accuracy rate. This suggested that such a question might be over complex for some occupants potentially due to limited familiarity of the building layout, limitation of short-term memory and lack of knowledge about floorplan. Alternative methods for gathering egress route from occupants should be explored in future research. As the drawing egress route helped the researcher to study the egress components and movement phase.

7.1.2 Importance of verifying responses from questionnaire

Section 5.4.1, there was a misinterpretation in the question 9, which asked about if occupants encountered any obstacles during evacuation, that showed the importance of verification of their responses as it affected the assessment of evacuation.

Furthermore, there was a discrepancy between video analysis and questionnaire responses, referring to Section 5.4.1 and 5.4.3 which could be attributed to several factors. Occupants might not remember what they did precisely during evacuation especially under stress. In this drill, no occupant reported to feel stressed so being stress could not explain the discrepancy but this could explain by the other psychological factors including response bias, occupants' perception of relevance and difficulty of recalling memory [83, 84]. Furthermore, using simple wording in questionnaires was important to avoid confusion when respondents interpret the questions. It was advisable to select words that have a singular meaning or those that are highly familiar to ensure clarity [85]. In these evacuation studies, video footage was collected, enabling a crosscheck with questionnaire responses to maintain data validity. The crosscheck procedure emphasized that when designing questions, it was important to consider the possibility of verifying the authenticity of responses and their ease of validation to not compromising the reliability of the responses.

Moreover, cross-referencing of data between questionnaire and video could help to formulate questionnaire by analyzing discrepancies between observed behaviours and self-reported actions in questionnaires. It could help to identify examples where questions might be misinterpreted by participants. This method provided an approach to refine questionnaire wording and structure to ensure that questions were clear to reduce probability of misinterpretation. For example, 5 respondents misinterpreted the question 9, as mentioned in Section 5.4.1. By the validating data from cross-referencing, it might show that the question 9 might be ambiguous. Therefore, adjusting the questionnaire based on these insights could improve the reliability of self-reported data in future drills.

7.2 Effectiveness of data collection in evacuation drill

7.2.1 Cost analysis of deploying observers

The evacuation drill engaged 21 observers, including 20 engineers and safety officers and who participated for 3 hours. The duration was divided into three parts: the 1st hour was dedicated to preparation activities such as attending a briefing session and setting up cameras and other materials; the 2nd hour focused on conducting and recording the evacuation drill; the 3rd hour involved attending a debriefing session and returning the materials used during the drill. However, this thesis did not mention the working hours spent on advance preparations such as conducting on-site visits and communicating with various stakeholders. Given that the minimum monthly salary of an experienced project graduate at CHF 6,212, the hourly wage is about CHF 34.5. Consequently, the cost for manpower during this drill was approximately CHF 2,070.7. The cost analysis indicated the need for exploring more cost-effective methods for monitoring future evacuation drills in CERN. The question arised concerning the utilization of mini-cameras and observers in data collection.

Deployment strategies

After evaluating the cost of evacuation drills, the deployment of mini-cameras and observers was one of the key to control the cost. This section illustrated two possible strategies for the future mini-cameras and observers placement.

The first strategy is to place the mini-cameras and observers in strategical location. For example, cameras and observers are positioned at key locations such as exits and potential location of presence of occupants. This approach may require to coverage of all critical areas and blind spots of surveillance cameras. However, this strategy heavily depends on the layout and size of building which may require a large number of devices to adequately cover all blind spot and critical points in CMS facility. Additionally, this method requires to predict possible egress routes of occupants.

On the other hand, the second strategy is to directly deploy the mini-camera and observers near occupant groups. This method allows to concentrated observation on occupant groups to capture their movement and decision from the very initial phase of the evacuation. Plus, it may reduce resource use if the number of groups are small like the drill in this time. However, the limitation of this method is that the number of cameras and observers needed may depend on the number of occupant groups which is hard to predict. Therefore, it is challenging to forecast the exact resources needed. Also, the observer may expose to occupants which can potentially influence participant behaviours.

Example and comparison between strategic location deployment and direct deployment

Both strategies offer different advantages and disadvantages. Strategic location deployment is not cost-effective for large areas with small number of occupant group. Direct deployment can target interested individuals or groups to records and limit expenditure for evacuation drills.

For the below case studies, the available resources are the same with the drill conducted (15 mini-cameras and 21 observers).

CMS cavern: The CMS cavern, despite its large and complex structure, accommodated only ten occupants who were divided into four distinct groups during the evacuation drill conducted on 6 February. Only two to four observers were needed, as the surveillance system already covers two of these occupant groups. The manpower cost could be reduced to approximately CHF 414.

Building 57 (B57): The B57 is a office building with 3 levels. The possible number of occupants is 50 and in 10 groups. There is no surveillance camera. The number of needed observer is 10 observers with hybrid deploying which is based on the the building design and location of occupant groups. For example, 6 observers can be deployed to staircases to cover the all exit and entry of stairs; 1 observer can be deploy to medical center and 3 observers can be follow the occupant group based on the interest on occupant characteristic. Hybrid deployment can address the issue of limited resources. At the same time, it enables observers to adequately monitor key areas such as exits and medical centers, as well as various groups of occupants, including patients. The estimated manpower cost could be CHF 1,035.

Restaurant R1: The number of occupant in R1 is 500 people, the number of occupant group isover 100. The restaurant has large open dining area without any surveillance camera. For this instance, 15 of observers is needed and are deployed based on strategical location such as exits, catering area, kitchen and dining area as the number of occupant group is much larger than the number of observers unless having particular interested occupant group. The estimated manpower cost might be CHF 2,070.7. Although the manpower cost did not reduce, it did not increase neither.

7.2.2 Cost analysis of video analysis

Understanding the layout of the building and the coverage of existing surveillance cameras is essential prior to deploying mini-cameras. This action helps to determine if key locations such as exits, lifts and workspaces are adequately monitored. An on-site visit may be necessary to identify any blind spots in surveillance coverage. Additionally, the functionality and operational capabilities of the cameras including recording functions and resolution must be assessed. Adjustments to camera angles should be attempted to achieve desired viewpoints. If these adjustments prove insufficient, the deployment of mini-cameras may be considered, keeping in mind that additional cameras will generate more data, requiring processing that increase the workload. This preparatory work may require up to two working days.

If the decision is made to utilize mini-cameras, the number of needed mini-cameras must be determined. Similar checks for functionality and operational capability such as recording functions and resolution are also necessary for the mini-cameras. These devices must be tested and appropriate placement determined. Three specific challenges related to using mini-cameras include overheating, insufficient battery life and limited video storage capacity but these issues could be solved by lowering recording quality. For instance, if mini-cameras are mounted on observers' helmets, the stability and functionality of the mounting need to be tested. Additionally, synchronizing the clocks of mini-cameras with the existing surveillance system would facilitate the alignment of timestamps during video analysis which enhances the efficiency and accuracy of data review. The preparation for deploying mini-cameras might take approximately one working day.

After recording the drill, video processing is necessary. For instance, this thesis involved analyzing nearly 100GB of video footage collected from 52 surveillance cameras and 13 mini-cameras during a drill that lasted 10 minutes. The analysis began by viewing the footage starting five minutes prior to the initiation of the evacuation and was repeated once to review ensuring no details were overlooked and verifying the summarized data. This processing took approximately four working days to complete.

Nevertheless, due to privacy regulations, blurring faces in the videos is required, which could extend the processing time by an additional five working days. Although Python was employed to automate face-blurring using an AI-based function, there were instances where faces were not adequately obscured. Consequently, manual intervention to blur faces in the videos was necessary. The total cost for preparation and processing was estimated at CHF 3727, calculated based on the salary of an experienced project graduate at CERN.

Values of using mini-cameras

Using mini-camera definitely add values to the data collection method because it record the drill above horizontal level which can provide more details on occupants' clothing and objects holding in hand. Video footage from surveillance camera were recorded from high angle with distance, it captures the details of occupants with blurry video.

Moreover, if observers use mini-cameras to record the drill, this provides critical flexibility in adjusting the camera angles. For instance, during an emergency evacuation drill at a facility, observers equipped with mini-cameras can easily can move their position or adjust camera angle to avoid being blocked and actively to capture study targets.

7.2.3 Cost analysis of using questionnaire

The designing questionnaire was the simplest among the three data collection methods used in this study. This process involved conducting a literature review and examining previous evacuation reports to formulate questions aligned with the study's interests. The format and requirements for the questionnaire were comparatively less demanding. However, it is noteworthy that two working days were dedicated to verifying the responses received from the questionnaire. The workload, including designing the questionnaire and processing responses, required approximately two working days, was worth near CHF 1242.

7.2.4 Conclusion of data collection methods

The comparison between using observers, cameras and questionnaires in evacuation drills were summarized in the following Figure 7.2. The comparative analysis was conducted and expressed in qualitative way. Observers offer high flexibility to record drill but they may introduce bias. Cameras provide accurate and comprehensive visual data but require significant preparation and privacy considerations. Questionnaires are useful for capturing first hand information directly and low cost but are hindered by biases and accuracy issues.

For CMS building, in long term, it will be good to keep questionnaire in the rest of evacuation drill as it is low-budget method. A template of questionnaire or question bank is suggested to build, so that some selected questions could keep to ask. If we are able to build the question bank, we can gather the response to make direct analysis from other data. The distribution of questionnaire was suggested to use online format. In long term, we can collect more data on targeted aspects which could be analyzed in quantitative. The selected question could focus on understanding the reason of exit choice, sequence of action during pre-evacuation phase and initial thought of hearing alarm. The length of questionnaire could be up to 15 questions. The focus of observers should be on pre-evacuation phase. it will be good if we know the location of occupant groups, so that observers could be directly deployed nearby. video analysis was suggested if have enough manpower as the post analysis and processing is time-consuming. If the manpower is limited with good coverage by surveillance camera, mini-camera is suggested to not use. On the other hand, if the coverage by surveillance camera is poor, mini-camera is suggested to use. Video analysis by using surveillance camera is prior to use than mini-camera as it is easier to synchonize timestamp of video footage from surveillance camera.

7.2.5 Suggestion of future data collection methods

For the CMS building, maintaining to use questionnaires in future evacuation drills is recommended as it is a cost-effective method. It is advisable to develop a standardized template or question bank, which would allow for the consistent use of selected questions across multiple drills. This would facilitate to a database which enable direct analysis when correlated with other data sets. It is suggested that questionnaires be distributed in an online format to improve data collection efficiency. In the long term, this approach will allow for the accumulation of targeted data that can be quantitatively analyzed. The focus of the questions should primarily be on understanding occupants' reasons for exit choice, the sequence of actions during the pre-evacuation phase and initial thought upon hearing the alarm. The questionnaire should ideally be up to 15 questions to minimize respondent fatigue and ensure high-quality data.

The role of observers should be focused on the pre-evacuation phase, specifically targeting areas where occupant groups are. This would enable more effective deployment of observers to enhancing data by early observation.

Video analysis is valuable but it should be undertaken only if sufficient manpower is available, given its time-consuming feature in terms of post-processing and analysis. If surveillance coverage is adequate, the use of mini-cameras may be unnecessary. However, if coverage is insufficient, mini-cameras is recommended. Preferably, video analysis should utilize footage from surveillance cameras as they offer easier synchronization of timestamps compared to footage from mini-cameras.

7.3 Comparison with previous CMS drill data

This section aimed to compare the CMS drill on 6th Februray 2024 with the previous CMS evacuation drills, as illustrated in Table 4.1.

7.3.1 Comparison with other unannounced drills

The unannounced evacuation drill on 6th February 2024 was the second shortest evacuation time (≈10min) with 48 occupants among the unannounced drills. In contrast, the unannounced drill on 22 January 2019 had the longest evacuation time(≈35min) with the highest number of occupants, 80 people. The lighter occupant load might have a more efficient evacuation process as one of the common mistake done by occupants was to badge for passing PAD/MAD device which might increase evacuation time substantially due to bottleneck situation. However, from their evacuation reports there was lack of information about occupant load in underground which increased the difficulty for comparison.

7.3.2 Comparison with announced drill

In announced drills, the occupant load was higher generally which took longer to complete. The detail about occupant distribution in UXC55 and USC55 was clearly to record which allowed researcher to have an easier comparison and tracking with other drills. Nevertheless, an announced drill means that occupants would know evacuation before activating alarm. When they heard alarm, they just simply started their evacuation which was unlike normal evacuation procedure to have pre-evacuation period. Therefore, it was hard to have apple to apple comparison to the unannounced evacuation drill on 6th February 2024.

7.4 Interpretation of simulation result

The simulation results reveal that there are significant variations of evacuation time across different scenarios as 59% of scenarios' CV value (13/22) is greater than 30% which unveil that it is important to understand the impacts of behavioural and design factors on evacuation time due to causing moderate variation. Also, the use of the CV is a rare tool to evaluate the variability of factors of evacuation time which may be worth to study the value of using CV for assessing how variables to affect evacuation time.

7.4.1 Behavioural and design factors

The results indicate minor variation in evacuation time due to different delay settings between experimental and literature data. This observation suggests that using different setting of pre-evacuation time might not have significant changing in outcome, but it should be aware that the delay settings between experimental and literature data were close. Also, the simulation consistently demonstrated longer evacuation time under maximum occupant load conditions. This finding is consistent with literature that associates higher occupant density with increased evacuation time due to greater interaction and potential bottlenecks. Moreover, the results in scenarios with different lift availability had shown significantly consistent different evacuation time. However, investigating the cumulative impact of these behavioural factors on evacuation, whether they amplified each other to create a snowball effect or diminishing each other's impact, remain an open question. At present, it is not possible to draw definitive conclusions regarding their interrelationships.

7.4.2 Model performance and reliability

The validation results have highlighted significant difference between the simulated and actual evacuation time. This deviation underscores potential limitation of the prediction capability of the model. The current model assumption and settings such as congestion time of PAD/MAD, usage of emergency handle/badge, pre-evacuation time and walking speed in announced and unannounced drill may need to be revisited and adjusted to reflect the variation of behaviour and design factors.

7.5 Limitation

7.5.1 Data uncertainty

One significant limitation is the potential bias introduced by the presence of observers, notably when nearly half of them were affiliated with the CMS Safety Office. The observers' presence could influence the occupants' behaviour, as they might recognize the personnel and consequently, perceive the situation as less urgent, considering it merely a drill. This recognition could diminish their sense of urgency, affecting the authenticity of their responses. Also, occupants and observers were using the same egress mean during evacuation as observers were asked to follow occupants to evacuate. When they were passing through the PAD/MAD, the presence of observers might contribute to increase congestion in front of PAD.

Furthermore, the evacuation drill involved only 10 participants, representing a small sample size that may not adequately reflect the diverse behaviours and responses expected in larger populations under full-load scenarios. For instance, the observed behaviours regarding the use of emergency handles or badges through Physical Assistance Devices/Mobility Assistance Devices (PAD/MAD) systems are based on a limited dataset, which may not be representative of the entire population at CMS. Additionally, to minimize safety concerns associated with the presence of visitors, the drill excluded them, further limiting the data's scope. This scenario necessitates reliance on sparse data to construct simulation models and define occupant characteristics. Expanding the sample size in terms of the number of occupants and evacuation scenarios or selecting more representative conditions could significantly enhance the accuracy of the predicted evacuation outcomes. The subjective nature of data collected through questionnaires and observer reports also introduces a degree of uncertainty due to potential biases.

7.5.2 Limitation of modelling

Uncertainty in simulation also arises from limitations in the model design, variability in input parameters, and inherent randomness. The complexity of the building and the dynamic nature of occupants' movements and initial positions contribute significantly to this uncertainty. Additionally, 22 scenarios were simulated with variable parameters such as delay time, walking speed, and occupant load and distribution, each adding to the uncertainty. Although the model was run 100 times for each scenario to gauge consistency, the optimal number of simulation runs should ideally be determined by testing for convergence within predefined criteria to assess variability more accurately [86].

The evacuation model's accuracy is potentially compromised by its reliance on architectural drawings (DWG files) and snapshots from Google Maps for constructing its geographic and structural features. These sources might not perfectly capture the true layout and detailed architectural nuances of the building, which could affect the validity of the evacuation simulation results.

Beside, the accuracy of the model could be affected by the assumptions including the possible evacuation route of the surface and their difference of walking speed between underground and surface. For example, their walking speed in the modelling based on the smoke-filled tunnel evacuation experiment [12]. When they arrived on surface level, it should be no longer applied. However, in this model, the difference of walking speed in two environment setting was ignored. In another example of exit choice, there were 3 possible exits in building SDX5 for occupants going to assembly point, as mentioned in Section 2.1. Therefore, their exit choice was assumed based on the CMS drill. Assumptions highlighted the potential limitation to the model's accuracy.

7.5.3 Other possible data collection method

It is important to note that the data collection method in this thesis focused on observers, questionnaires and video analysis. While these methods provide useful insights, there are other data collection techniques that were not explored. For example, some sensor-data collection method such as RFID tracking. In CMS, the RFID chip test for tracking visitors at CMS was implemented [87]. The automatic data collection method can increase accuracy of flow tracking and reduce the possibility of human error. From there, the potential of these methods was observed. Future research could benefit from a broader exploration of these advanced methods to further improve data collection efficiency and effectiveness.

Method	Advantages	Disadvantages	Data quantity	Data validation	Data bias	Workload	Cost
Observers	• Data clarification: Observers can report observed behaviours in their interpretation • Cover blind spot of camera: cover place that blind spots of cameras • High flexibiliy: can adjust position based on observed occupants and incidents	• Subject to observer bias: Observers' perceptions may influence the data. • Limited coverage: Can only observe one location at a time • Training may require: Observers may need to be trained to ensure the consistent and accurate way for data collection. • Can be intrusive: Their presence might affect occupants • Human error: Observers might report incorrect or misinterpret behaviour • Difficult to record event in time: Reporting with timestamp could be difficult due to not unitfy timestamp	Medium	Medium	Medium	Medium/Low	High/Medium
Cameras	• High accuracy of data without bias: Capture precise movements and actions with timestamp • Good coverage: Can monitor majority of building (at least key area) if cameras are placed strategically • Non-intrusive: Not interfere with the behaviour of occupants during the evacuation (for surveillance camera)	• High setup time: Require certain preparation work and testing before the drill • Privacy issues: Must comply with privacy laws • Require heavy processing: Heavy analysis workload and videos may need editing for privacy • Intrusive: potentially interfere occupants (especially for additional camera) • Potential technical issues: Equipment failure, battery issues or improper camera angles	High	High	Low	High	High/Medium
Questionnaires	• First hand information: Direct feedback from respondent • Relatively easy to do including design, distribution and collection • Cheap	• Collected data might restrained by the format: e.g. length and complexity • Potential inaccuracies in self-reported data: Responses may be influenced by memory bias or other factors.	Low	Low	High	Medium/Low	Low

Figure 7.2: Summary of data collection methods

Chapter 8

Conclusion and future work

The study conducted unannounced evacuation drills in the CMS facility at CERN. The evacuation drill conducted provided evacuation data in a complex and underground environment that contributed to understanding evacuation performance such as pre-evacuation distribution and simulation models for other underground research facilities.

The study revealed several insights into evacuation performance in the CMS. Conducting an unannounced drill that captured behaviours, pre-evacuation and evacuation time of the occupants. By utilizing questionnaire, observation and video analysis, the discrepancies between the self-reported behaviours and their actual actions during the evacuation were unveiled. It implied the improvement of survey design. Also, it suggested to establish a framework of data collection method and the cross-referencing of data from multiple sources. Moreover, the evacuation modelling fed by drill data enabled to have analysis and test of various evacuation scenario which was able to study the impact of behavioural and design factors such as occupant load, distribution and usage of lift and emergency device on evacuation.

Future research could focus on several areas for enhancing the understanding and effectiveness of evacuation in complex environment. Firstly, developing standardized tools and methodologies for data collection including questionnaires, observation sheets and methods. It will improve the consistency and comparability of data across different drills and studies. Establishing a database to store and analyze evacuation data is critical which could be leveraged by machine learning to identify trends and patterns.

Moreover, exploring the use of non-intrusive technologies such as RFID to monitor evacuation activities can minimize the influence of observers on occupant behaviour, thereby providing more accurate and authentic data. Further refining evacuation simulation models to incorporate detailed behavioural and design parameters including the usage of emergency handles and badges in PAD/PAD and characteristics of different occupant groups especially visitors will allow for more precise simulations. Investigating advanced data collection technologies that minimize participant influence and enhance data accuracy is also essential. These technologies can be applied not only in fire safety engineering but also in other fields such as social science and transport engineering.

Acknowledgement

There are no secrets to success. It is the result of preparation, hard work and learning from failure.

Colin Powell

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Lastly, AI language tools such as ChatGPT were utilized to refine the language in the thesis.

Appendix A

Questionnaire sample

Evacuation Experience Questionnaire

Thank you for taking the time to answer this questionnaire. Your responses are valuable in understanding the evacuation process and improving future safety measures. This questionnaire was created in collaboration with Lund University. Your responses will be kept confidential, anonymous and used for research purposes only.

Please answer the following questions based on your evacuation experience.

Section 1: After triggered evacuation alarm

1. Where were you when you heard the alarm? Please refer to Appendix.
   Building: ☐ USC55 ☐ UXC55 ☐ R57 ☐ Surface ☐ Other: ______________________
   Floor: ☐ U2 ☐ U1 ☐ U0 ☐ W1 ☐ W2 ☐ W3 ☐ Other: ______________________
2. What was the first clue that prompted you to evacuate?
   ☐ Saw/heard fire ☐ Heard evacuation alarm ☐ Informed by other(s) ☐ Other: ______________________
3. What did you think about the clarity of the alarm?
   ☐ I did not hear the alarm ☐ Good ☐ Fair ☐ Poor ☐ Other: ______________________
4. When you heard the alarm, did you initially think it was:
   ☐ A real emergency ☐ An evacuation drill ☐ A false alarm
5. Please list the sequence of actions you took after hearing alarm. Number each action in the order you performed them (e.g., 1, 2, 3, etc.). If you did not perform a given action, please write a cross in the corresponding box.

☐ Conducted work-related duties (e.g. shutting down equipment) [Please specify: ______________________]	☐ Engaged in unrelated activities (e.g. entertainment)
☐ Gathered belongings (e.g. wallet, mobile phone, tools)	☐ Encouraged others to evacuate (e.g. alert others to evacuate)
☐ Sought for more information (e.g. check out the surroundings)	☐ Called the authorities (e.g. use red phone to report to fire brigade)
☐ Discussed emergency with other(s) (e.g. conversations about the situation)	☐ Rescue (e.g. check state of injury, firefighting)
☐ Got dressed (e.g. jackets, coats, PPE)	☐ Read evacuation plan
☐ Waited for somebody or something (e.g. for colleague(s), for job completion)	☐ Other: ______________________

6. How long did it take you to decide to evacuate after hearing the alarm approximately?
   ☐ Up to 30 seconds ☐ Up to a minute ☐ Between 1 and 4 minutes ☐ More than 4 minutes
7. How did you determine the evacuation route? Please select all applicable options.
   ☐ Knew the closest exit ☐ Used the way I came in ☐ Used the way I am familiar with ☐ Avoid fire or smoke ☐ Followed exit signs ☐ Checked the evacuation plan ☐ Asked other(s) ☐ Followed other(s) ☐ Waiting time for lift ☐ Lift lobby size ☐ Lift size ☐ Less congested route ☐ Other: __________

Section 2: During evacuation

8. Did you carry any item(s) in your hand(s) throughout the evacuation? Please select all applicable options.

   ☐ Laptop(s) ☐ Mobile phone(s) ☐ Documents(s)/Book(s) ☐ Work tool(s)/Equipment
   ☐ Bag(s)/Backpack(s) ☐ Nothing ☐ Other: ______________________

9. Were there any factors that slowed down your evacuation? Please select all applicable options.

☐ Obstruction (e.g. blocked door, queue, counterflow of people, congestion)	☐ Wait for the next lift (e.g. lift was full or overloaded)
☐ Not familiar with the facility	☐ Unclear exit signages
☐ Help other(s) (e.g. guiding, carrying items)	☐ Injury (e.g. pain)
☐ Other: ______________________	☐ None, there were no factors that slowed down my evacuation.

10. Did you turn back? Please select all applicable options.

    ☐ No, I did not turn back ☐ Yes [please specify the reason] ____

11. Did you experience any of the following feeling(s)? Please select all applicable options.

    ☐ Stressed ☐ Confused ☐ Threatened ☐ Calm ☐ Neutral

12. Which lift shaft did you take?

    ☐ PM54 ☐ PM56

13. How long did you wait for the lift?

    ☐ Up to 1 minute ☐ Between 1 and 2 minute(s) ☐ Between 2 and 5 minutes ☐ More than 5 minutes

14. You felt safe when you were waiting for lift in the lift lobby. Do you agree with this statement?

    ☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree

15. How long are you willing to wait before deciding to take the stairs or another lift?

    ☐ Up to 1 minute ☐ Between 1 and 3 minute(s) ☐ Between 3 and 5 minutes
    ☐ Between 5 and 10 minutes ☐ More than 10 minutes ☐ No time limit on willingness to wait

16. What are your concerns when you use a lift to evacuate? Please select all applicable options.

    ☐ Trapped in lift ☐ Fire or smoke spread into lift ☐ Unacceptable waiting time for lift ☐ Lift fall down
    ☐ Electrical failure ☐ Other: ______________________ ☐ No concern for using lift evacuation

17. If you can use both stair and lift for evacuation, which means will you choose?

    ☐ Very likely stair ☐ Likely stair ☐ Neutral in taking stair or lift ☐ Likely lift ☐ Very likely lift

18. How did you exit the cavern/lift area?

    ☐ Badging in the PAD ☐ Breaking emergency handle in PAD/MAD

19. There is sufficient evacuation information (e.g. exit sign) to boost my evacuation. Do you agree with this statement?

    ☐ Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree

20. Please draw your evacuation route in the Appendix. (Mark with ×**start** your starting point and depict the evacuation path to the lift)

Section 3: Background
21. Have you participated in an evacuation before? Please select all applicable options. ☐ Yes, due to a real emergency ☐ Yes, due to an evacuation drill ☐ Yes, due to a false alarm ☐ No
22. When was your last evacuation in the below locations? If you have not participated in the corresponding location(s), please write down **X**. CMS: ________month(s) CERN except CMS: ________month(s) Outside CERN: ________month(s)
23. When was your last CERN - LHC Large Experiments training course? ☐ Less than a month ago ☐ 1-3 month(s) ago ☐ 3-6 months ago ☐ 6-12 months ago ☐ 1-3 year(s) ago ☐ No
24. Where do you usually work? Please select all applicable options. Building: ☐ USC55 ☐ UXC55 ☐ R57 ☐ Surface ☐ Other: ______________________ Floor: ☐ U2 ☐ U1 ☐ U0 ☐ W1 ☐ W2 ☐ W3 ☐ Other: ______________________

Comments

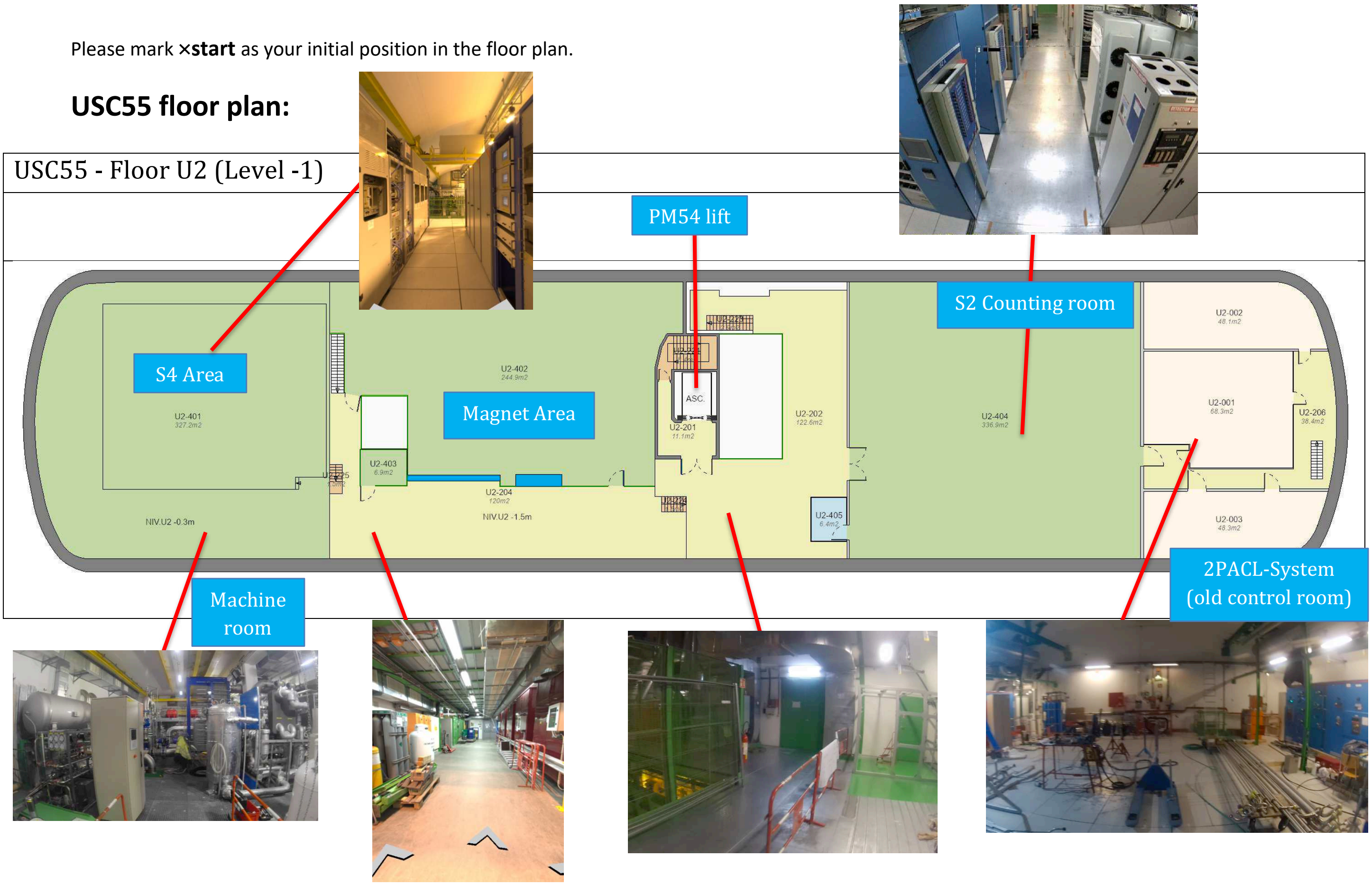
Thank you for your participation.

Please return the questionnaire to safety guide/ TSO in the assembly point

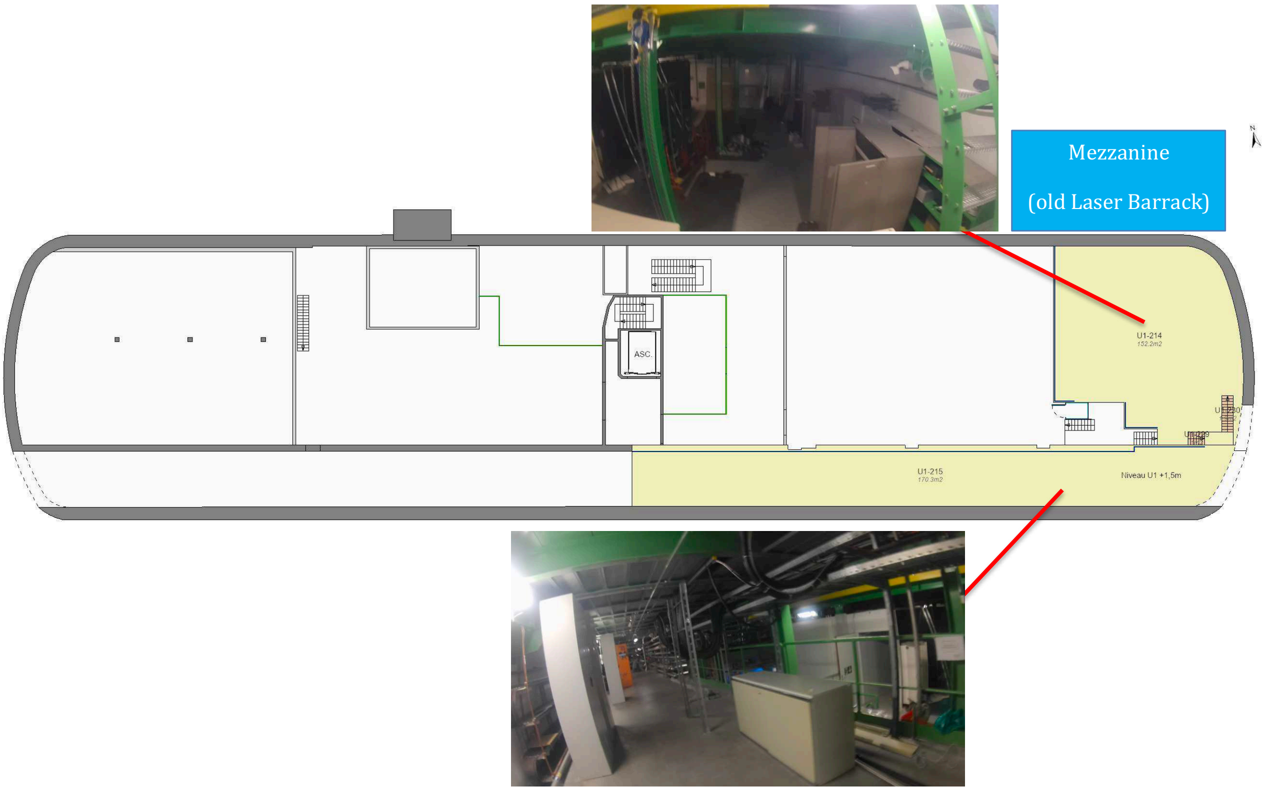
Appendix

Please mark ×**start** as your initial position in the floor plan.

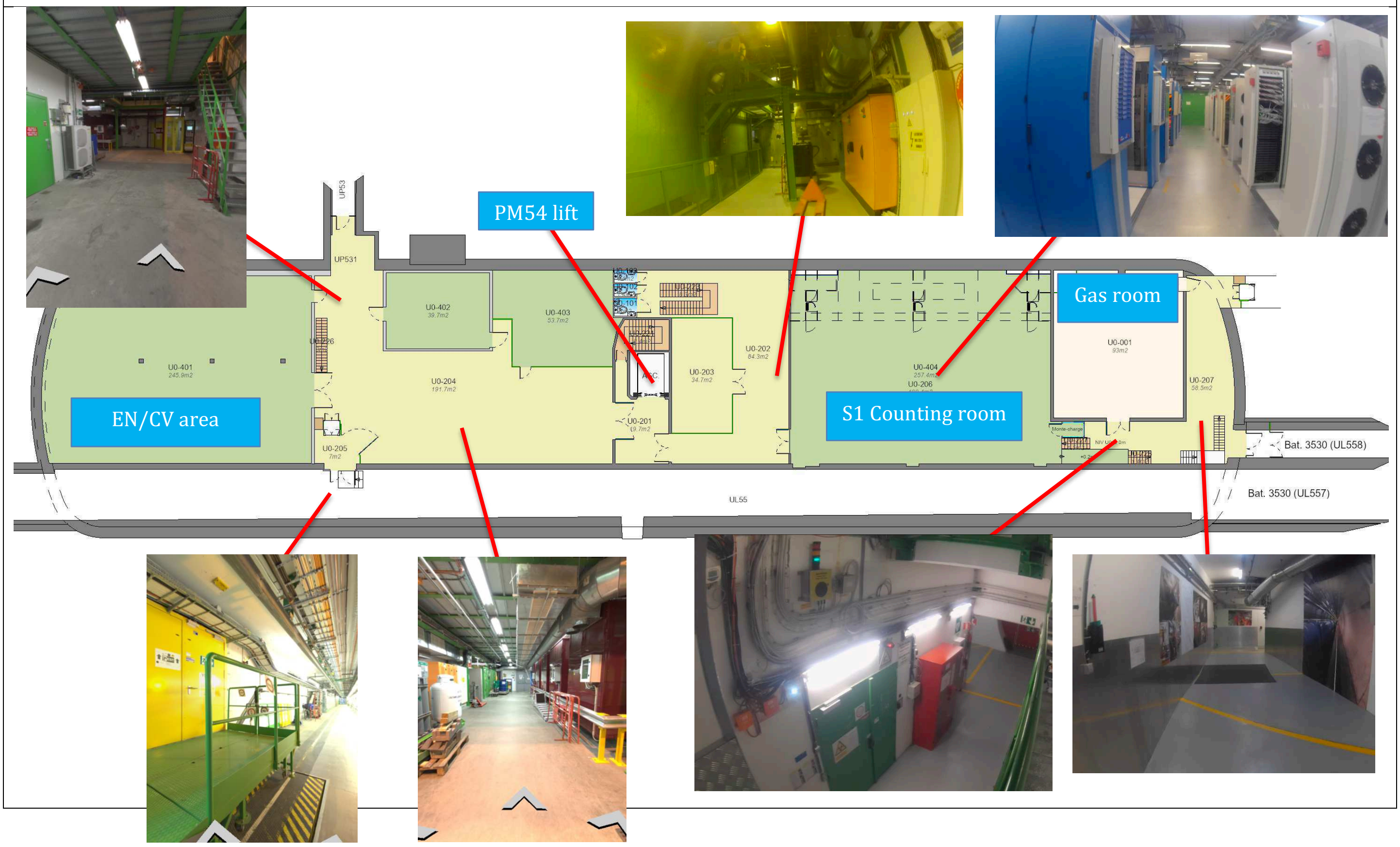
USC55 floor plan:



USC55 - Floor U1 (Level -2)

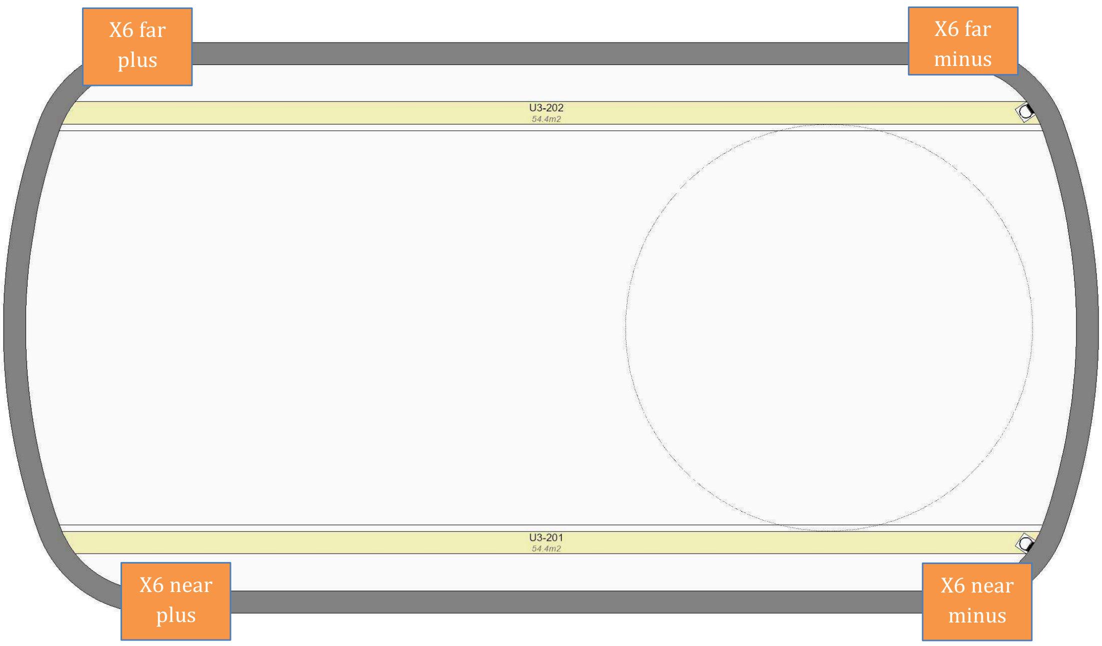


USC55 - Floor U0 (Level -2)

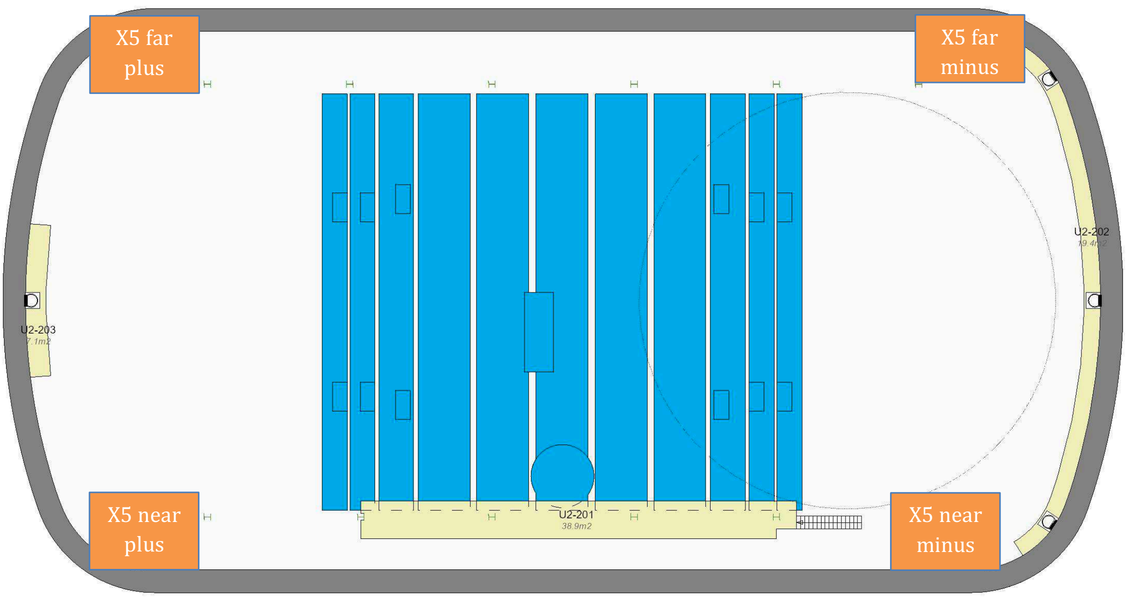


UXC55 floor plan:

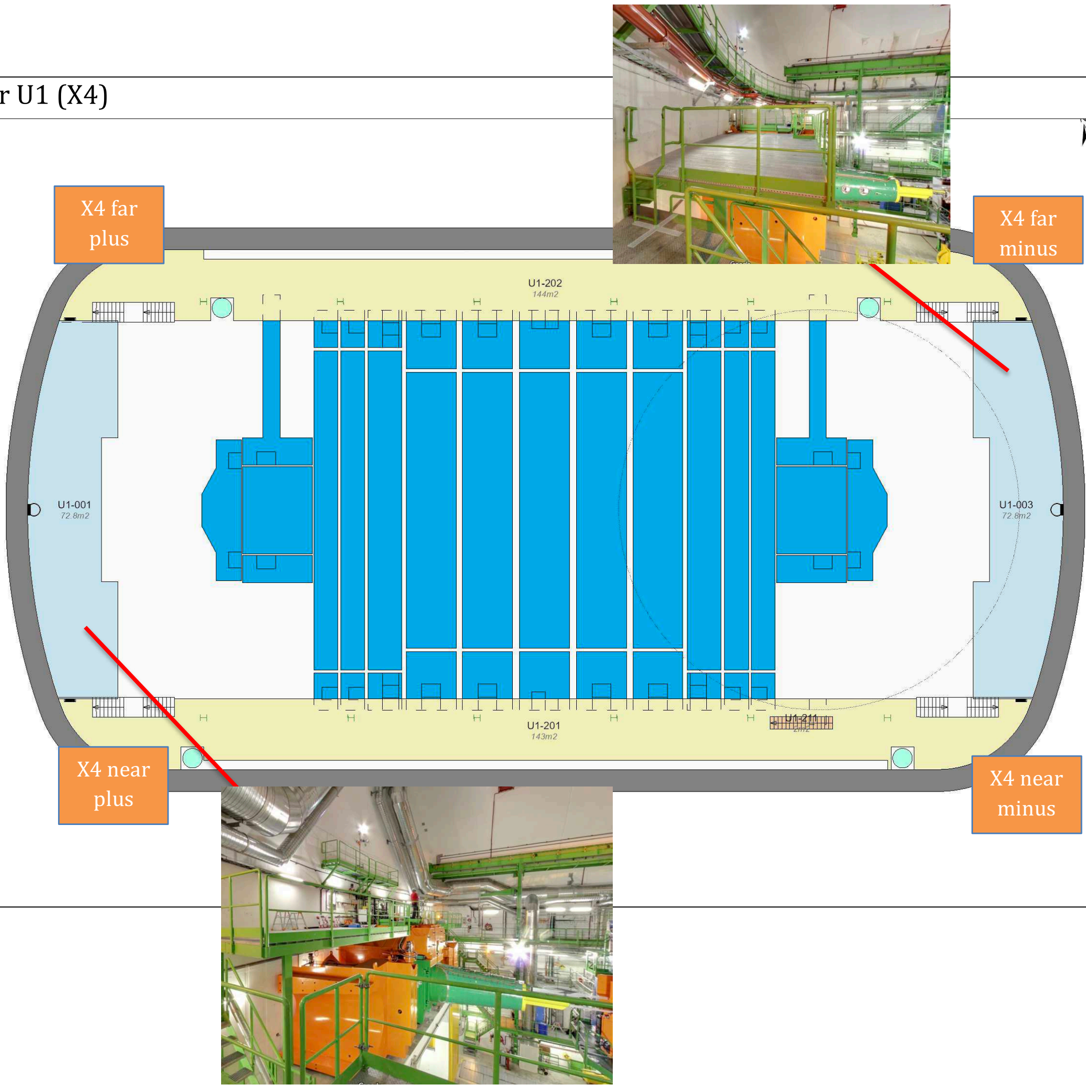
UXC55 – Floor U3 (X6)

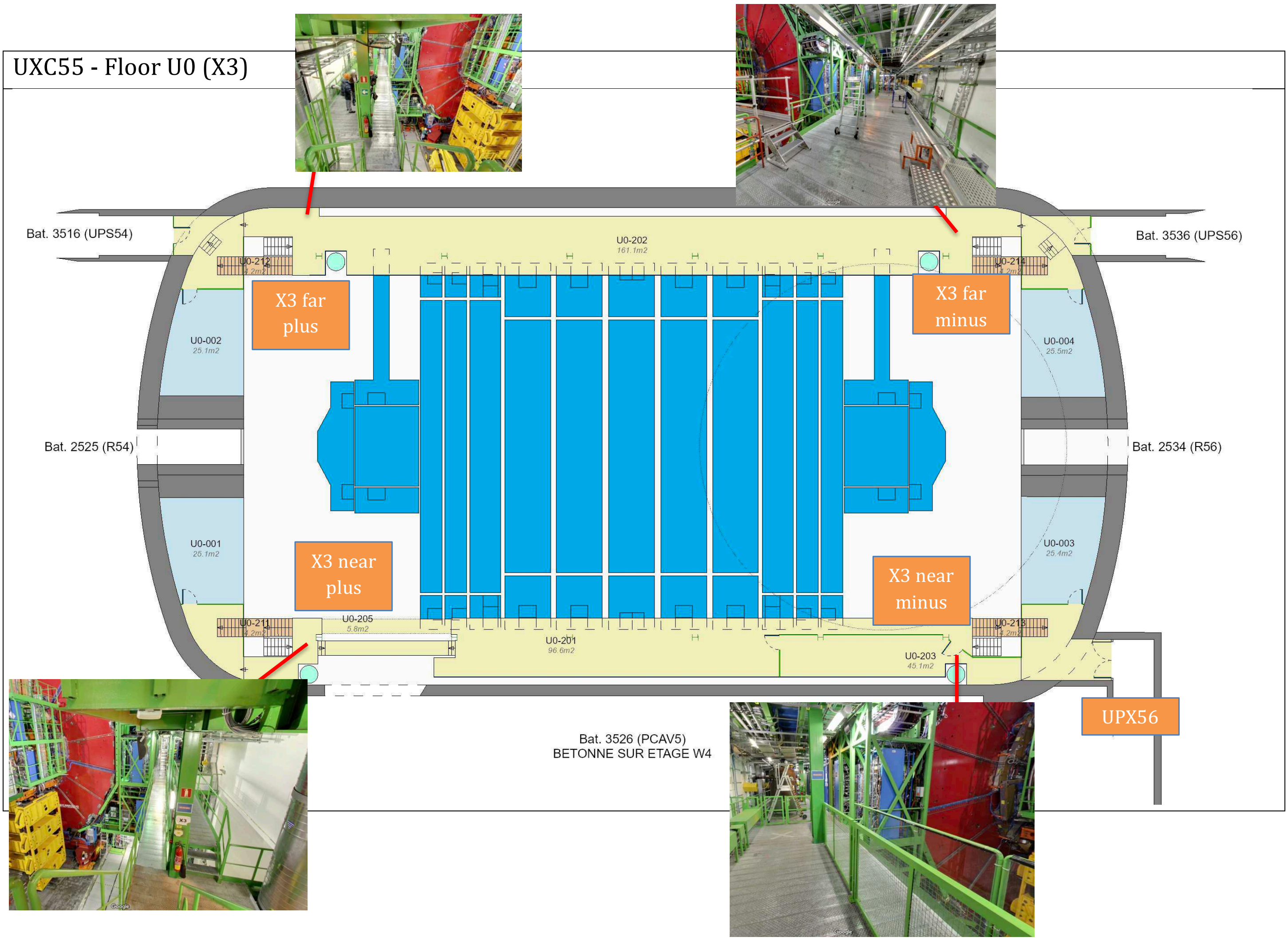


UXC55 – Floor U2 (X5)

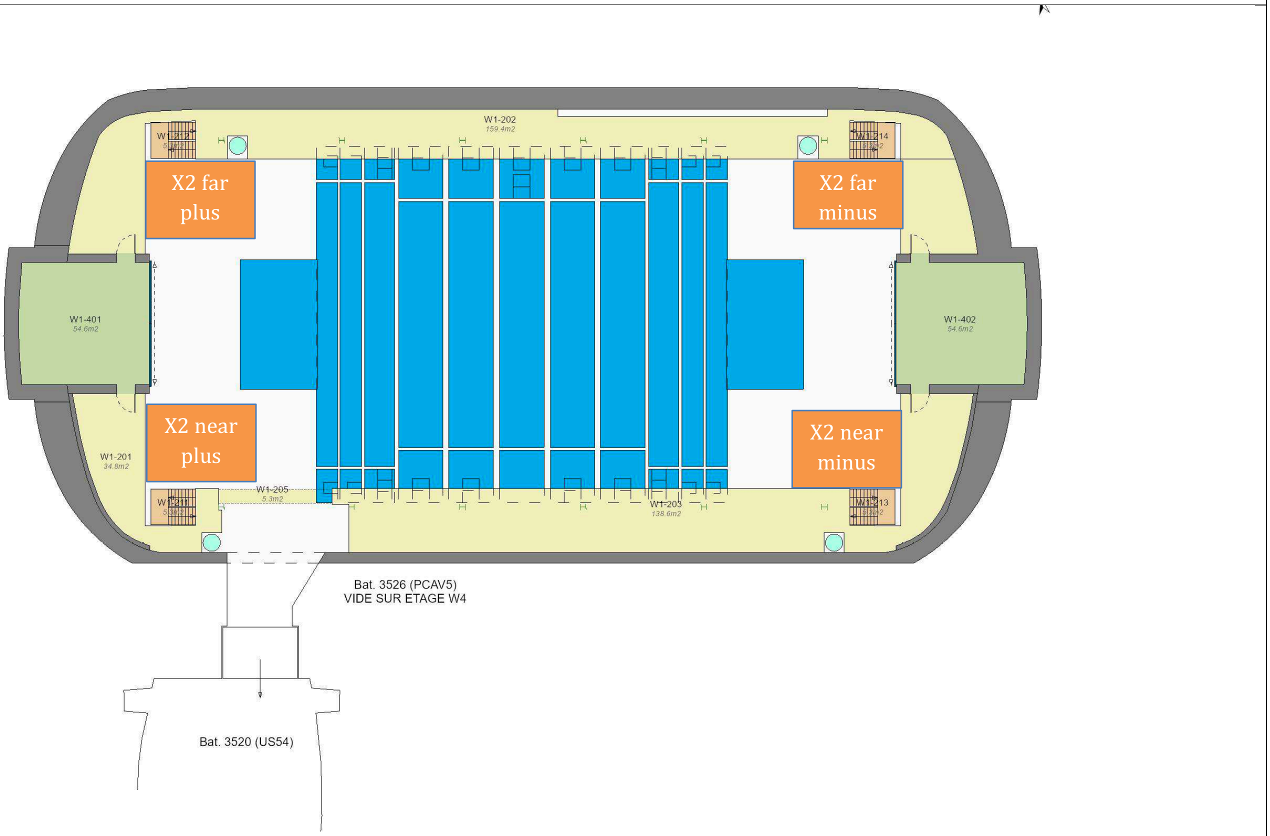


UXC55 – Floor U1 (X4)

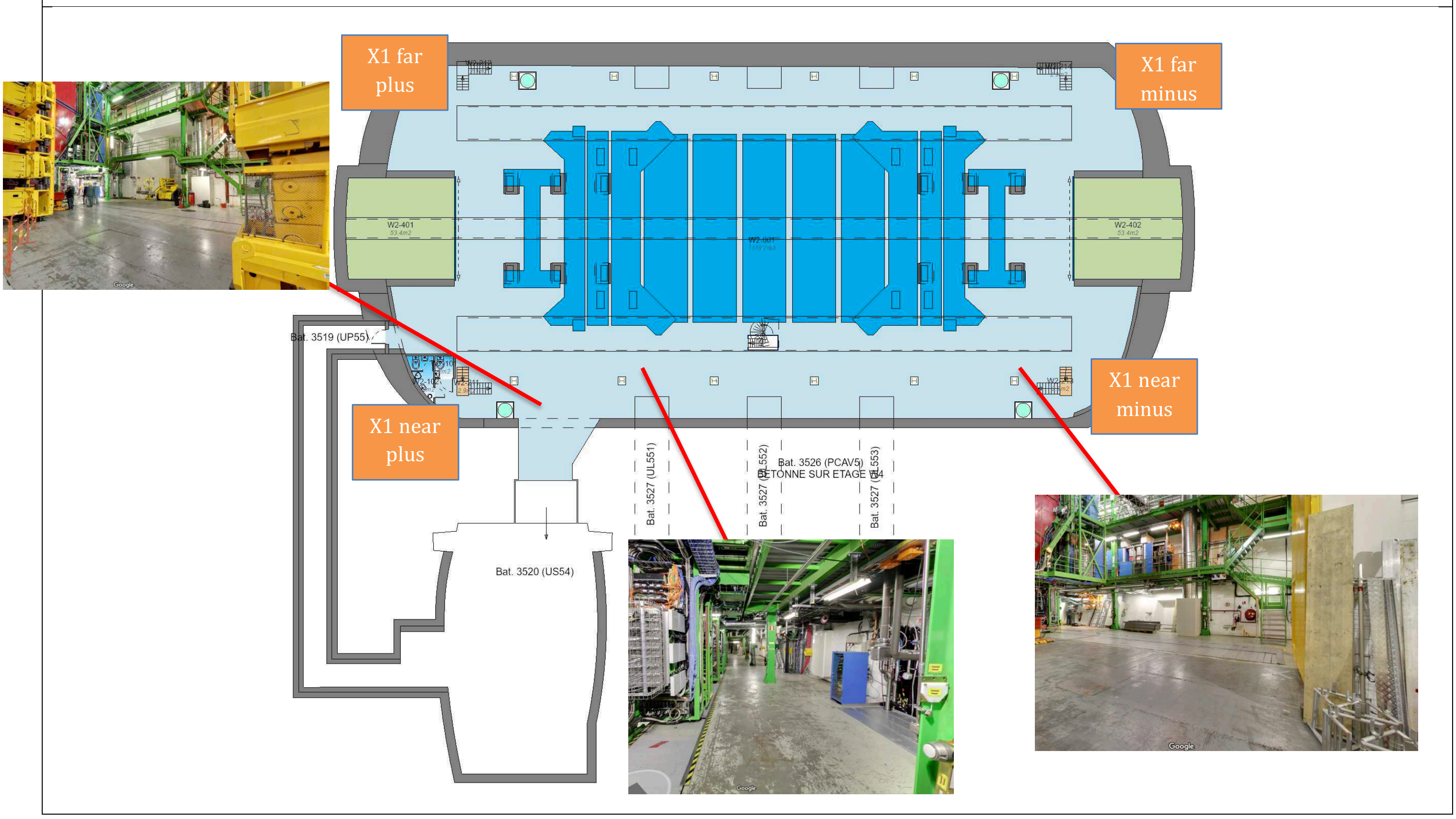



UXC55 - Floor U0 (X3)
Bat. 3516 (UPS54)
Bat. 3536 (UPS56)
U0-202
161.1m2
U0-212
U0-214
X3 far
plus
X3 far
minus
U0-002
25.1m2
U0-004
25.5m2
Bat. 2525 (R54)
Bat. 2534 (R56)
U0-001
25.1m2
U0-003
25.4m2
X3 near
plus
X3 near
minus
U0-211
U0-213
U0-205
5.8m2
U0-201
96.6m2
U0-203
45.1m2
UPX56
Bat. 3526 (PCAV5)
BETONNE SUR ETAGE W4

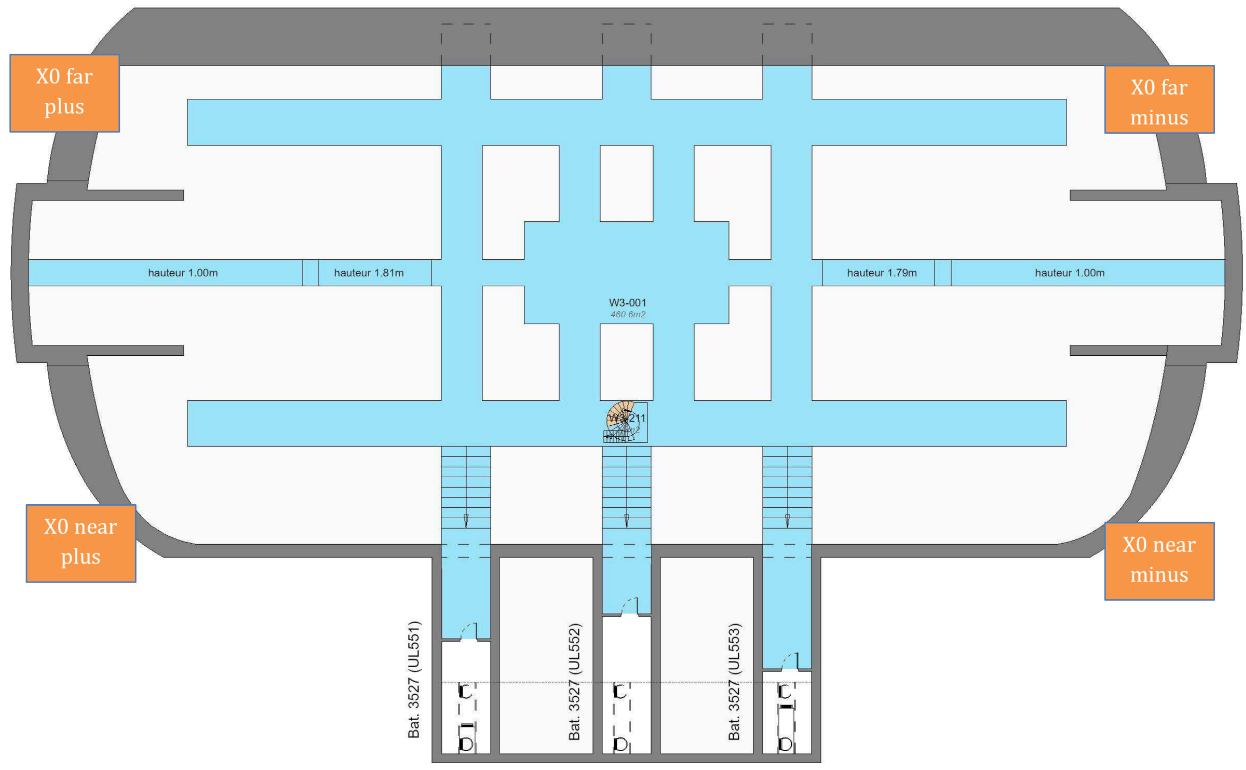
UXC55 - Floor W1 (X2)



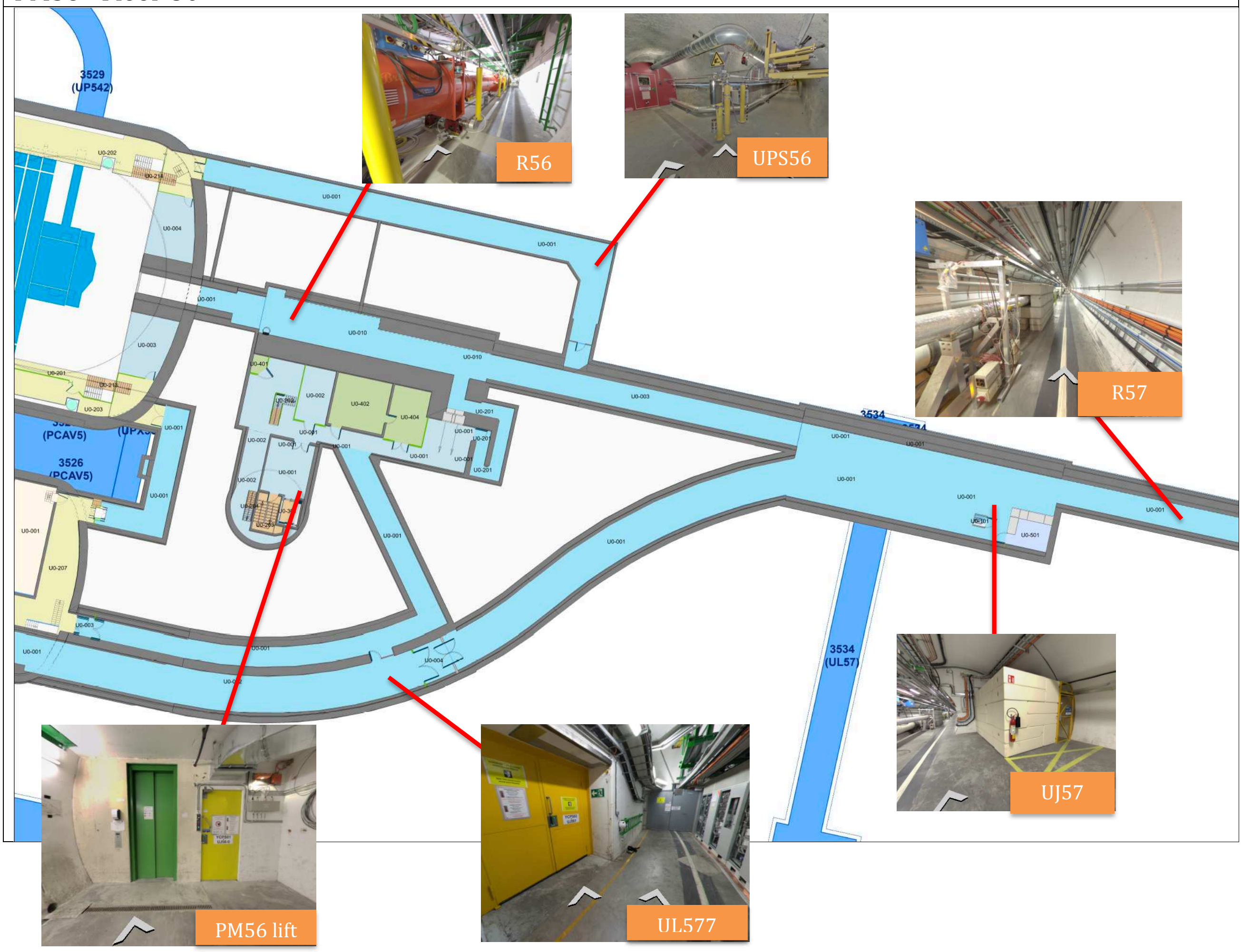
UXC55 - Floor W2 (X1)



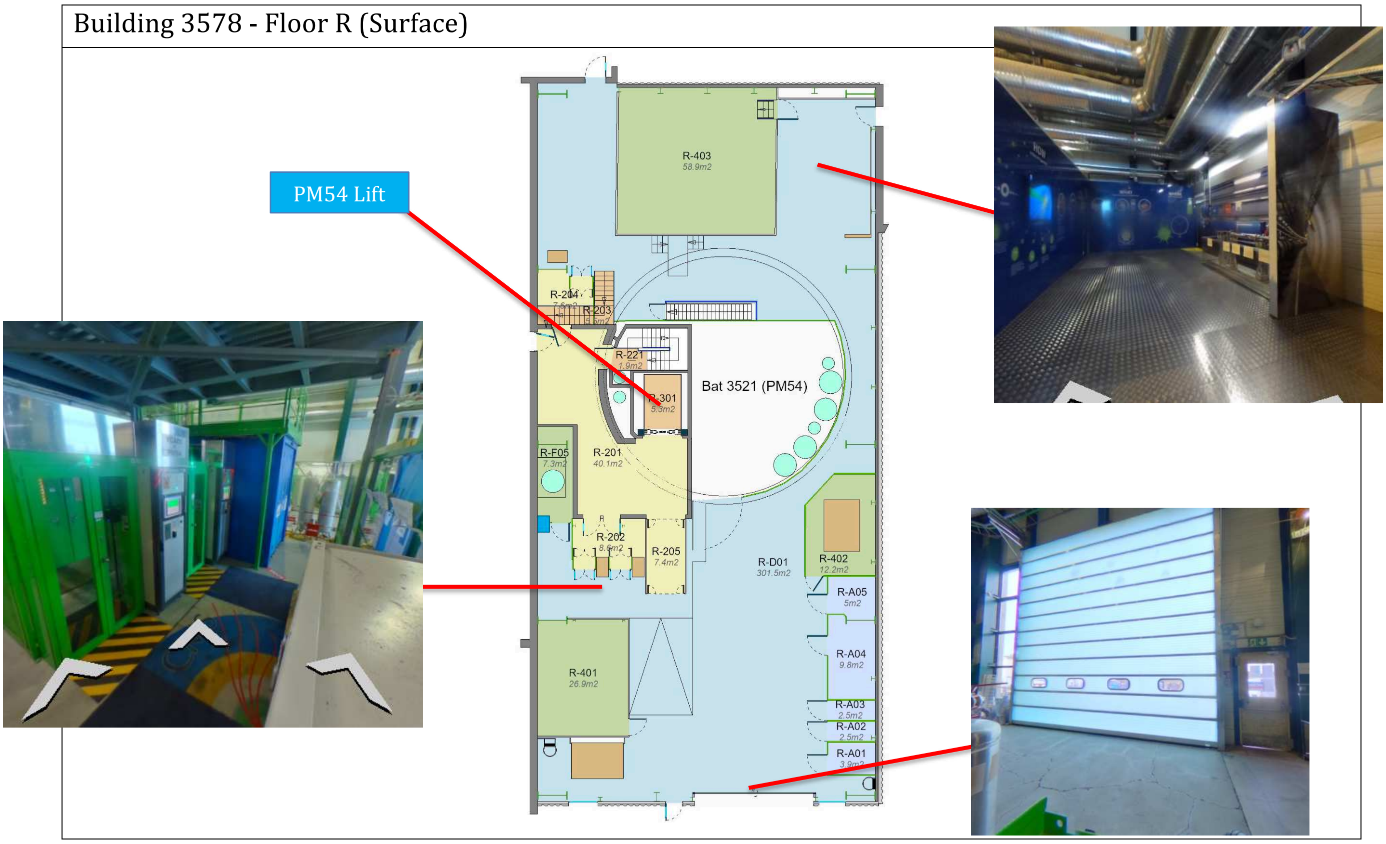
UXC55 - Floor W3 (X0)



PM56 - Floor U0



Building 3578 floor plan:



Appendix B

Observation sheet sample

Observation Sheet

General Information	
Observer Name:	Date:
Building/installation number:	Camera ID:
Starting Location:	Starting time of alarm:
Evacuation: ☐ unannounced ☐ scheduled ☐ with smoke production ☐ without smoke production ☐ other	

Please mark down your observation for the below items.

Section 1: Building

Building/ Installation	YES	NO	Not observable	Remarks
Evacuation alarm	☐	☐	☐	Clarity of alarm: ☐ Good ☐ Fair ☐ Poor
Correct operation of technical installations (closure of fire doors, etc)	☐	☐	☐	
Closure of doors and windows	☐	☐	☐	
Use of lift	☐	☐	☐	

Please indicate below the behaviour you observe among the occupants. If you observe more than one person doing the same thing, please specify the number of people in the remarks. **(specify the number of such occupants)**.

Section 2: After triggered evacuation alarm

#	Behaviour of occupants	YES	NO	Remarks
1.	Conduct work-related duties (e.g. clearing up, shutting down equipment)	☐	☐	
2.	Gather belongings (e.g. wallet, mobile phone, tools)	☐	☐	
3.	Get dressed (e.g. jackets, coats, PPE)	☐	☐	
4.	Discuss emergency with other(s) (e.g. conversations about the situation)	☐	☐	
5.	Seek for information (e.g. check out the surroundings)	☐	☐	
6.	Wait for somebody or something (e.g. for colleague(s), for job completion)	☐	☐	
7.	Engage in unrelated activities (e.g. entertainment)	☐	☐	
8.	Encourage others to evacuate (e.g. alert others to evacuate)	☐	☐	
9.	Call the authorities (e.g. use red phone to report to fire brigade)	☐	☐	
10.	Rescue (e.g. check state of injury, firefighting)	☐	☐	

11.	Close doors/ windows	☐	☐	
12.	Read evacuation plan	☐	☐	

Section 3: During evacuation

#	Behaviour of occupants	YES	NO	Remarks
13.	Choose the closest exit	☐	☐	
14.	Carry object(s) during evacuation ☐ Laptop(s) ☐ Mobile phone(s) ☐ Documents(s)/Book(s) ☐ Work tool(s)/Equipment ☐ Bag(s)/Backpack(s) ☐ Other: ______________________	☐	☐	
15.	Encounter obstruction (e.g. blocked door, queue, counterflow of people, congestion)	☐	☐	
16.	Confusion in choosing route	☐	☐	
17.	Wait for the next lift (e.g. lift was full or overloaded)	☐	☐	
18.	Help others (e.g. guiding, carrying items, reduced mobility)	☐	☐	
19.	Miss to use green handle(s)	☐	☐	
20.	Somebody turned back	☐	☐	
21.	Occupant(s) displaying anxiety or feeling overwhelmed	☐	☐	

Section 4: End of Evacuation

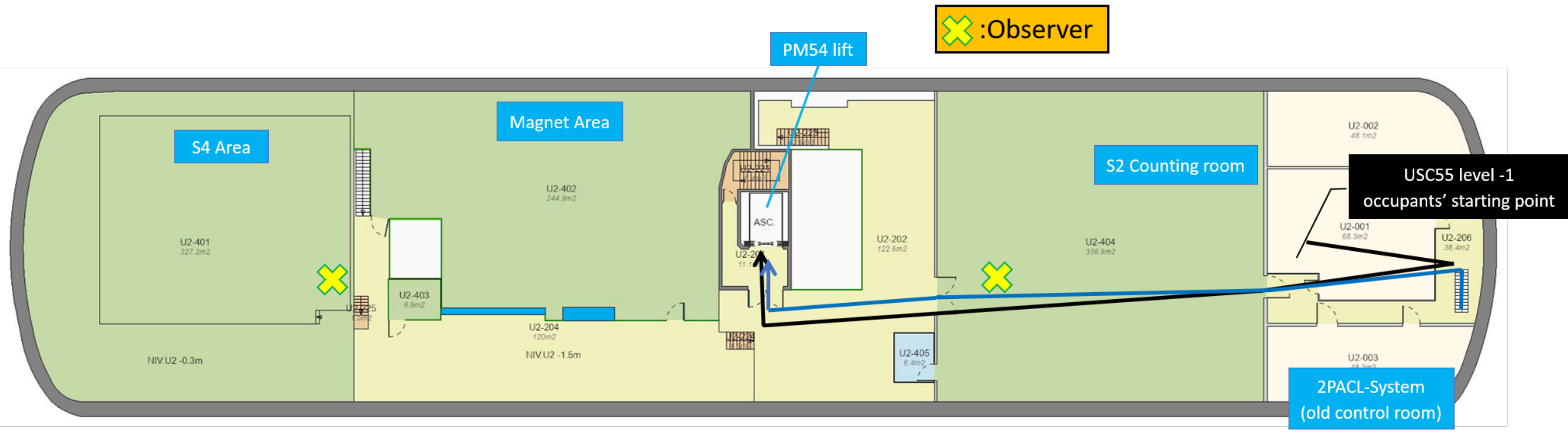
#	Behaviour of occupants	YES	NO	Remarks
22.	Complete evacuation	☐	☐	
23.	Assembly point reached	☐	☐	
24.	Headcount of occupants by the emergency guides	☐	☐	
25.	Correct reporting by emergency guides to Fire Brigade	☐	☐	

Additional observations/ comments

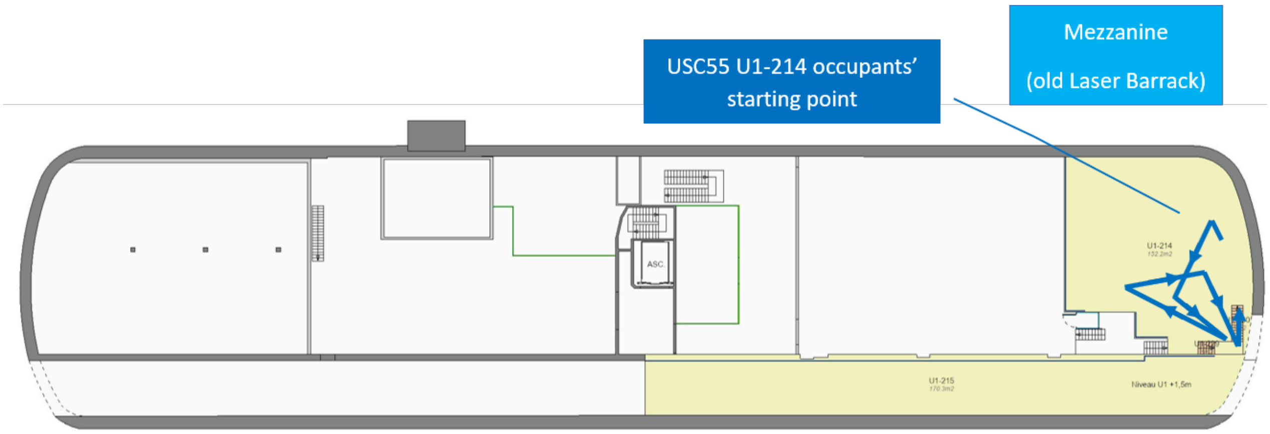
Thank you for your participation!

Appendix C

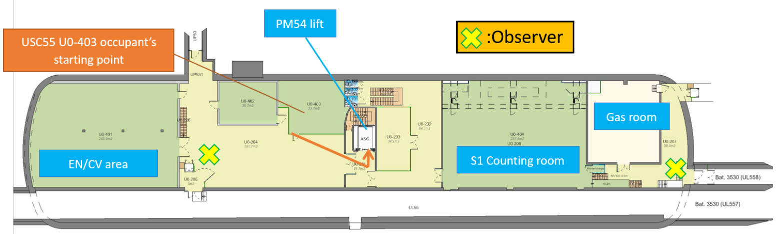
Evacuation route of occupants in USC55



:Observer
PM54 lift
S4 Area
Magnet Area
S2 Counting room
USC55 level -1
occupants' starting point
2PACL-System
(old control room)
U2-401
327.2m2
U2-402
244.9m2
U2-403
6.9m2
U2-204
120m2
U2-202
122.6m2
U2-404
336.9m2
U2-405
6.4m2
U2-002
48.1m2
U2-001
68.3m2
U2-206
38.4m2
U2-003
ASC
NIV.U2 -0.3m
NIV.U2 -1.5m



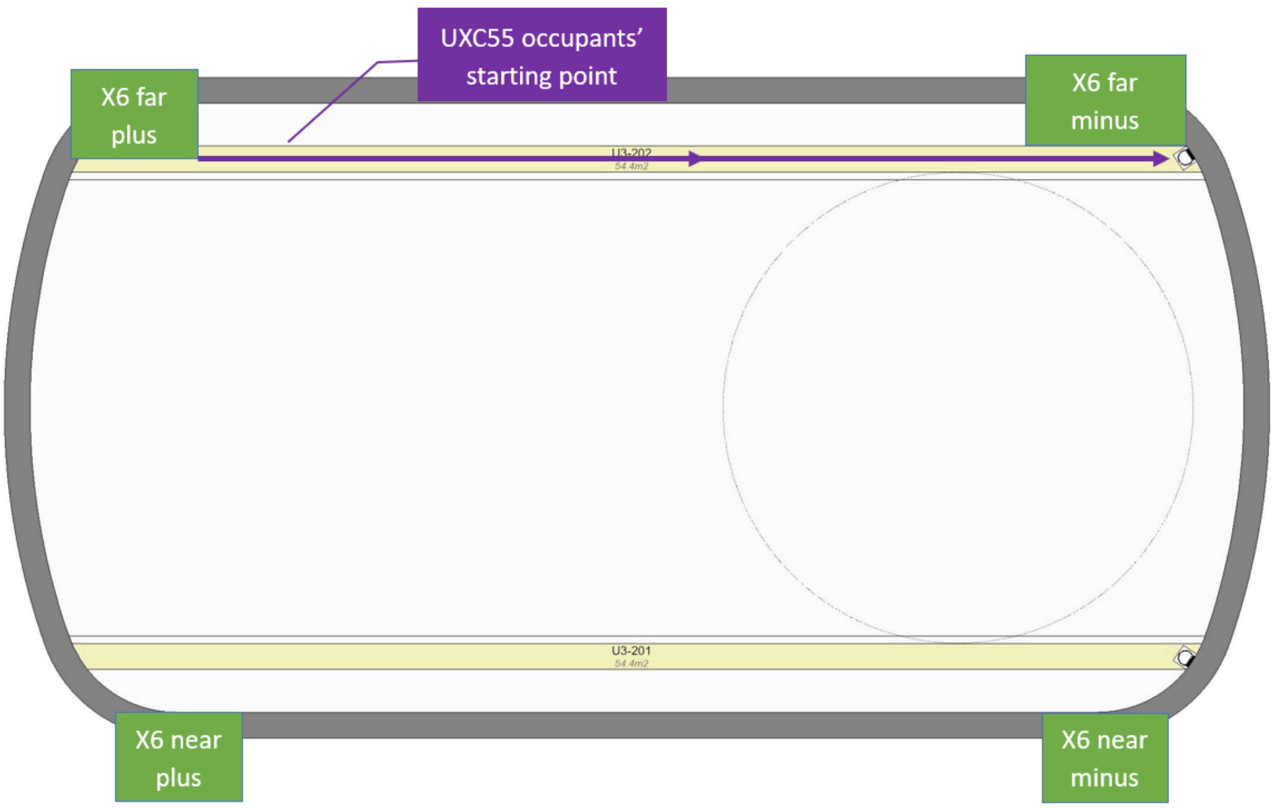
Mezzanine
(old Laser Barrack)
USC55 U1-214 occupants' starting point
ASC
U1-214
U1-215
Niveau U1 +1,5m

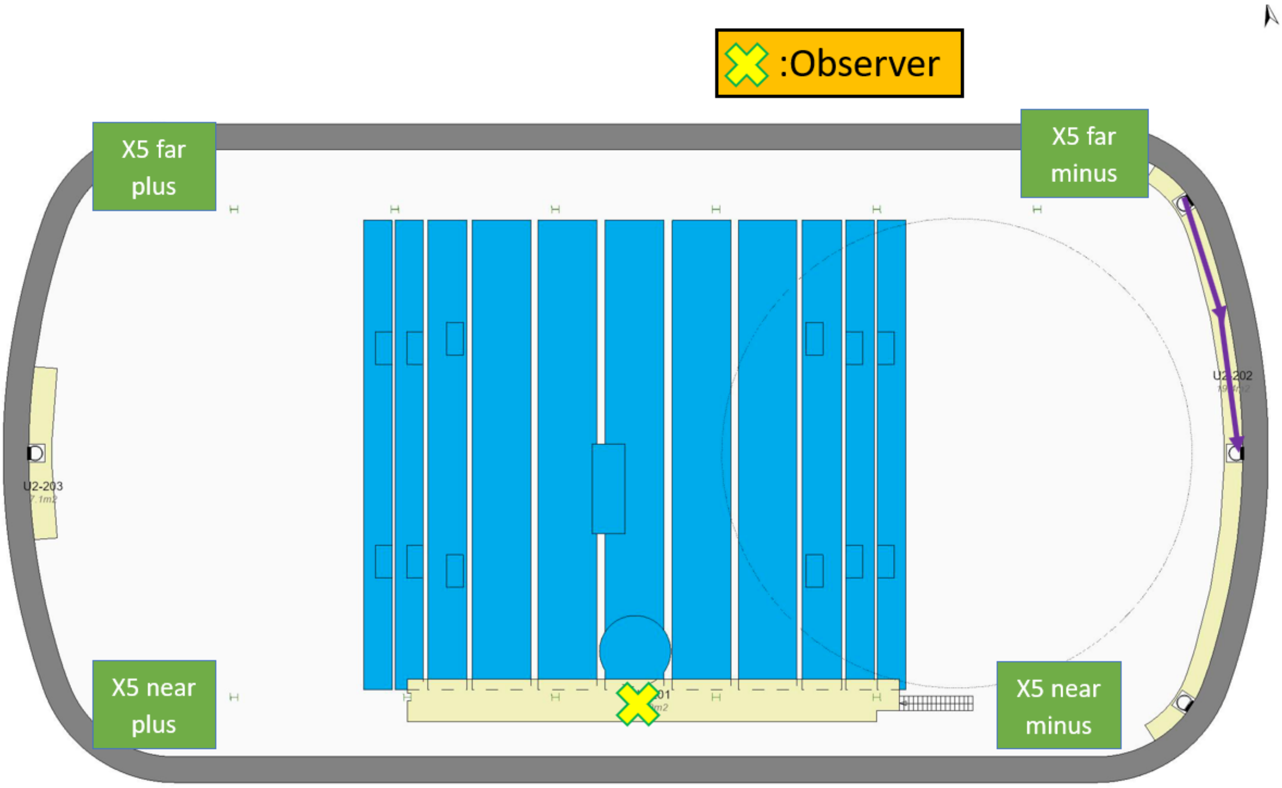


USC55 U0-403 occupant's starting point
PM54 lift
:Observer
Gas room
EN/CV area
S1 Counting room
Bat. 3530 (ULS58)
Bat. 3530 (ULS57)

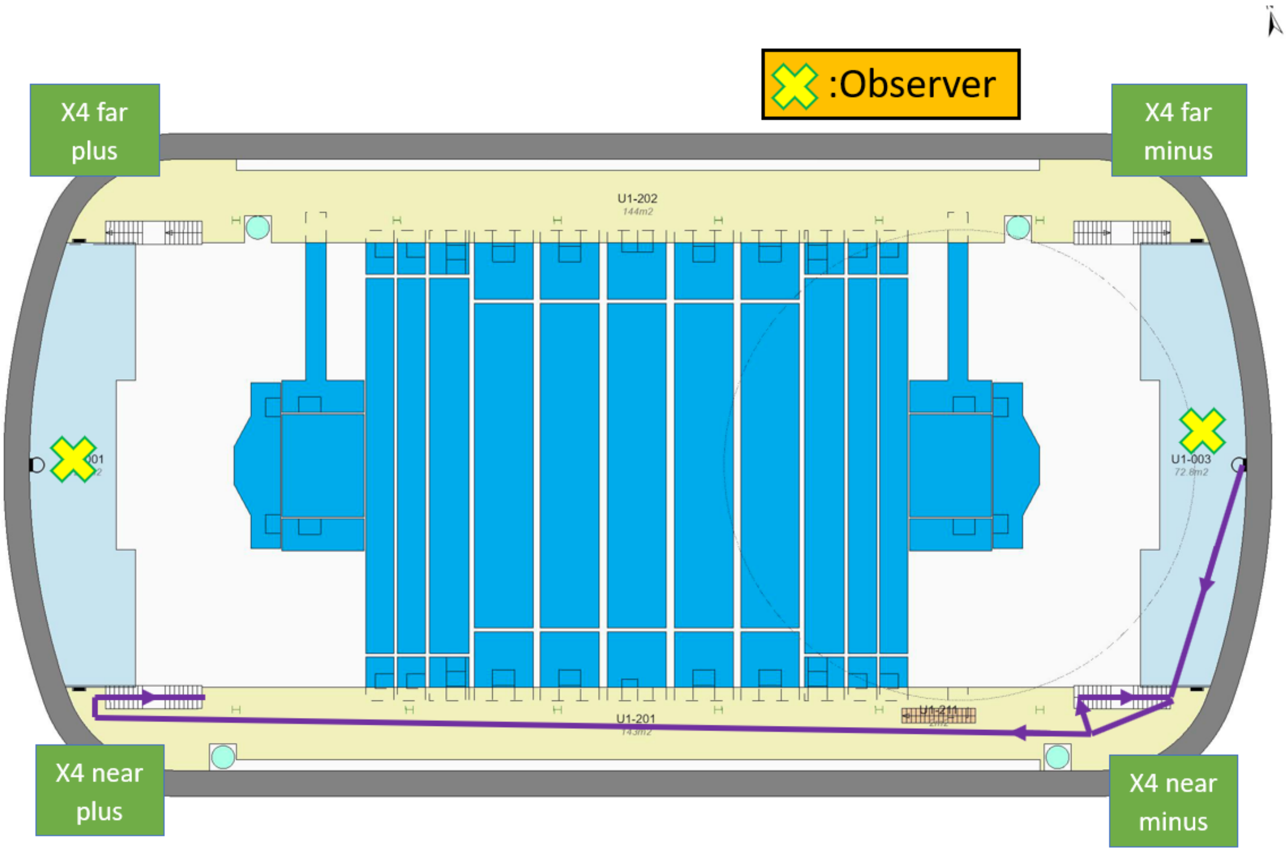
Appendix D

Evacuation route of occupants in UXC55

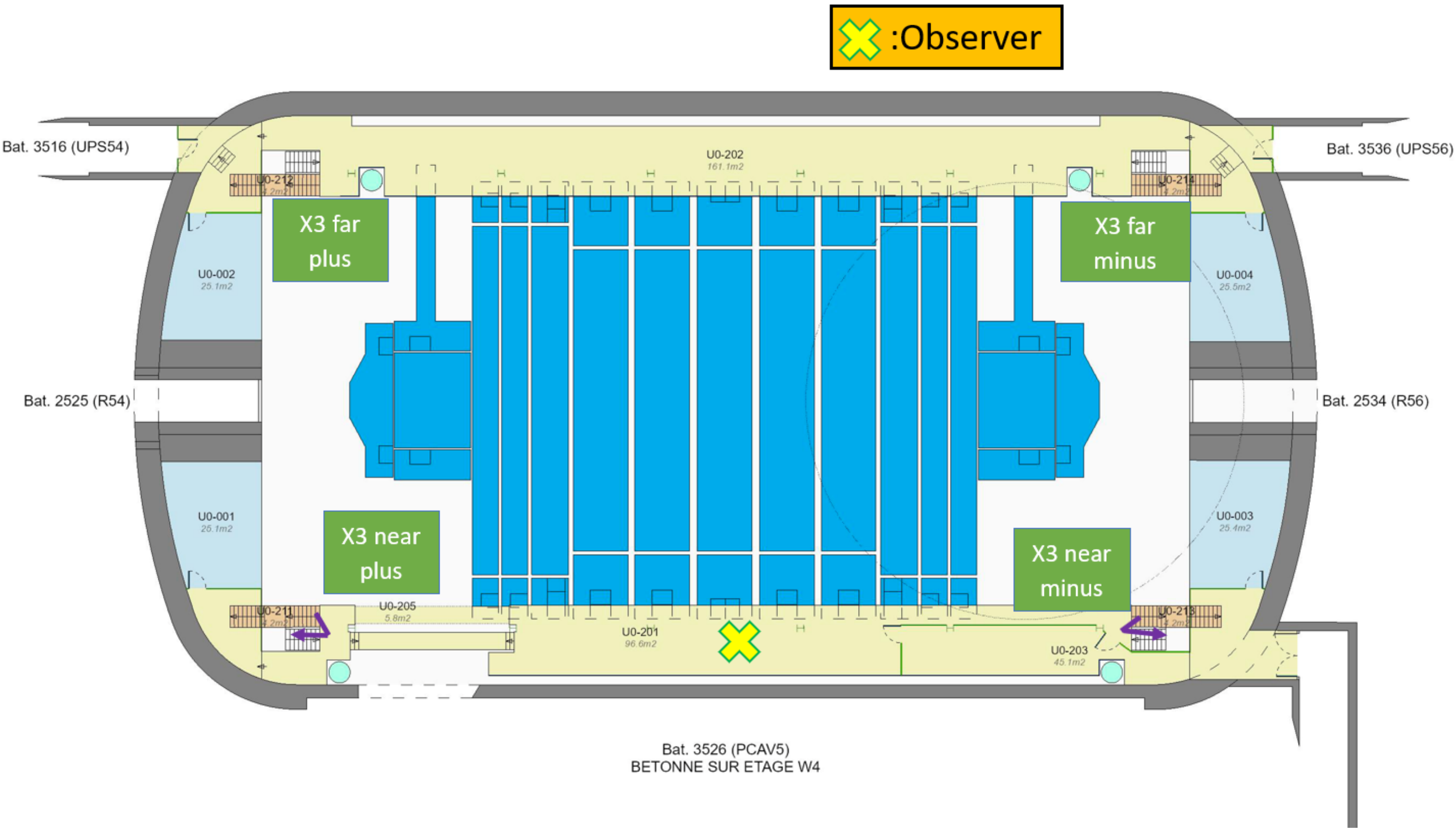

UXC55 occupants' starting point
X6 far plus
X6 far minus
U3-202
54.4m2
U3-201
54.4m2
X6 near plus
X6 near minus

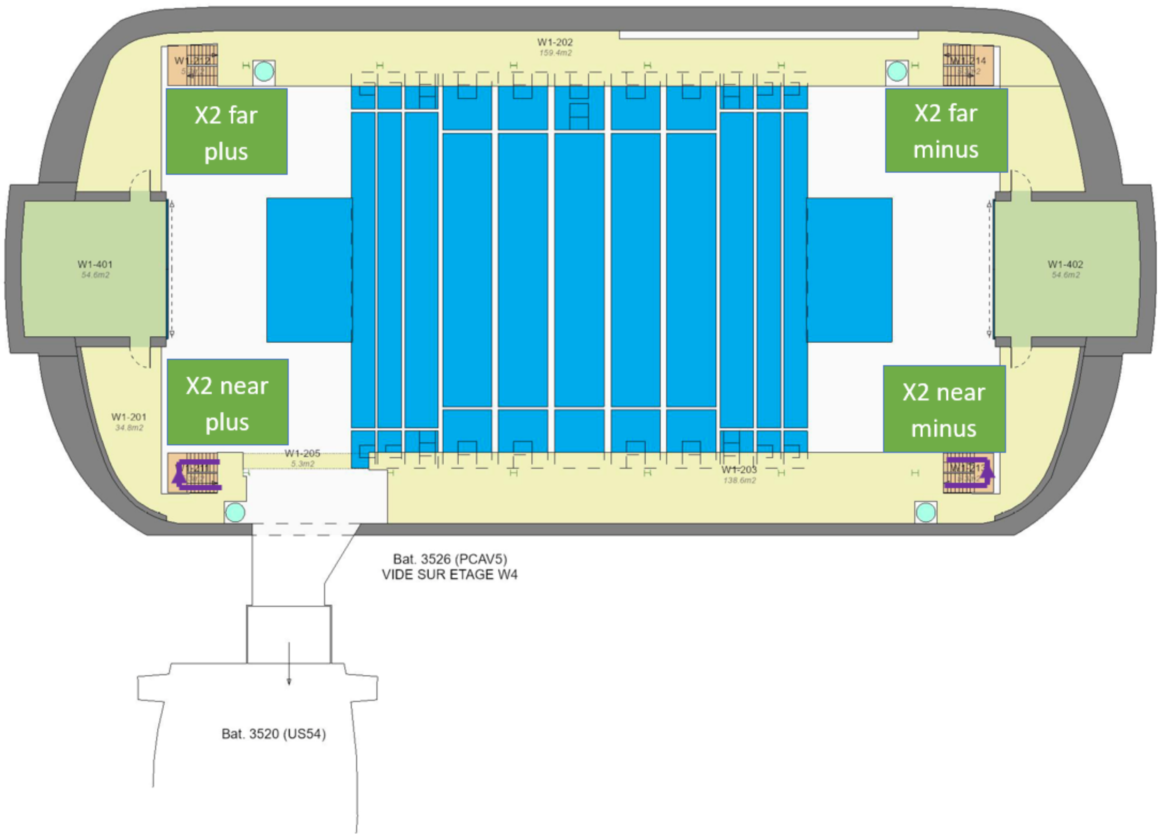


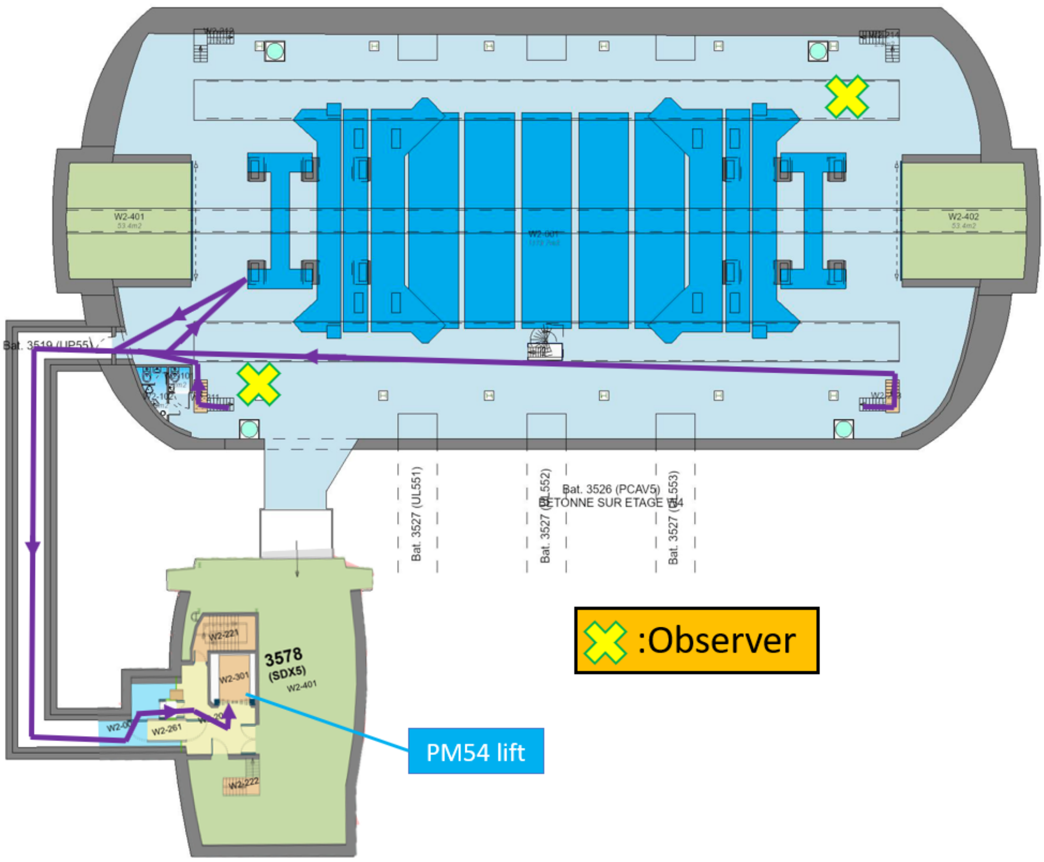
:Observer
X5 far plus
X5 far minus
X5 near plus
X5 near minus
U2-203
U2-202



:Observer
X4 far plus
X4 far minus
X4 near plus
X4 near minus
U1-202
144m2
U1-201
U1-003
72.8m2


:Observer
Bat. 3516 (UPS54)
Bat. 3536 (UPS56)
U0-202
161.1m2
X3 far plus
X3 far minus
U0-002
25.1m2
U0-004
25.5m2
Bat. 2525 (R54)
Bat. 2534 (R56)
U0-001
25.1m2
U0-003
25.4m2
X3 near plus
X3 near minus
U0-205
5.8m2
U0-201
96.6m2
U0-203
45.1m2
Bat. 3526 (PCAV5)
BETONNE SUR ETAGE W4


W1-202
159.4m2
X2 far plus
X2 far minus
W1-401
54.6m2
W1-402
54.6m2
X2 near plus
X2 near minus
W1-201
34.8m2
W1-205
5.3m2
W1-203
138.6m2
Bat. 3526 (PCAV5)
VIDE SUR ETAGE W4
Bat. 3520 (US54)


W2-401
W2-402
Bat. 3519 (UP55)
Bat. 3527 (UL551)
Bat. 3527 (UL552)
Bat. 3526 (PCAV5)
BETONNE SUR ETAGE W4
Bat. 3527 (UL553)
3578
(SDX5)
W2-221
W2-301
W2-261
W2-222
PM54 lift
:Observer

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