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Abstract. This document presents the results of a literature review performed in order to assess the suitability of different evacuation modelling tools for the calculation of evacuation times and assessment of fire safety in underground physics research facilities. This document is part of the research collaboration between Lund University and the European Organization for Nuclear Research (CERN), concerning performance-based fire risk assessment for the underground facilities of the Future Circular Collider (FCC). The review presents an overview of current modelling methods with different degrees of sophistication and provides recommendations on the most appropriate methods to be used in relation to the scenario under consideration. The use of simplified evacuation models is recommended for the simulation of people movement in simple mono-dimensional evacuation scenarios in long tunnel arcs. Advanced evacuation models (e.g. agent-based models) are recommended for the simulation of the evacuation process in the area of the experimental caverns. In case of evacuation scenarios in which complex interactions between people and the underground environment take place, advanced models are recommended as well.

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1. Background

The European Organization for Nuclear Research (CERN) is currently evaluating the feasibility of the conceptual designs of the Future Circular Collider (FCC). This work includes the evaluation of different design approaches in order to aid the definition of the design of the facilities. In this context, a collaboration project has been initiated with a set of institutions working on performance-based fire risk assessment. Part of this collaboration focuses on a review of the capabilities of existing evacuation simulation tools for the fire safety design of underground nuclear research facilities. The present document summarizes the findings of the work conducted at Lund University and present the results of this review.

2. Objectives

A review of literature related to the use of modelling tools for the simulation of evacuation in underground physics research facilities has been performed. The main objectives of the review were to 1) identify the key factors influencing the evacuation of people in underground physics research facilities (including behavioural and design factors), 2) review the capabilities of the available evacuation models to simulate people movement and human behaviour (tools ranging from simplified models to advanced agent-based simulation tools), 3) identify the most suitable evacuation modelling tools to be used in relation to the infrastructure and the specific design issues under consideration, 4) provide recommendations for future enhancements of evacuation models for their application in such type of complex facilities.

3. Methods

Given the scarcity of previous applications of evacuation modelling tools for underground physics research facilities, the findings of the literature review are based on 1) a review of the capabilities of evacuation models, 2) applications of evacuation models in similar environments (e.g. other underground infrastructures such as tunnels) and 3) a review of the key design features of underground physics research facilities (including the type of egress components available and the population involved in hypothetical emergency scenarios).

The material for the literature review was retrieved from different scientific databases (e.g. ScienceDirect, Google Scholar). The information on the evacuation model capabilities was based on the stated capabilities of models as presented in their manuals/technical references and previous application of the models.

4. Delimitations

It should be noted that the present review of literature is focused primarily on the use of evacuation models for fire-related hazards. In nuclear physics research facilities, other types of hazards may be present (i.e., radioactive hazard, cryogenic fluids). Given the current field of application of evacuation models is mostly restricted to fire protection applications and crowd safety analysis, other types of hazards will not be taken into consideration while reviewing the capabilities of evacuation models. Nevertheless, in case of scenarios without interactions between occupants and the hazard, the applicability of evacuation models might hold.

Refuge alternatives (e.g., rescue chambers) may be included in the safety design of underground physics research facilities. Since the present document focuses on evacuation strategies rather than defend-in-place, this type of solution is not taken into consideration.

5. Key factors affecting the evacuation process

In order to assess the capabilities of evacuation models to predict human behaviour in case of emergency in underground physics research facilities, the first step is the identification of the factors affecting such scenarios. Two main categories of factors have been identified for the evacuation process, namely 1) Behavioural factors and 2) Design factors. Behavioural factors concern all variables which may affect the behaviours that people may have in case of emergency. Particular emphasis is given to the variables specific to the case of underground physics research facilities rather than the general variables which affect any type of evacuation in buildings. Design factors concern instead some of the typical characteristics concerning the configuration of this type of facilities. This includes the type of egress components used for evacuation as well as the conditions in which the escape routes are in case of emergency.

5.1. Behavioural factors

The majority of evacuation models make use of an engineering time-line model (Gwynne and Rosenbaum, 2016; Ronchi and Nilsson, 2016) to represent the sequence of actions performed by evacuees in case of emergency. This model includes different times which correspond to different phases of the evacuation process. After an alarm is activated, two main phases can be identified, namely 1) pre-evacuation time and 2) movement time. The pre-evacuation time is the time needed by evacuees to realize that an emergency is taking place and to take the decision to start a purposive movement towards a safe place. The movement time instead considers the time needed to reach a safe place once the decision to leave the premises has been taken. Different factors affect these two main phases for the case under consideration, thus a review needs to be performed in order to identify which inputs need to be represented in evacuation models.

Factors affecting the pre-evacuation time

Several factors can affect the pre-evacuation time. This includes the type of alarm available in the facility and its audibility in relation to the position where the evacuee is located. Other notification systems can also have an impact on this time, i.e., the availability of staff which is familiar with the emergency procedures can have a positive impact on the reduction of the pre-evacuation time. This is linked to the possibility to alert people on the incoming danger and decrease the time to take an active decision to leave the premises. In addition, researchers involved in the preparation of an experiment might be reluctant to leave the premises.

It should be noted that in physics research facilities, during technical stops, occupants are expected to have good familiarity with the premises, while in long shutdowns, lower familiarity is expected due to the presence of contractors and visitors. Contractors are obliged to receive safety training prior accessing the facilities. Visitors may be allowed to access the long straight sections of the tunnels (e.g. as in the Large Hadron Collider (LHC) at CERN) and being close to the access shafts. The groups of visitors are generally made of small groups of people followed by at least one trained guide. For example in the Large Hadron Collider (LHC), there are on average 200-300 groups of visitors (approximately 12 people each) per year.

The staff present in the area includes population who is familiar with the environment and it is likely to have participated in an evacuation drill in the premises (e.g., fire drills are arranged in CERN in selected facilities every year mostly to test technical systems and usability of egress means). Nevertheless, given the possible presence of visitors during an emergency, it is not possible to assume that all people are familiar with the emergency procedures. The population type for workers is deemed to be mostly made by male adults and it rarely includes people with disabilities (this presence would imply a pre-defined handling strategy such as the presence of accompanying persons, fire brigade, stop of other activities, etc.). Visitors group may be assumed to be more balanced in gender. According to several studies investigating the type of distributions to be used for the representation of pre-evacuation time in evacuation modelling, a log-normal distribution is generally recommended (Purser and Bensilum, 2001). It is argued that this may be linked to the impact of social influence on pre-evacuation and the presence of delayed decision makers (Lovreglio et al., 2016; Nilsson and Johansson, 2009).

It should be noted that evacuation models today are not designed to represent explicitly some of the actions that occupants might do before the pre-evacuation time phase. This includes both fire extinguishing attempts as well as pre-alarm activities. This issue has been largely discussed in the evacuation modelling community (Gwynne et al., 2011) and the general recommendation is to represent these time components as additional delays within the pre-evacuation times.

Factors affecting the movement time

The main factors affecting the movement time are 1) the physical and psychological abilities of the population involved, 2) the familiarity with the facility (i.e. population way-finding abilities), 3) occupant loads.

As mentioned earlier, it is reasonable to assume that the majority of the workers population (approximately 80%) is made by male adults given the gender in-balance in physics research (Clark Blickenstaff, 2005) while visitors' gender may be assumed to be more balanced. It is also reasonable to assume that the population will not include the whole spectrum of population types (no children, limited number of elderly people). In physics research facilities, there are generally no fitness requirements in order to work underground, but workers must hold a general fitness for work certification provided by an occupation physician. This implies that people should be able to jog, but not necessarily to run. In fact, the type of population present in the premises has an impact on the movement speeds that needs to be assumed. Truncated normal distributions are generally assumed for the representation of movement speeds and different values for the distributions can be found for adult populations (Korhonen and Hostikka, 2009; Thompson and Marchant, 1995).

The groups of visitors involved in an emergency are deemed to include at least one employee of the facilities who is familiar with the egress routes, thus it is reasonable to assume that people will mostly be able to follow the prescribed (shortest) escape route. In addition, most of the areas in which the experiments take place are made of simple straight tunnels, with a low complexity in terms of way-finding. Exceptions are the experimental caverns and the areas around them in which a more complex configuration may be present.

According to fundamental diagrams (i.e. the relationships between walking speeds, densities and flows) (Fruin, 1987; Predtechenskii and Milinskii, 1978; Seyfried et al., 2006), movement speed decreases when densities increases. The occupant load in the tunnels is assumed to be low enough to not allow densities to reduce drastically movement speeds in the tunnels. For this reason, people movement along the tunnels can be represented with a simple 1D model. In contrast, such type of assumption cannot be used when people are approaching areas in which there are stricter flow constraints (e.g. lobbies, protected zones close to the experimental caverns, complexity of layout), since it is necessary to account for the impact of densities on flows/speeds.

5.2. Design factors

The configuration of physics research facilities is made of two main parts, namely 1) very long and deep (circular or straight) underground tunnels (in the order of km of lengths) and 2) experimental caverns connected with shafts to the ground (access shafts for people and service shafts for machinery). Given the fact that the arcs of the tunnels are very long and the distance between emergency exits may exceed the typical distances adopted in standard road/rail tunnels, people may be expected to walk long distances. Similarly, since the tunnels are place hundreds of metres below ground (e.g. even in the order of 300-400 m), the evacuation to the surface should consider long vertical distances to be covered. For this reason, both long ascending stairwells and elevators should be considered as egress components that may be available in such type of facilities. It is therefore very important to verify how the configuration of the underground infrastructure relates to the physical exertion of the population involved in ascending stair evacuation (Ronchi et al., 2015). Similarly, the use of Occupant Elevators for Evacuation (OEEs) should be taken into account in order to investigate the effectiveness of evacuation strategies which require long vertical distances to be crossed.

Another issue to be considered is that since long tunnels are present, areas with limited compartmentation may be present, thus requiring considering the impact of smoke on human behaviour. This is generally associated with a reduced walking speed in relation to the visibility conditions (Jin, 2008; Ronchi et al., 2013a), the impact of smoke on route choice (Fridolf et al., 2013) and the impact of toxic gases on people incapacitation (Purser, 2010). This is often studied through the use of the Fractional Effective Dose and Fractional Effective Concentration, concepts which are currently used in the fire protection design of underground infrastructures (Purser, 2008) and that have been largely used to investigate underground safety design and tunnel accidents, such as the Mont Blanc fire (Purser, 2009).

The assessment of the space available for evacuation should also consider the presence of large equipment which might reduce the escape routes. In addition, in case of long distances to be covered, transportation means may be adopted in order to facilitate the time to move along the tunnels.

6. Capabilities of evacuation models

Different classifications are available in the literature to categorize evacuation models. Among the most used classifications, it is possible to consider the type of assumptions employed for the representation of the space, which can be 1D, 2D or 3D, the modelling approach employed for the representation of people movement (macroscopic, microscopic or mesoscopic) and the type of simulation approach (equation-based vs agent based) (Ronchi and Nilsson, 2016).

When using a one-dimensional (1D) model for the representation of people movement, an equation-based approach is generally employed to represent the movement of people. This can consider a flow which is impeded or unimpeded, i.e. different assumptions can be adopted on the fact that densities reduce or not the movement speed of people. Unimpeded flows can be simply calculated considering the basic relationships between movement speed, space and time. In case of impeded flows, hydraulic-inspired models are often adopted such as the capacity method presented in the Society of Fire Protection Engineering Handbook (Gwynne and Rosenbaum, 2016) or the movement can be based on fundamental diagrams (Predtechenskii and Milinskii, 1978). In both cases, people are represented at an aggregate level (i.e. adopting a macroscopic approach rather than looking at each individual) and their movement is the result of the flow constrictions and densities obtained from the geometrical configuration of the space. Pre-evacuation times are generally added to the movement model as a separate component.

The use of a two-dimensional (2D) model is associated with different representations of the space. They are generally classified into coarse network, fine network, continuous or hybrid (Ronchi and Nilsson, 2016). A coarse-network model represents the space as a series of nodes linked with arcs and the movement takes place within this network. A fine network approach makes use of a grid-based representation of the space (i.e. either very fine nodes and arcs or a grid of cells). This method is often labelled as cellular automata since the space is subjected to a discretization, which is generally based on squared or hexagonal cells (Bandini et al., 2011; Ronchi et al., 2013b). A continuous approach generally assumes the movement of individual agents in the space in a system of coordinates. A hybrid model makes use of a combination of different approaches (Chooramun, 2011).

Equations and rules (i.e. typical of an agent-based approach) for people movement can be used in a 2D model. It should be noted that despite a microscopic agent-based approach is the most common approach in 2D evacuation models adopted in fire safety engineering, this method can be used in conjunction with several other approaches for people movement. This can include a Newtonian force-based simulation of agents (Helbing and Molnár, 1995)), steering models (Reynolds, 1999), models based on cognitive heuristics (Moussaïd et al., 2011), etc. In case an agent-based microscopic approach is adopted, distributions of pre-evacuation times can be used to represent the behaviour of each individual agent in the 2-dimensional space.

The three-dimensional (3D) representation of the space is today represented in different manners. A common approach is the adoption of links in the vertical direction which connect the 2D space (i.e. stairs, elevators, etc.). The majority of the 3D evacuation models use today this approach. Some evacuation models allow instead the direct representation of walkable surfaces (i.e. ramps, inclined surfaces) which are not at the same z coordinate (Kuligowski, 2016).

It should be noted that evacuation models may be applied adopting both a deterministic approach and a probabilistic approach when considering the evacuation scenarios. A probabilistic approach is generally recommended given the possible variability of human behaviour in emergency evacuations (Ronchi et al., 2014).

6.1. Simplified vs advanced models

After the general description of the assumptions and classifications adopted in evacuation modelling, the present section performs a review of the advantages and limitations of what are here called simplified models and advanced models.

Simplified models are here intended as models adopting a macroscopic approach (i.e. people are represented in the model at an aggregate level), hand calculations such as equations-based hydraulic models (Gwynne and Rosenbaum, 2016) and a 1-dimensional representation of the space. Advanced models are here intended as microscopic model in which person is modelled as an autonomous individual agent. Advanced models are intended as models that adopt an agent-based modelling approach where a set of rules for the interactions of the agents with the space and other agents are employed. The space is represented through a 2D/3D approach.

Simplified models allow a rapid input setup given the simplicity of the assumptions adopted. They are generally not expensive from a computational perspective, thus allowing the simulation of multiple scenarios in a relatively short time. This is particularly valuable in case the safety designers are interested in performing sensitivity analyses. Given the simplicity of the people movement assumptions, fire and smoke spread calculations can be easily coupled in this type of models. This type of models also generally allows a high level of transparency given the simplicity of the calculations performed (e.g., simple hand-calculations which can be easily verified by a third party examiner). Limitations of these models include the difficulties in representing complex geometries and behaviours given the lack of interactions among agents. Similarly, the coupling with complex sub-models which may be needed for the simulation of a particular scenario or behaviour is difficult given the simple structure of the modelling approach. Table 1 presents a summary of the main advantages and limitations of simplified models.

Table 1. Summary of advantages and limitations of simplified models.

Simplified models	
Advantages	***Limitations***
• Quick input setup • Computationally cheap • Multiple scenarios can be simulated quickly • Fire/smoke spread calculations can be easily included • Transparency given the simplicity of the calculations	• Not suitable for complex geometries • Not suitable for complex behavioural simulations • Coupling with complex sub-models is difficult

Advanced models allow a more accurate representation of the geometric layout given the possibility to represent spaces in 2D/3D. The interactions of agents with the space and other agents can be simulated giving the possibility to simulate for instance group interactions. Advanced sub-models for the simulations of complex geometric characteristics or behavioural scenarios can also be implemented. This includes coupling with sub-models for the simulation of transportation means, elevators, occupants' fatigue, staff behaviours, etc. The main limitations of these models are linked to the time needed for the calibration of the model input set up (i.e. this can be time consuming, and it depends on the availability of a Graphics User Interface, GUI). The representation of fire and smoke spread generally relies on the interaction with other complex simulators, thus requiring the availability of results from this type of models in order to account for the impact of fire and smoke on human behaviour. Another drawback of these models concerns computational time, which is definitely more expensive than in the case of simplified models. A summary of the main advantages and limitations of advanced models is presented in Table 2.

Table 2. Summary of advantages and limitations of advanced models.

Advanced models	
Advantages	***Limitations***
• More accurate representation of the geometric layout • Simulation of complex behavioural scenarios • Coupling with advanced sub-models is possible	• Model input set up may be time consuming • Need to import data from external fire/smoke spread simulator • Computationally expensive

7. Evacuation models for underground physics research facilities

The present sections discuss the suitability of different types of evacuation models for the fire safety design of underground physics research facilities.

Based on the discussion presented in the previous sections, it is possible to identify the main characteristics that are needed in an evacuation model for the simulation of evacuation in different egress components of an underground physics research facility. The level of complexity of different parts of the facilities varies significantly from an evacuation point of view. In fact, these facilities include long tunnel arcs where fire and smoke may have a significant impact on the evacuation procedure, while the people movement is generally unimpeded. For this type of sections of the facilities, simplified models are generally recommended since they allow the study of multiple evacuation scenarios in a relatively short time (e.g. sensitivity analyses) and the level of complexity required in the simulation of the interactions of the agents with the space is generally low (i.e. the evacuation generally takes place as a 1-directional movement from the location in which the occupants are initially located to the safe place). An exception to this recommendation is the case in which there is a need to simulate very complex interactions between tunnel occupants (i.e. scenarios in which the actions of staff for notification needs to be investigated) or cases in which the focus of the simulation is the interaction between the occupants and the means of transportation available in the tunnels. Previous studies on tunnel evacuations (Ronchi, 2012, 2013) have shown that a combination of multiple models may be beneficial in cases in which these higher complexities occur.

In contrast, the areas close to the experimental caverns and access shafts generally present a significantly higher level of complexity if compared to the tunnel arcs. For this reason, advanced models are generally recommended for these areas given the need to simulate the impact of geometrical flow constraints on the evacuation process. In addition, the object of the evacuation study may also be the vertical egress to the surface, thus requiring the simulation of the complex interactions between the arrival times of people in the lobby, the waiting time for elevators and the choice between elevators and stairs. In this instance, the simulation of egress might require dedicated sub-models for the issues associated with vertical egress such as the simulation of different elevator strategies (Ronchi and Nilsson, 2013, 2014) or the simulation of ascending stair evacuation which might be associate with physical exertion (Ronchi et al., 2015).

Table 3 presents a checklist of the needed characteristics that should be present in an evacuation model in order to simulate the evacuation process in different parts of underground physics research facilities and in relation to the type of scenario under consideration.

Table 3. Checklist of characteristics in evacuation models in relation to the portion of the underground physics research facilities and the scenario under consideration.

Long tunnel arcs	***Experimental caverns with access shafts***
• Quick computational time (1D models may be preferable) • Easy implementation of fire and smoke effects on evacuation • Representation of staff behaviours • Representation of social interactions (if needed) • Issues associated with long distances (choice of movement speeds, transportation means, etc.)	• Complex 2D representation of the space • Representation of flow constraints • Representation of 3D elements of the space (if needed) • Occupant Evacuation Elevator modelling (if needed) • Representation of ascending stair evacuation (e.g. fatigue, etc.) • Representation of choice between different vertical egress components (stairs vs elevators)

In case of an evacuation study which includes parts of the underground facilities with different levels of complexity, it is recommended to use a combination of approaches to enhance the trade-off between computational resources and model results accuracy. It is desirable that future models include pre-defined frameworks for coupled evacuation analyses which makes use of both simplified models and advanced models.

8. Conclusions

This document has presented a general overview of the evacuation-related characteristics of underground physics research facilities and the capabilities of evacuation models to represent evacuation scenarios. Two main areas are taken into consideration, namely 1) long tunnel arcs and 2) area surrounding the experimental caverns. Recommendations concerning the use of appropriate evacuation models for these two areas have been provided, specifically:

1) Simplified models are recommended for the simulation of people movement in simple 1D evacuation scenarios in long tunnel arcs.
2) Advanced models are recommended for the simulation of the evacuation process in the area of the experimental caverns. In case of more complex interactions between people and people and the environment in long tunnel arcs, then advanced models are recommended also for them.

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