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Fire Safety and Evacuation Analysis of a Passenger Ship

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Dissertation

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Abstract

In this study, fire safety of passenger vessels is investigated through evacuation analysis in accordance to the requirements of MSC Circular 1238. For better understanding of the implemented plan of advocate scenarios and the concepts behind evacuation, a theoretical description of fire characteristics and dynamics is given on the basis of research of literature. Furthermore, the regulations framework for fire safety and evacuation is outlined.

In order to perform the evacuation analysis, Pyrosim (an FDS based program) and Pathfinder software will be used to model fire and evacuation scenarios respectively. The evacuation process is examined for two fire intensity scenarios; a moderate and an extreme. For each fire scenario several ignition locations are considered, so as to identify the position that causes the most casualties. In addition, different behaviors and speeds are assigned to passengers so as to simulate a variance in ages and genders. Finally, an evaluation of how time is affecting the evacuation process is made.

The results exported by the simulations indicate that fire location affects occupants differently in day and night scenarios. Specifically, a fire closer to the exit is more preferable in a day scenario while a fire in a greater distance to the exit is more preferable in a night scenario. Additionally, the variation in speeds has a greater impact on younger passengers, causing increased casualties in lower speeds. Lastly, the most critical time span resulted to be the inactive time right before the night scenario evacuation begins.

Table of Contents

List of Figures

List of Tables

1. Introduction

Fire is considered one of the most hazardous events in maritime safety, causing a great deal of damage to properties and the environment, leading to injury or even death to people. In the wake of major maritime disasters, such as the Scandinavian Star and Morro Castle, and in light of the growth in the number of passengers of high density ferries and large cruise ships, issues concerning the adequate treatment of a fire case scenario and the secure evacuation of the passengers are receiving new interest. The significant growth of fire incidents onboard vessels is presented in figure 1. As demonstrated below, in the past decade at least one major accident is caused by fire and as the IMO Correspondence Group on Casualty Analysis (March, 2013) stated in FSI 21/5 “there have been a number of significant fire incidents on Ro-Ro passenger vehicle decks since 1994 and there is no sign of these diminishing. Since 2002 there has been a very serious incident every other year, resulting in six constructive total losses”. Therefore, there is a need for accurate prediction of the impacts a fire can cause on people and properties and a way of eliminating these impacts.

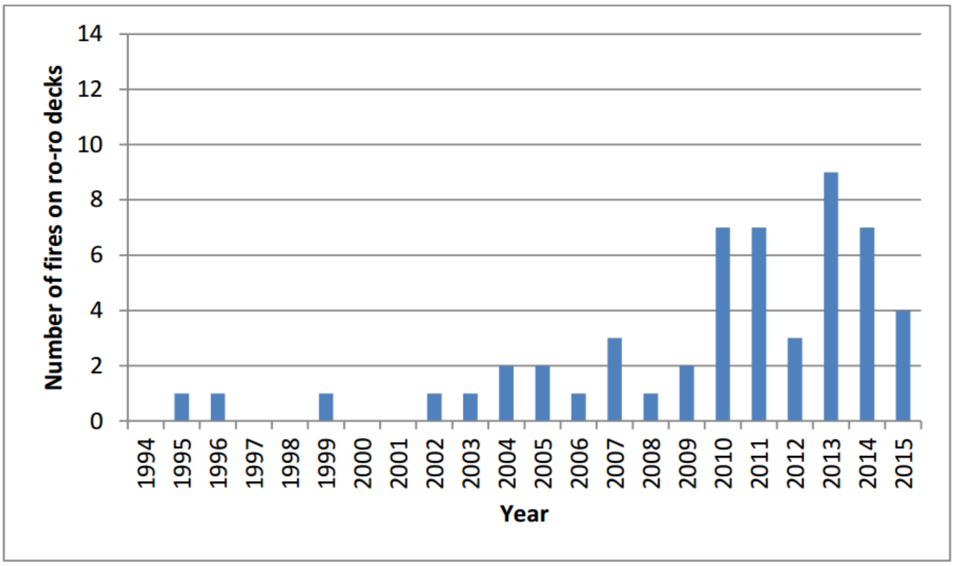

Figure 1 Number of fires past decade (Source: Wikman et al. 2017)

Injuries or deaths by smoke inhalation have been the primary cause of fire incidents. As Gann et al. (1994) and Hall (2005) reported, nearly 75 percent of all fire deaths occurred in places remote from the fire origin as smoke travels throughout the space. Therefore, apart from the heat released in fires, exposure to the toxic gases and smoke must also be dealt with carefully to provide adequate life safety to its occupants. Significant is the fact that, smoke production characteristics, especially in an enclosed space, can negatively affect occupant escape abilities and tenability. Therefore, a secure way of escape must be determined in all enclosed facilities in order to prevent the blockage of the occupant at the maximum possible percentage.

1.1 Literature Review

According to Apte et al. (2005), “a design fire is a quantitative description of a fire that is representative of a particular scenario or sequence of events. The description is given in terms of the heat release rate history, production rates of various products, and the various combustion parameters, as well as the probability of the event or scenario. Typically this would form the basic input to a fire model describing a fire scenario, with the fire engineer deciding on the appropriate design variables and parameters to be used on any particular project".

Multiple sources were consulted in order to compile a credible set of design inputs. Such sources were used as help and guidance, and contributed into the formation of this research work. Since the research relies on the background information derived from these literatures, a brief discuss of their contents is given for better understanding and analysis of the experimental results.

When describing the best possible solution for fire protection, the first three areas of concern are structural fire protection, fire detection and fire extinguishing as mentioned by Zhang (2000). The design of the spaces and the fire detection and alarm systems should be made driven by the need for safe evacuation and adequate treatment of any fire accident. Thus, Zhang's research focuses on the design parameters that affect the results of a fire to a great extent. By making assessments on different zones of a vessel, and by taking into consideration both active and passive protection measures, a proposition for alterations on the existing designs was made. A great emphasis was given on the casualties smoke can occur to passengers, as it is the main cause of incapacitation during evacuation process.

The second step in developing an ideal design for fire protection is to be able to foresee the growth of a fire and the possible behavior of passengers trying to escape. One of the first approaches ever made on this matter was by Galea et al. (2003), who used the maritime EXODUS software to simulate the ship evacuation and the SMARTFIRE software to simulate the fire growth. Their research provides an example application, demonstrating the use of the models in performing fire and evacuation analysis for a large passenger ship. The research was exceeding the requirements of MSC circular 1033, therefore four (4) scenarios were examined; two main scenarios (day & night) for evacuation without the presence of fire, and two extra scenarios for fire involved evacuation. Time needed for passengers to evacuate safely was measured as well as the casualties occurred in the fire simulation.

A newer approach on fire and evacuation modeling was made years later by Azzi et al. (2011). As it is stated in that research, "fire accidents onboard ships are statistically the most frequent hazards that ships encounter at sea", therefore a focus on new alternative designs that rely on evaluation of the design performance is considered necessary. Such evaluation can be done through the simulation of fire and evacuation scenarios that help to assess the possible hazards of fire accidents. That kind of modeling is already in use in the civil sector, and the research of Azzi et al. (2011) is using these tools to integrate both fire and evacuation models for a more realistic approach on the consequences of fire on human evacuees. Their research uses the FDS environment to simulate the fire and the EVI environment to simulate the evacuation of the passengers. The IMO guidelines are being followed for the evacuation, and a single fire scenario was used to simulate two evacuation scenarios.

In addition to what Azzi et al. (2011) state, Spyrou et al. (2013), perform a design evaluation using fire simulation models for different severity fire cases. Their research focuses on calculating a risk index while taking into consideration the associated probability of ignition and the reliability of the installed fire extinguishing systems as well as the human factor. The case study's conclusions, give an evaluation of fatalities per ship year, offering a basis for the required safety level when designing a new ship.

Another research by Themelis & Spyrou (2012) focuses on the assessment of passengers ship fire safety. Specifically, a designed fire is generated with the use of HRR values of materials used in cabins. Fire growth intensity, restriction of heat release rate resulting from ventilation shortage, occurrence of flashover, and the final decay are key processes modeled. A smoke detector is used in order to trigger the fire suppression system while the effect of human intervention is also taken into account. The aim of the paper is to establish the means to assess the design selections that affect the success of the fire safety system, and evaluates the probability of success on different fire cases.

A more recent paper on evacuation analysis is delivered by Salem (2016) who gives emphasis on the consequences of the various quantities produced by fire such as toxic gases, soot visibility, heat transferred due to conduction, convection and radiation. The research deals with four different fire cases, calculating for each one the available safe egress time (ASET) and the products affecting it. In order to explore the effect of propagation of uncertainty from the random inputs into the predicted ASET, the Monte Carlo Simulation technique is used (Salem, 2016). From the evaluation of the results exported, visibility and temperature appeared to be the main causes to affect the available safe egress time.

Taking into consideration the acts completed so far in the direction of simulating fire and evacuation scenarios, and the continuous need for more data regarding the design and the evacuation process, this study deals with multiple fire and evacuation models so as to define the best solution in the unlikely event of a fire accident.

1.2 Scope and Objective

It goes without saying that a human life is the most significant factor to prioritize its safety during an accident; therefore, the emphasis of this study is placed on indicating the issues that most affect human survival throughout a fire evacuation process onboard. Based on this perspective, three major aspects that affect fire evacuation will be examined. Initially there will be an evaluation of the dangers of the various positions of the fire in a confined space, a main vertical zone in the cabin area of a passenger ship. The following aspect to be examined consists of the use of various human behavior models, as well as a variance on the speed depending on the gender, age and physical condition of each passenger. Moreover, further investigation on how speed affects the evacuation process will be completed. Lastly, the final aspect that will be inspected is how time affects each passenger's evacuation ability. This will be a useful tool to be taken into consideration when designing the areas of a ship, the fire extinguishing systems and evacuation plan onboard.

2. Fire – Important Factors that Affect Human Survival

Fire is the visible effect of the process of combustion; more particular it is the process involving rapid oxidation at elevated temperatures accompanied by the evolution of heated gaseous products of combustion, and the emission of visible and invisible radiation. Oxidation occurs all around us in the form of rust on metal surfaces, and in our bodies by metabolizing the food we eat. However, the key word that sets combustion apart from other forms of oxidation is the word “rapid”.

The combustion process is usually associated with the oxidation of a fuel in the presence of oxygen with the emission of heat and light. Oxidation, in the strict chemical sense, means the loss of electrons. For an oxidation reaction to occur, a reducing agent; the fuel, and an oxidizing agent; usually oxygen, must be present. As heat is added, the fuel molecules and oxygen molecules gain energy and become active. This molecular energy is transferred to other fuel and oxygen molecules, which creates a chain reaction. A reaction takes place where the fuel loses electrons and the oxygen gains electrons. This exothermic electron transfer emits heat and/or light. The reaction will keep going as long as there is enough heat, fuel and oxygen creating the source of fire ignition. This is known as the fire triangle (see Figure 2).

Figure 2 Fire Triangle (Source: edplace.com)

As far as the combustion process is concerned, it occurs in two modes: the flaming and the non-flaming, smoldering or glowing embers. In order for the flaming mode to be successful, it is necessary for solid and liquid fuels to be vaporized. Consequently, the solid fuel vapors will be thermally driven off, or distilled and the liquid fuel vapors will evaporate. It is this volatile vapor from the solid or liquid fuels that we see actually burning in the flaming mode. This gas or vapor production, emitted from the fuel, is referred to as pyrolysis. Once a flame has been established, heat transfer from the flame to the fuel surface continues to drive off more volatile gases, which perpetuates the combustion process. For continued burning in the flaming mode, a high burning rate is required, and the heat loss associated with transfer of heat from the flame area by conduction, convection, and radiation must be less than the energy output of the fire. If the heat loss is greater than the energy output of the fire, the fire will extinguish. Both modes, flaming and non-flaming surface modes, can occur individually, or in combination. Flammable liquids and gases only burn in the flaming mode. Wood, straw, and coal are examples where both modes may exist simultaneously.

Flaming combustion can occur in the following two forms:

1. Premixed flames, where the fuel and oxygen are mixed prior to ignition. For example the flame on a Bunsen burner, gas stove, or propane torch.

2. Diffusion flames, where the fuel and oxygen are initially separate but burn in the region where they mix, like a burning of a pool of flammable liquid or the burning of a log.

2.1 Stages of a Fire

There are four generally recognized stages of a fire: the incipient stage, the growth stage, the fully developed stage and the decay stage (Babrauskas, 2008). The incipient stage is a region where preheating, distillation and slow pyrolysis are in progress. Gas and sub-micron particles are generated and transported away from the source by diffusion, air movement, and weak convection movement, which are produced by the buoyancy of the products of pyrolysis. The growth stage is a region of fully developed pyrolysis that begins with ignition and includes the initial stage of combustion. There are many factors affecting the growth stage, such as the combustibles near the fire, and it is during the shortest of the 4 stages when a deadly flashover can occur. When the fire is fully developed, all the combustible materials have ignited and is considered the hottest and most dangerous phase of the fire. Invisible aerosol and visible smoke particles are generated and transported away from the source by moderate convection patterns and background air movement. The decay phase is usually the longest stage of a fire and is characterized by a significant decrease in oxygen or fuel, eventually leading to the end of the fire. During this period there is always the danger for existence of non-flaming combustibles that can potentially start a new fire. The aforementioned stages of a fire are depicted in figure 3.

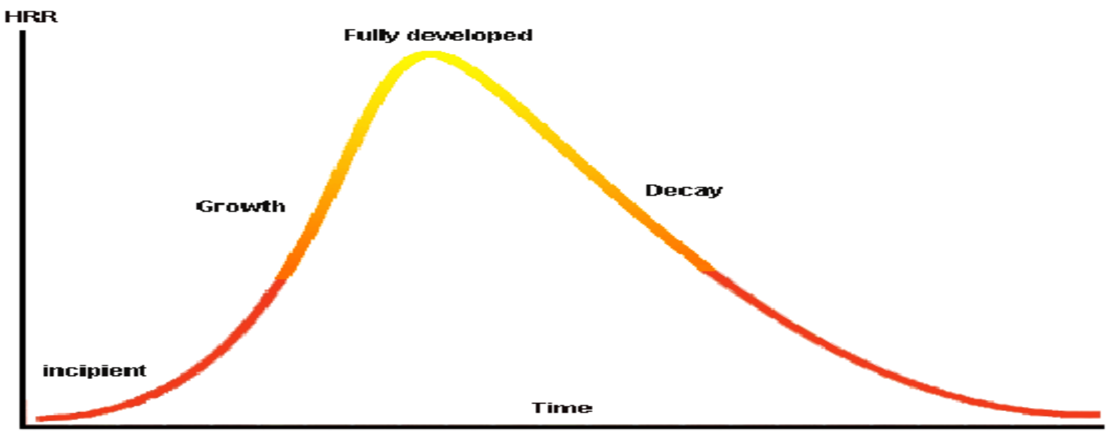

Figure 3 Stages of a Fire (Source: tathrafirebrigade.org.au)

When it comes to the results of a fire, exposure to toxic smoke can have a lot of effects on human health, causing different levels of psychological stress, irritation, burns, hyperventilation and incapacitation. Survival in a fire situation depends on two parallel events. These being the developing hazard from the fire, and the process by which occupants escape (Purser, 2002).

2.2 Fire Dynamics

The way that fires start, spread and develop is a part of a fire dynamics study. Such a study considers the ways in which heat is transferred, the rate of heat release and the temperature produced. These factors will be elaborated in the subsections below.

2.2.1 Heat Transfer

Heat transfer is an area of thermal engineering that focuses on the transport, exchange, and redistribution of thermal energy. The three ways that heat can be transferred have been termed conduction, convection, and radiation.

In conduction, energy slowly diffuses through a medium from a point of higher temperature to a point of lower temperature, whereas in radiation, energy is transmitted with the speed of light by electromagnetic waves (or photons), and a transmitting medium is not required (Ezekoye, 2016).

- Conduction

  Conduction heat transfer only occurs in a medium. This is a distinction between conduction and radiation, which does not require a medium. The medium or state of matter in which conduction takes place can be a gas, liquid, or solid. The distinction between conduction and convection heat transfer is associated with whether the medium has some ordered flow or bulk motion. Heat transfer, when there is a mass average velocity, is termed convection. Heat transfer that takes place in a stationary frame of reference is called conduction.

- Convection

  From a conceptual viewpoint, convection is not a basic mode of heat transfer. It occurs by a combined effect of conduction (and/or radiation) and the motion of the transmitting medium. Convection plays a very important role in fires. It transports the enormous amount of chemical energy released during a fire to the surrounding environment by the motion of hot gases. This motion may be induced naturally by the fire itself (hot gases rise and cold air rushes to replace them) or by a source external to the fire, such as a prevailing wind. Based on this distinction, the subject of convective heat transfer is usually subdivided into natural (free) and forced convection. Obviously, both natural and forced convection may occur simultaneously, resulting in a mixed mode of convective heat transfer. A further subdivision based on whether the flow occurs inside or outside the body under consideration is also often made. For application of convective heat transfer to fire science, natural convection around objects is clearly far more important than forced convection inside a pipe (Atreya, 2016).

- Radiation

  Thermal radiation is the dominant mode of heat transfer in flames with characteristic lengths exceeding approximately 0.2 m. It is for this reason that quantitative analysis of fire dynamics requires a working knowledge of thermal radiation. All objects with a finite temperature emit thermal radiation through a physical mechanism related to electron oscillations and transitions. As an object's absolute temperature increases, these electron oscillations and transitions become more rapid, resulting in increased radiant emission. Since all objects emit radiation, all objects also have a certain amount of thermal radiation impinging upon them (originating from other emitting objects). It is the net difference between incoming and outgoing thermal radiation that leads to a net rate of radiant heat transfer between objects at different temperatures, and quantification of this rate is usually the ultimate goal of a radiation heat transfer analysis (Tien et al., 2016).

2.2.2 Heat Release Rate

Since heat is the energy output of the fire, the focus of interest in regards to the scientific aspect is the measuring of heat. What is even more of interest is the rate at which heat is released rather than the total amount. Heat is measured in units of Joules and therefore the Heat Release Rate (HRR) can be measured in Joules per second, which is referred to as Watts. Since a fire puts out much more than 1 Watt, it is usually convenient to quantify the HRR in kilowatts (1000 W) or megawatts (a million watts).

HRR is not just 'one of many' variables used to describe a fire. It is, in fact, the single most important variable in describing fire hazards (Babrauskas, 2016). The reasons for this vary, but the most significant ones can be summarized into the facts that: a) HRR is the driving force for fire, b) most other variables are correlated to HRR and c) high HRR indicates high threat to life. Taking a closer look, HRR can be viewed as the engine driving the fire. This tends to occur in a positive-feedback way where heat produces more heat. A direct result of it is the increase in generation of most undesirable fire products, which follows the increase of HRR. Smoke, toxic gases, room temperatures and other fire hazard variables generally march step-in-step with HRR as HRR increases. In addition, high HRR fires are intrinsically dangerous and highly threatening for human life. This is because high HRR causes high temperatures and high heat flux conditions, which may prove lethal to occupants.

2.2.3 Temperature

Temperature comes as an aspect of great importance when referring to fire. When measuring the temperature of a fire, focus is applied on the temperature produced by the flames. Although measuring of flame temperatures to a high degree of precision is quite difficult, estimation can be done with the help of a handbook value, which turns out to the adiabatic flame temperature. Flames can be subdivided into two types: flames in the open, and room fires.

When the temperatures of the evolved gases become high enough, the flashover phenomenon might be occurred. As Babrauskas (2008) states, there is a fairly broad agreement in the fire science community that flashover is reached when the average upper gas temperature in the room exceeds 600 ^{o}C. The peak value is governed by ventilation and fuel supply characteristics and so such values form a widely frequency distribution. The maximum value, which is fairly regularly found, turns out to be around 1200^{o}C, although a typical post-flashover room fire will more commonly be 900~1000 ^{o}C. The peak expected temperatures in room fires are slightly greater than those found in free-burning fire plumes. Such a case is expected, as a flame that is far away from and does not heat up the enclosure, radiates to surroundings, which are essentially at 20 ^{o}C.

On the contrary, if the flame is big enough (or the room small enough) for the walls to heat up substantially, then the flame exchanges radiation with a body that is several hundred ^{o}C which results in smaller heat loses, and, therefore, a higher flame temperature.

2.3 Fire Products

Fire products, especially toxic gasses, soot and temperature may affect human life. The most famous and frequently encountered asphyxiate gas in fire is carbon monoxide, which has also been identified as the major cause of death (Babrauskas, 2008). Carbon monoxide is present in every fire due to incomplete combustion, a phenomenon that is more common in spaces with reduced ventilation such as a room environment. Carbon monoxide molecules have the ability to bond with hemoglobin better than the oxygen molecules, and as a result there is a reduction in oxygen supply to the body and especially the brain. This can cause loss of consciousness as well as occupant escape capabilities to impair or even prevent a successful escape (Purser, 2002). A critical characteristic of asphyxia is the sudden onset whereby the effects of incapacitation rapidly become severe; such that escape becomes almost impossible once the victim is aware of the effects of fire. Furthermore, the first symptom of incapacitation appears to be on motivation. Therefore, the victims may tend to sleep rather than making an escape attempt, making the carbon monoxide the primary cause of death in fires (Purser and Berrill, 1983).

Second in the list of most famous toxic gases, carbon dioxide (CO_2) is also deadly in high doses. Although not an asphyxiant gas by itself, low concentration of oxygen (less than 15 percent) and very high concentrations of carbon dioxide (greater than 5 percent) can have similar asphyxiant effects (Purser, 1984). The presence of carbon dioxide also stimulates breathing, causing hyperventilation, dizziness, drowsiness, and unconsciousness, superimposed on the respiratory effects. In a toxic environment, a high $CO2$ concentration would increase the uptake of asphyxiant gases and significantly reduce time to incapacitation (Purser, 2002).

Despite the fatal consequences of Carbon Monoxide and Dioxide, soot is the main reason to cause incapacitation in the attempt to evacuate. The term soot is connected to the term of smoke, which is defined by Mulholland (2002) as "the smoke aerosol or condensed phase component of the product of combustion". In simpler terms, it is the solid carbon particles present in smoke (Glassman, 1986). It is a product of pyrolysis, generally formed in the fuel-rich regions of the flame. The soot particles grow in size "through gas-solid reactions, followed by oxidation (burnout) to produce gaseous products, such as CO and CO2" (Tewarson, 2002). It can be measured in terms of its mass and particle size distribution. However, the primary properties of interest to the fire community are light extinction, visibility, and detection (Mulholland, 2002). Soot is usually reported as optical obscuration or optical density and therefore smoke emission is one of the critical items characterizing a design fire, affecting visibility during escape and changes in human behavior. The presence of a thick smoke not only significantly reduces escape speed, but it also induces emotional stress. This is especially evident in an irritant smoke (Jin, 2002) and affects occupant escape speeds. Design information to model occupant escape behaviors in smoke can be found from Jin's research in the SFPE Handbook (2002).

In order to examine occupant survivability, fire products have to be measured. This is achieved by calculating the coefficients of total Fractional Effective Dose of toxic gases (FED) and the concentration of smoke in order to calculate the optical density.

2.3.1 FED

To assess the toxic potency of each toxic gas, which is the amount of gas needed to be dispersed into 1 m^3 in order to cause a 50% probability of lethality, a number of physical fire models have been developed. Once the toxic potency of these fire species is determined, the intake amounts are weighted accordingly and calculated using the equations proposed by Purser (2002). This quantity is calculated for every time frame, which is integrated over time to calculate the final Fractional Effective Dose (FED) at that point in time. As a mixture of gases is often present in any fire, to calculate the interacting effects of different asphyxiating gases, a formula has been given by Purser (2002) to estimate the time to reach incapacitation. In its simplest form, the FED is "the ratio of the exposure dose for a gaseous toxicant produced in a fire to that exposure dose statistically determined from independent data to produce an effect in 50% of subjects."

The value of FED is measured according to Purser's definition and presented in equation [1]:

$$FED_{tot} = FED_{CO} \cdot HV_{CO2} + FED_{O2} \qquad [1]$$

Where, the partial quantities can be calculated by equations [2] to [4].

$$FED_{CO} = \sum_{t-\Delta t/2}^{t+\Delta t/2} \frac{K \cdot [CO]^{1.036}}{D \cdot 60} \cdot \Delta t \qquad [2]$$

$$HV_{CO_2} = \frac{\exp\,(0.1903 \cdot [CO_2] + 2.0004)}{7.1} \qquad [3]$$

$$FED_{CO_2} = \sum_{t-\Delta t/2}^{t+\Delta t/2} \frac{1}{60 \cdot exp[8.13 - 0.54 \cdot (21\% - [O_2])]} \cdot \Delta t \qquad [4]$$

The values used in these equations are:

Δt (s): time step

[CO][ppm]: the mean value of CO concentration in Δt

$[CO_2]$, $[O_2]$: volume percent concentration (mean values in Δt)

K, D: constants regarding human activity as shown in Table 1.

Table 1 K, D Values (Source: Purser, 2002)

Activity	K	D
Rest	2.819×10^{-4}	40
Light work	8.292×10^{-4}	30
Heavy work	1.658×10^{-4}	20

Fire species depending on their toxicity, amount produced and simultaneous occurring can greatly affect the escape abilities of an occupant and determine how successful an attempt to escape will be. Generally, a FED value lower than 1.0, is considered non-lethal, but in order for someone to safely evacuate a place the suggested value according to ISO/TS 13571 is 0.3. The choice of such low value has to do with the variability among humans to withstand toxic effects, as some are more sensitive than others.

Table 2 FED Categories (Source: Azzi et al. 2011)

FED Range	Injury Category
$\mathbf{0 \leq FED \leq 0.3}$	Negligible
$\mathbf{0.3 \leq FED \leq 0.7}$	Mild Injury
$\mathbf{0.7 \leq FED \leq 1.0}$	Serious Injury
$\mathbf{1.0 \leq FED}$	Fatality

2.3.2 Visibility

Visibility plays a major role when trying to escape a fire. Three factors are directly related to visibility: environmental conditions, object's conditions and human visual ability. The former two factors define visual stimulus, and the latter defines visual sensitivity. When talking about visibility in fire smoke, certain things must be taken into account. Firstly, the characteristics of fire smoke, which are composition, shape, and size of the particles, which depend on the combustible materials involved and, secondly, the conditions of combustion. These characteristics are also highly dependent on surrounding flow and temperature fields and vary with time.

There are two reasons for the decrease in visibility through smoke: luminous fluxes from a sign and its background are interrupted by smoke particles and reduce its intensity when reaching the eyes of a subject, and luminous flux scattered from the general lighting of corridors or rooms by smoke particles in the direction of a subject's eyes is superimposed on the reduced flux mentioned before (Yamada & Akizuki, 2016).

The calculation index for the inability of moving due to heavy smoke is derived through equation [5], which estimates visibility:

$$S = {}^{C}/_{K} \qquad [5]$$

Where C is a non-dimensional constant characteristic of the type of the object being viewed though smoke with values of $C = 8$ for light-emitting signs and $C = 3$ for light-reflecting sings. K is the light extinction coefficient, which is assumed the most useful quantity for assessing visibility in a space:

$$K = K_m \cdot \rho \cdot Y_{SOOT} \qquad [6]$$

The light extinction coefficient, *K,* is a product of the density of smoke particulate $\rho \cdot Y_{SOOT}$ (where Y_{SOOT} is the soot yield), and a mass specific extinction coefficient that is fuel dependent, K_m (McGrattan K. et al. 2010).

3. Fire Safety at Sea

Cases of fires breaking out at sea and fires breaking out on land have significant but obvious differences. The victims involved in a fire on land will usually have easier access to a safe place, rather than the victims of a fire at sea who are surrounded by water and, in most cases, do not have access to land. The only route of escape is by using a lifeboat or a life raft. Bad weather can also occur in producing great danger even in case of an evacuation from a blazing ship onto a lifeboat.

Fire is one of the major causes of total loss in maritime sector. As statistics shown, fires and explosions are responsible for one fourth (1/4) of the maritime casualties (Wikman et al. 2015). Extremely important fire events have been occurred onboard passenger ships, such was the Morro Castle, the Lakonia, and the Scandinavian Star resulting to hundreds of human losses not only due to the event of fire, but also due to due to fire and poor evacuation procedures onboard.

In order to increase maritime safety, in terms of fire events, the International Maritime Organization (IMO) has introduced fire safety regulations through the SOLAS (Safety of Life at Sea) convention and FSS (Fire Safety System) code. A brief description of fire safety and regulations is presented in next subsections.

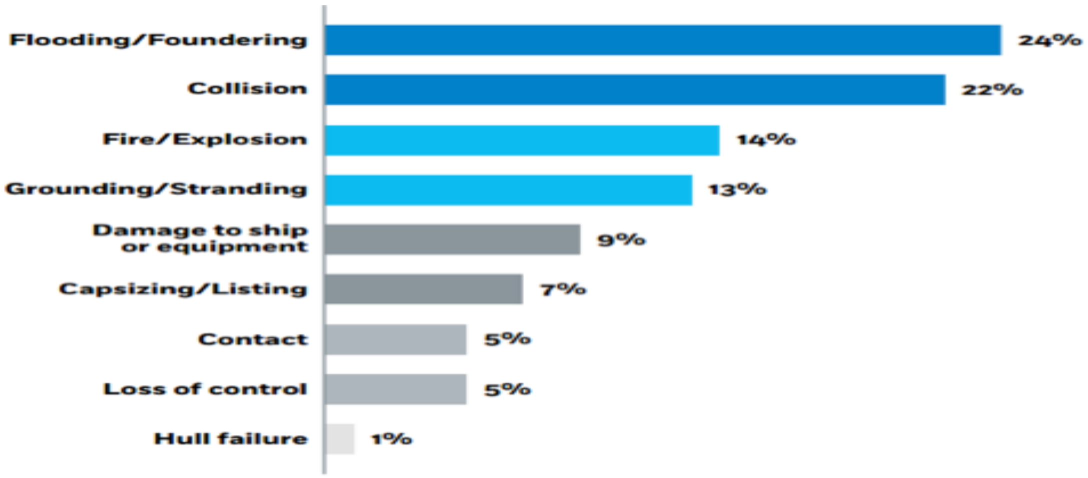

Figure 4 Distribution of very serious casualty events 2011-2014 (Source: Wikman et al. 2015)

3.1 Philosophy & Principles of Fire Protection Onboard

There is one significant question that must be answered when fire events take place onboard a ship: What is considered a priority to be protected in cases of fire accidents? Of course, the question can easily be answered as nothing is valued as high as the human life, but for the second place on the list of priorities the property and the environment are considered equally important. In the past decades the value of the property was considered of higher importance than the possible disaster of the environment, but it seems like nowadays the two of them keep altering place.

Human life will always be the highest priority to protect on board not only in fire incidents but also in incidents such as grounding and collision. This can be enhanced by the fact that most of the SOLAS regulations on fire protection are dealing with the protection of human lives.

Alongside, the environment protection comes up to great importance due to the growing consciousness of protecting the environment. The phase out of the use of halon, the famous ozone depleting substance on board, is a good example of this. This comes as a result of the need to be able to extinguish a ship fire and in the same time minimize pollution of the air or the sea.

Protecting the property, the ship, is a major priority for the ship owner. Fire detectors, alarms and fire extinguishers are meant not only protect human lives but also to ensure the less possible damage for the vessel. However, protecting the ship sometimes turns to be more difficult even than protecting human lives, as there are many examples of fire casualties where the fire grew beyond the stage of control causing cases of explosion and total loss.

In order to develop a system capable of delivering satisfactory protection, the priorities of the ongoing measures should be of having kept as by the following order (Manum, 1994):

- Prevent fire form developing;
- Detect a fire (early);
- Contain the fire;
- Alarm;
- Evacuation;
- Deployment / fire-fighting / smoke ventilation.

3.2 Development of Regulations

On ships over 500 GT, fires and explosions are the third largest cause of accidents, after collision and grounding as Pillai (2014) mentions. Having that in mind and taking a look at the history of fire accidents on ships is easy to understand why fires and explosions have such an important role when it comes to the formation of the regulations.

The two most important guides regarding the fire safety on board are SOLAS (International Convention for the Safety of Life at Sea) and FSS (Fire Safety System code). Both of them have been developed based mainly on the biggest disasters caused by fire throughout history.

Fire and explosion accidents have caused the lives of many people; therefore it only comes as a logic reaction to amend the regulations regarding the safety of human life each time a new accident revealed a blur point on the existing ones. That said, an analysis of accidents that forced the regulations to a change regardless of the number of deaths occurred, would give us a clear image of how we reached today's SOLAS and FSS form.

The first version of SOLAS passed right after and in response to the sinking of the RMS Titanic and prescribed a number of lifeboats and other emergency equipment along with safety procedures. The treaty took place in 1914 but never entered into force due to the outbreak of the First World War as stated in the International Convention for SOLAS (1948). In the years following that, fire incidents and explosions on board passenger ferries rose awareness regarding mainly the materials used and the need for non-combustible materials which is reflected on the later versions that were adopted by

SOLAS in 1929 and 1948. Significant example of that period that will be shown in more detail below is the fire incident at SS Morro Castle. Particularly, the 1948 version of SOLAS was the first one to give a great emphasis on fire safety by adding three new parts on Chapter II; Fire protection, fire detection and fire extinction.

The 1960 Convention was adopted on 17 June 1960 and entered into force on 26th May 1965. It was the fourth SOLAS Convention and was the first major achievement for IMO. It represented a considerable step forward in modernizing regulations and keeping up with technical developments in the shipping industry. Furthermore, the 1960 version of SOLAS included both passenger ships and cargo ships into the fire safety regulations.

In 1974 a completely new Convention was adopted to allow SOLAS to be amended and implemented within a reasonable time scale. By that time a number of accidents caused by fire and explosions such as those on TSMS Lakonia and SS Yarmouth Castle that caused the life on over 200 people made clear that new amendments were necessary. The 1974 SOLAS came into force on May 25th 1980 and, after some revision and modifications, is still the one used until today. The main difference regarding fire safety is that for the first time SOLAS had an independent chapter (Chapter II-2). In addition, SOLAS 1974 made it obligatory for all ships to be built with non-combustible materials and to have a permanent fire extinction system and a fire detection system.

From 1974 to 1992 small amendments were made regarding fire safety, mainly focusing on specific fire extinguishing systems and the range of ships the regulations would cover (1981 Revision of SOLAS). In 1990, a fire on Scandinavian Star caused the death of 158 people and led IMO to adopt a new set of regulations regarding fire safety. In December of 1992 the conversations were completed and the new amendments included installation of fire extinction systems according to the ones used on hotels - a combination of sprinklers, automated smoke detection system and fire proof doors and rooms. In addition a method for making the evacuation in case of fire easier was developed.

Although there was great effort to cover as many aspects as they could, the 1992 SOLAS was difficult to adopt as it wasn't clear in many cases on how to apply the regulations. This led to new amendments in 1996, until the year 2000 when the Chapter II-2 was completely reformed.

On the 1st of July 2002, the SOLAS 2000 amendments were applied. The new form of Chapter II-2 focused on a fire case scenario regardless of the type of the ship. This made it easier to apply in any case, starting from the measures that have to be taken in order to prevent a fire, followed by the detection, the extinction and finally the evacuation. Furthermore, in order to make the regulations more user friendly, the technical details of the multiple fire systems used were transferred into the FSS code. In addition, two new parts were added to Chapter II-2, part E which focuses on the human factor and the necessary training of the crew, and part F which focuses on alternative designs in order to prevent fire accidents. Thus, FSS is consisted of the new form of Chapter II-2, including all the details required for the engineer and were too much of information to be included in SOLAS.

3.3 Fire Accidents

A brief description of the most significant fire accidents that influenced the development of regulations is presented below:

- *SS Moro Castle (1930)*

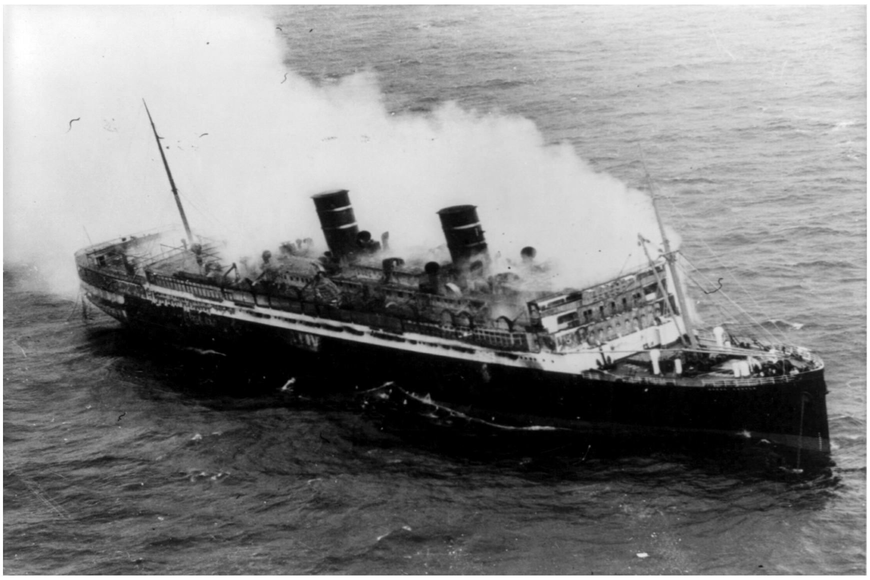

Figure 5 SS Moro Castle (Source: Brown, 1939)

At around 2:50 a.m. on September 8th, while the SS Morro Castle was sailing around eight nautical miles off Long Beach Island, New York, a fire was detected in a storage locker within the First Class Writing Room on B Deck, which quickly spread within minutes. Captain Warms attempted to beach the ship, but the growing need to launch lifeboats and abandon ship forced him to give up this strategy. Within 20 minutes of the fire's discovery (at approximately 3:10), the fire burned through the ship's main electrical cables, plunging the ship into darkness (Brown, 1939). As all power was lost and the fact that passengers and crew were cut off by the fire amidships, gave them only the option to abandon ship. Only six of the ship's 12 lifeboats were launched—boats 1, 3, 5, 9 and 11 on the starboard side and boat 10 on the port side. Although the combined capacity of these boats was 408, they carried only 85 people, most of whom were crew members (Brown, 1939).

Many passengers lost their lives for lack of knowledge on how to use the life preservers. As they hit the water, life preservers knocked many individuals unconscious, leading to subsequent death by drowning, or broke victims' necks from the impact, killing them instantly. The total number of passengers and crews deceased was 135 (Brown, 1939).

- *TSMS Lakonia (1963)*

The passenger ship TSMS Lakonia, sailed by Greek Line, was sailing on a Christmas cruise on December 22nd, 1963 around 11 pm while the ship was about 180 miles north of Madeira when fire broke out (Galliano and Watson, 2008).

There were 646 passengers and 376 crewmen on board, a total of 1,022 people. Evacuation of the ship was extremely difficult. Some lifeboats burned before they could be lowered. Two of the lifeboats were swamped, spilling their occupants into the sea; one when it was lowered only by one end, and the other when its davits broke off. Chains had rusted in many of the davits, making boats difficult or impossible to move. In the end, just over half of the lifeboats made it safely away from the Lakonia, some of them less than half full. Several people who dived overboard struck the side of the ship on the way down, killing them before they hit the water (Galliano and Watson, 2008).

Figure 6 TSMS Laconia (Source: Galliano and Watson, 2008)

When all of the boats were away, there were still people adrift in the water and over 100 people left on board the burning ship. The Lakonia continued to burn fiercely and was rocked by violent explosions. Those who remained on board flocked to the glass-enclosed Agora Shopping Center at the stern of the ship. After several hours, the flames closed in on them, and they were forced to descend ropes and rope ladders into the ocean. The port and starboard gangways were lowered as well, and people walked down the gangways single file into the sea (Galliano and Watson, 2008).

A total of 128 people died in the Lakonia disaster, of which 95 were passengers and 33 were crew members. Only 53 people were killed in the actual fire. The rest died from exposure, drowning and injuries sustained while diving overboard (Galliano and Watson, 2008).

- *SS Yarmouth Castle (1965)*

On November 13th 1965, a fire broke out at room 610 which apparently was full of old mattresses, papers, old wall panels, broken chairs and other highly flammable debris such as paint, floor cleaner and wax. After the fire, more careless mistakes came to light. The USCG found no general alarm was sounded to warn passengers (Marine Board of Investigation, 1966). The radio man claimed he had left his post, and when he became aware of the fire, could not make his way back to the radio shack. It was this same explanation given for the crew of Yarmouth Castle never calling out a SOS distress signal to alert those vessels able to assist in the rescue (Marine Board of Investigation, 1966). Other factors, such as freshly painted ropes and winches also contributed into the continuous difficulties to abandon ship. The fire resulted in 87 people losing their lives, while three of the rescued passengers later died in hospital, bringing the death toll to 90. The steamship's loss prompted new laws for safety at sea (Marine Board of Investigation, 1966).

- *Scandinavian Star (1990)*

The passenger vessel Vognmandsruten SS Scandinavian Star was cruising between Oslo in Norway and Fredrikshavn in Denmark on April 7th, 1990 when fire broke out resulting in 159 deaths. The first fire on board started shortly before 2 AM when the ship had reached open water. A pile of bedclothes and carpets in a corridor on the port side had been set on fire. The fire was discovered by some passengers and extinguished (Solheim et al, 1992).

A second fire was started in another corridor, likely to have also been a pile of laundry that had been set on fire. Tests showed that huge amounts of hydrogen-cyanide (HCN) was produced when the surface lining material combusted. The concentration in the breeding gas would cause the death of people within five minutes (Solheim et al, 1992).

Figure 7 Scandinavian Star (Source: Solheim et al, 1992)

Event reconstruction experiments showed that the combination of the narrow corridor and the reaction to fire properties of the laminate onto the asbestos board set the corridor very rapidly in a flash-over situation. It was mainly the surface laminate lining (1.6 mm) with its melamine finishing that gave the energy to the fire and the production of the lethal gases. The fact that the substrate of asbestos had low heat conductivity also contributed to the flash over conditions (Solheim et al, 1992).

The ship was not equipped with sprinkler systems or any other automatic fire fighting system, any automatic fire detection or alarm system. During the fire captain ordered his Filipino crew to turn off air conditioning system as the captain imagined it was feeding air to the fire. After this was done smoke entered cabins suffocating trapped passengers. The captain and his crew also abandoned ship without evacuating passengers. Many passengers were still onboard the burning ship after it was towed to harbor (Solheim et al, 1992).

- *Norman Atlantic (2014)*

The ANEK Lines' Norman Atlantic ferry was ablaze December 28th, 2014 around 4.30 AM local time with an estimated 423 passengers and 55 crew, with more than 200 vehicles aboard while the Ro-Ro ferry was 44 nautical miles northwest of the island of Corfu, Greece. Of the 200 vehicles aboard, several were tanker trucks containing olive oil, which may have contributed to the fast growing fire (ANEK Lines, 2014).

Norman Atlantic was sailing from Patras, in Western Greece, to Ancona, Italy. When the fire broke out in the Adriatic Sea, a great number of passengers were asleep in their cabins, making it more difficult to evacuate fast enough. Norman Atlantic crew put out a distress signal and over dozens of people managed to board a lifeboat. Early reports say the fire broke out in the lower deck garage and lifeboats were ablaze, passengers were unable to board most lifeboats and began looking for life vests and making their way to the top of Norman Atlantic to await rescue (ANEK Lines, 2014).

Figure 8 Norman Atlantic (Source: ANEK Lines, 2014)

As of December 29th, 9.00 AM, over 24 hours after the fire began, all passengers had been evacuated with the death toll ending at ten lives lost. Passengers adrift on the stricken ferry in high seas braved rain, hail, freezing temperatures, heavy smoke inhalation and burning shoes from the hot decks while awaiting a very slow, painful rescue. Four injured passengers included three children and a pregnant woman who were being treated for hypothermia. Government officials indicate 427 survivors (ANEK Lines, 2014).

4. A Simulation Approach to Fire Safety

Simulation software is based on the process of modeling a real phenomenon with a set of mathematical formulas. It is, essentially, a program that allows the user to observe an operation through simulation without actually performing that operation. Simulation software is used widely to design equipment so that the final product will be as close to design specs as possible without expensive in process modification. Advanced computer programs can simulate power system behavior, weather conditions, electronic circuits, chemical reactions, feedback control systems, atomic reactions, and even complex biological progress. In theory, any phenomena that can be reduced to mathematical data and equations can be simulated on a computer. Simulation can be difficult because most natural phenomena are subject to an almost infinite number of influences. In our case, we focus on software designed to simulate fire and people flow in a specified field.

4.1 Fire Simulation – Pyrosim

The idea that the dynamics of a fire might be studied numerically dates back to the beginning of the computer age. Indeed, the fundamental conservation equations governing fluid dynamics, heat transfer, and combustion were first written down over a century ago. Despite this, practical mathematical models of fire (as distinct from controlled combustion) are relatively recent due to the inherent complexity of the problem. As Hottel (1984) noted in his brief history of the early days of fire research, "a case can be made for fire being, next to the life processes, the most complex of phenomena to understand".

To date, two distinct approaches to the simulation of fires have emerged. Each of these treats the fire as an inherently three-dimensional process evolving in time. The first to reach maturity, the "zone" models, describe compartment fires. Each compartment is divided into two spatially homogeneous volumes, a hot upper layer and a cooler lower layer. Mass and energy balances are enforced for each layer, with additional models describing other physical processes appended as differential or algebraic equations as appropriate. Examples of such phenomena include fire plumes, flows through doors, windows and other vents, radiative and convective heat transfer, and solid fuel pyrolysis. Descriptions of the physical and mathematical assumptions behind the zone-modeling concept are given in separate papers by Jones and Quintiere, who chronicle developments through 1983. Model development since then has progressed to the point where documented and supported software implementing these models are widely available.

The relative physical and computational simplicity of the zone models has led to their widespread use in the analysis of fire scenarios. So long as detailed spatial distributions of physical properties are not required, and the two-layer description reasonably approximates reality, these models are quite reliable. However, by their very nature, there is no way to systematically improve them. The rapid growth of computing power and the corresponding maturing of computational fluid dynamics (CFD), has led to the development of CFD based "field" models applied to fire research problems. Virtually all this work is based on the conceptual framework provided by the Reynolds-averaged form of the Navier-Stokes equations (RANS). The use of CFD models has allowed the description of fires in complex geometries, and the incorporation of a wide variety of physical phenomena. However, these models have a fundamental limitation for fire applications - the averaging procedure at the root of the model equations (McGrattan et al, 2016).

One of the most advanced fire simulation software at the moment is Pyrosim, although in order for one to understand how it works, it is needed to focus on its ancestor, the FDS software.

- Fire Dynamics Simulator

Fire Dynamics Simulator (FDS) is a CFD model of fire-driven fluid flow. The computer program solves numerically a large eddy simulation form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow and combustion of pyrolysis products, heat radiation and convective transfer of heat between gases and solid surfaces, pyrolysis, flames and smoke spread, sprinklers activation, heat and smoke detectors, and suppression with an emphasis on smoke and heat transport from fires, to describe the evolution of fire. FDS is free software developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce, in cooperation with VTT Technical Research Centre of Finland. Smokeview is the companion visualization program that can be used to display the output of FDS. The first version of FDS was publicly released in February 2000. To date, about half of the applications of the model have been for design of smoke handling systems and sprinkler/detector activation studies. The other half consists of residential and industrial fire reconstructions. All objects in the space in which the fire is to be simulated must respect the space division onto orthogonal 3D computational meshes composed of cells. Creating the input geometry for FDS simulations is a complicated, laborious and time-consuming process especially for complex models with several complicated components. Throughout its development, FDS has been aimed at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion (McGrattan et al., 2016).

- Pyrosim

PyroSim is a GUI developed by Thunderhead Engineering Consultants, Inc., USA in order to facilitate preparation of inputs for FDS simulations. The main functions of PyroSim cover an interactive creation of complex models (the use of ground plans, creation of multiple repetitious objects, curved walls, stairways, etc.), import of existing input FDS files, PyroSim files and CAD files (Thunderhead Engineering, 2010). PyroSim enables importing a ground plan, saving it as a background image and displaying it in its 2D or 3D View modes. The background image scale can be modified to correspond to the computational mesh chosen for intended FDS simulation. This feature greatly facilitates the creation of geometry of complicated models. In the 2D View mode, there are several useful tools for creating the basic elements and their combinations (obstructions, holes, vents, wall holes, blocks, block holes, rooms, particle clouds), which represent the input FDS geometry of objects appearing in buildings. The PyroSim interface provides immediate input feedback and ensures the correct format for the FDS input file. In summary, Pyrosim interface includes highlights such as:

- Import CAD files to create and manage complex models.
- High-level 2D and 3D geometry drawing tools.

- Integrated parallel processing.
- Flexible unit system that supports working in either metric or English units.
- Tools to manage multiple meshes.
- Multiple language translations.
- HVAC (Heating, Ventilation, and Air Conditioning) systems integrated into the CFD simulation.
- Import of existing FDS models.
- Integrated post-processing.

The current PyroSim version (PyroSim2017) includes FDS (version 6.5.3) and allows running FDS simulations (Glasa et al. 2012).

4.2 Evacuation Simulation - Pathfinder

High occupancy in areas such as buildings and ships has created a growing need to adequately address fire safety concerns. The logical way to address these concerns is by the use of Fire Safety Engineering (FSE) and a Performance Based Design approach (PBD). An evacuation analysis is very often a key part of the PBD process. To perform such an analysis engineers could use a wide range of engineering tools, from hand calculation based on hydraulic models to advanced methods. When the space to be analyzed is particularly complex, it is necessary to use advanced evacuation modeling (computational simulations tools) when conducting an evacuation analysis. Currently there are much simulation software available (over 60), each one with its specific characteristics.

Models can be categorized by their availability, overarching method of simulating occupants, purpose, type of grid/structure, perspective of the occupants, perspective of the building, internal algorithms for simulating occupant behavior and movement, the incorporation of fire effects, the use of computer-aided design drawings, visualization methods, and validation techniques. However, regardless of the software used, the user needs to establish specific modeling parameters based on his engineering judgment, which can have a significant impact on the overall results (Salgueiro et al. 2012).

- Pathfinder

The model chosen for this analysis was Pathfinder. The model is widely used in the Fire Engineering community and in the last few years, it has become one of the standard tools when it comes to evacuation modeling. Pathfinder is an agent-based egress simulator developed by Thunderhead Engineering; it uses steering behaviors to model occupant motion (Thunderhead Engineering, 2016). It consists of three modules:

- a graphical user interface,
- the simulator and
- a 3D results viewer.

Pathfinder provides two primary options for occupant motion: an SFPE mode and a steering mode. The SFPE mode implements the concepts in the SFPE Handbook of Fire Protection Engineering. This is a flow model, where walking speeds are determined by occupant density within each room and flow through doors is controlled by door width. The steering mode is based on the idea of inverse steering behaviors. Craig Reynolds first presented steering behaviors in 1999. Steering behaviors are a set of motion based reactive procedures used for navigating autonomous agents in their environment. To produce complex behaviors, e.g. flocking or queuing at a doorway, several steering behaviors can be combined with each other at a time.

Each of the basic steering behaviors is executed separately or in parallel, and the different steering goals have to be combined to one result that is passed to the locomotion layer. Example applications using steering behaviors are simulation of pedestrians, vehicles in urban environments and emergency evacuation of human crowds. One problem inherent to existing approaches to arbitrating between single steering behaviors is that their combination may lead to suboptimal, undesired, or even catastrophic results in certain situations. In order to resolve this problem inherent to steering behavior, Amor (2003) refined the steering behaviors into inverse steering behaviors. Inverse steering behaviors change the original concept of steering behaviors and facilitate improved arbitration between different options by using cost based heuristics. With inverse steering behaviors, decisions are made by evaluating costs of a discrete set of possible solutions. Pathfinder's steering mode allows more complex behavior to naturally emerge as a byproduct of the movement algorithms - eliminating the need for explicit door queues and density calculation (Salgueiro et al., 2012).

The following scheme shows the set of procedures and algorithms, which allow occupants displacement from point of origin to point of destination.

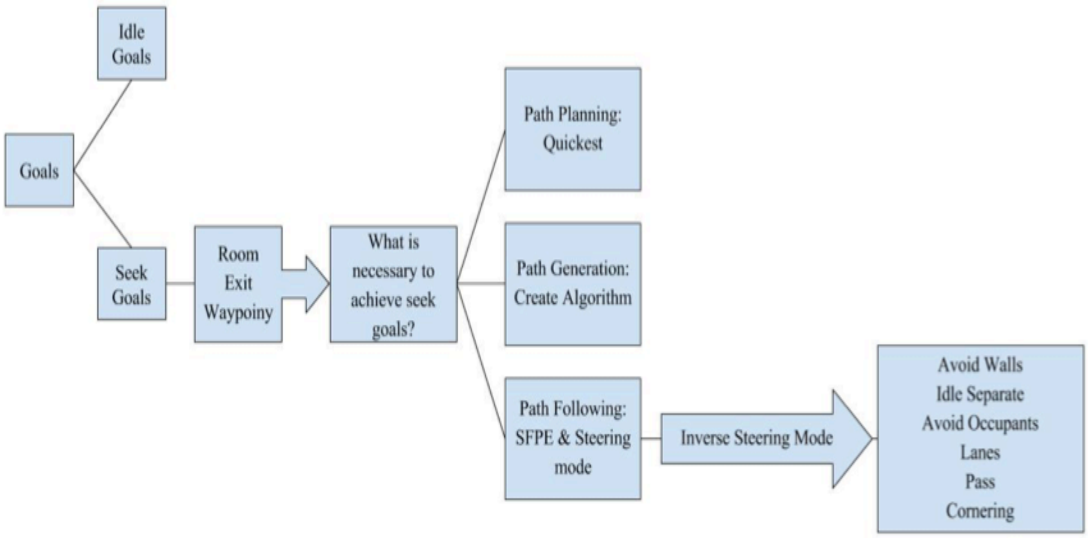

Figure 9 Occupants Displacement

5. Case Study: Passenger Ship

5.1 Simulation Parameters

In order to demonstrate the application of the fire and evacuation tools, multiple evacuation scenarios in fire conditions were simulated. The geometry of the evacuated space, details of the simulated fires and the evacuation scenarios are presented in the following sections.

- Geometrical Arrangements

Safety regulations require that a ship should be divided into vertical zones for fire protection purposes. The layout considered in this paper consists of a main vertical zone (MVZ), supposedly on deck 6. The arrangement is a typical shipboard accommodation space with passenger cabins spread along 3 long corridors as shown in figure 10.

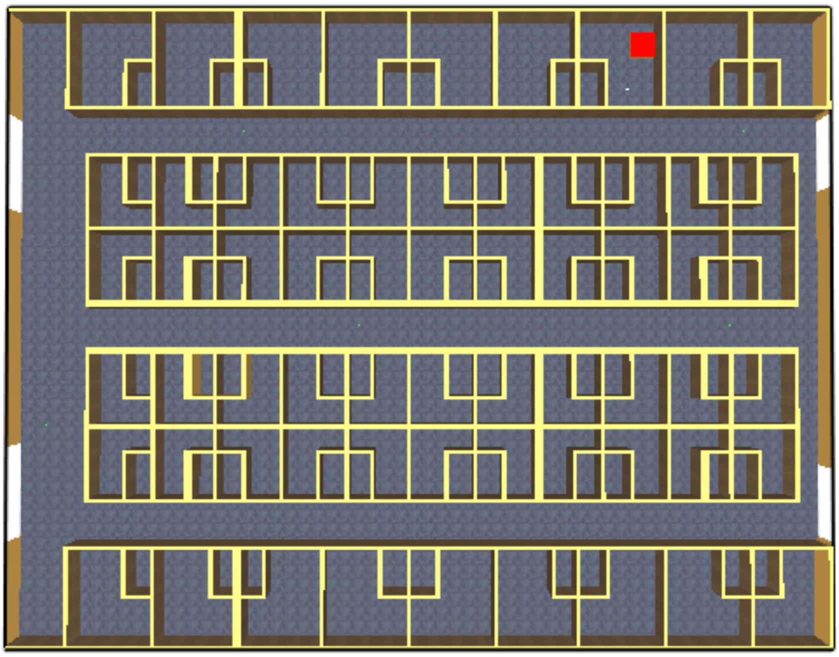

Figure 10 Main Vertical Zone

The general dimensions of the MVZ are 35 m Long 27 m Wide 2.25 m Height. There are 62 cabins, 18 of which can accommodate 4 passengers and 44 of them can accommodate 2 passengers, making it a total of 160 passengers. All the cabins follow the SOLAS instructions for designing passenger spaces, thus cabins designed for 4 passengers are 14.5 m^2 and cabins designed for 2 passengers are 8.5 m^2. The arrangement of the cabins and the total area of each cabin were created on top of an existing design. Corridors and doors were also designed according to SOLAS regulations. Therefore, corridors are at least 1.5 m wide between handrails and cabin doors at least 0.90 m wide. Fire doors are 3 m wide.

- Materials

For the materials used, the guidelines of SOLAS and FSS were adopted. Thus, PVC material is used for the covering of the walls, while the inner allows heat transfer. The floor covering is governed by the same properties as a wool carpet, with a high flashover temperature point in order to prevent extension of fire.

For the furnishing, an average of the materials used in a cabin, were considered (see Table 4).

Table 3 Generic groups of combustible materials in cabin (Source: Spyrou et al., 2013)

Materials	%Contribution	Average heat of combustion (MJ/kg)	Yield CO (g/g)	Yield CO_2 (g/g)	Yield soot (g/g)
Textiles	28.0%	22.5	0.051	1.420	0.065
Wood based	34.0%	17.33	0.004	1.280	0.015
Plastics	38.0%	24.81	0.046	1.832	0.081
Average	100%	21.62	0.0331	1.529	0.0541

- Fire Characteristics

Two main factors were to be calculated in order to create the necessary fire, the elements of the reaction and the characteristics of the heat release. So as to simulate a realistic reaction, an average of the characteristics of materials used in a cabin was selected, as shown in table 5.

For the heat release, the Heat Release Rate per Unit Area model was used. That being, two different scenarios were examined, a moderate fire of 1400 kW HRRPUA and an extreme fire of 1800 kW HRRPUA according to the basic scenarios chosen and demonstrated in the study on fire safety assessment of passenger ships by Spyrou et al. in 2013 (see figure 11). For both scenarios the fraction used is shown in the table 5.

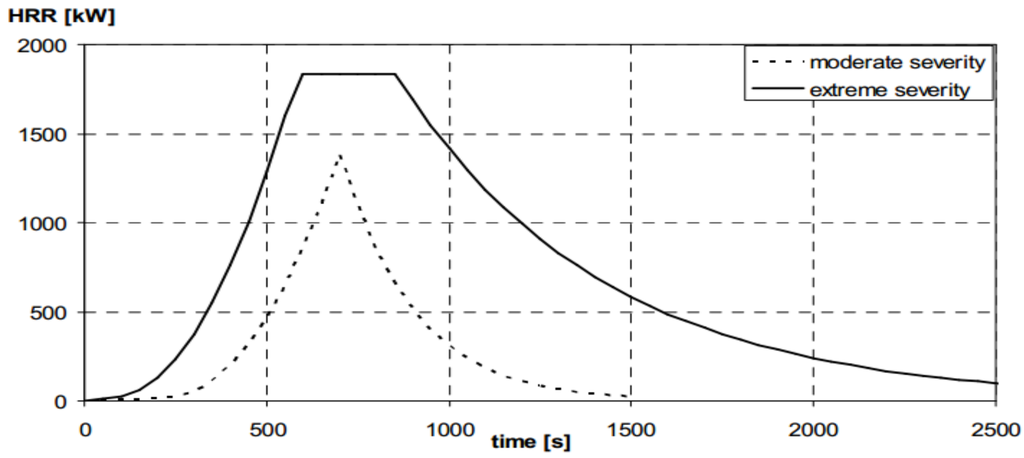

Figure 11 HRR depending on severity (Source: Spyrou et al., 2013)

Table 4 Fraction Times

Time (s)	Fraction
0.0	0.0
179.0	0.065
333.0	0.271
500.0	0.726
533.0	1.0
750.0	1.0

➢ Population

For the population, the general guidelines proposed by IMO on evacuation analysis for passenger ships (MSC.1/Circ.1238) were used. Therefore, the composition of the population, the speed of passengers and the awareness time are based on the IMO guidelines (see table 6). It must be stated, that these guidelines are not referring to evacuation scenarios with the presence of fire, but their parameters can also be used in such cases. Due to small differences in speeds of passengers, in this study only 2 different groups will be examined (see table 7).

Table 5 IMO population's composition (Source: MSC.1/Circ.1238)

Passengers	Percentage of passengers (%)
Females younger than 30 years old	7
Females 30-50 years old	7
Females older than 50 years old	16
Females older than 50 years, mobility impaired	20

Males younger than 30 years old	7
Males 30-50 years old	7
Males older than 50 years old	16
Males older than 50 years, mobility impaired	20

Table 6 Present study's population composition

Passengers	Percentage of passengers (%)	Number of passengers
Females, no mobility impaired	30	48
Females, mobility impaired	20	32
Males, no mobility impaired	30	48
Males, mobility impaired	20	32

- Evacuation

According to IMO there should be two different main scenarios simulating the evacuation of passengers: one day case and one night case. The difference between the two cases is the awareness time. Following the guidelines the awareness time for the day case should be 5 minutes from the time the alarm sets off and 10 minutes for the night case, which are also used in this research.

The maximum unhindered travels proposed by IMO, are those derived from data published by Ando (1988), which provides male and female walk rates as a function of age. These are distributed according to figure 12 below.

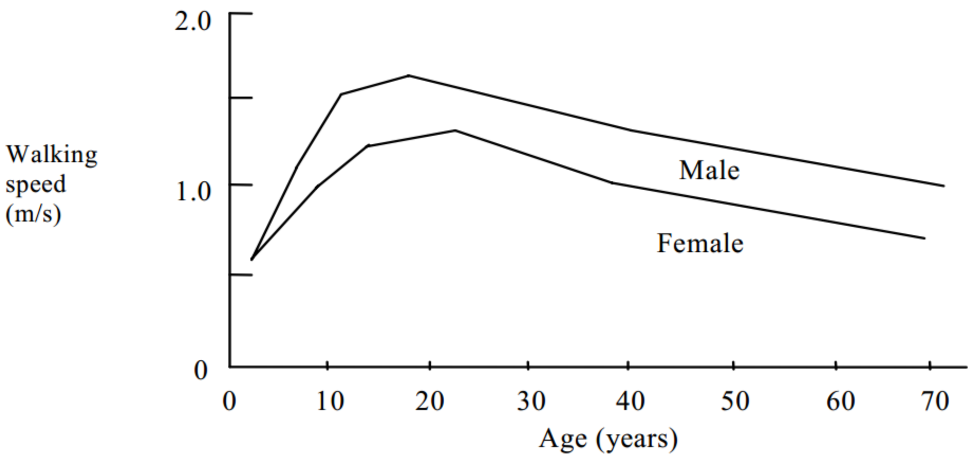

Figure 12 Walking speeds as a function of age and gender (Source: MSC.1/Circ.1238)

Therefore, according to the groups described before, the minimum and maximum values of walking speeds to be modeled as a statistical uniform distribution, and referred in table 8. In this research, the speeds used vary due to multiple different scenarios and will be stated therefore in each different simulation.

Table 7 Speeds according to gender and age (Source: MSC.1/Circ.1238)

Passengers	**Walking Speed**	
	Minimum (m/s)	**Maximum (m/s)**
Females younger than 30 years old	0.93	1.54
Females 30-50 years old	0.71	1.19
Females older than 50 years old	0.56	0.94
Females older than 50 years, mobility impaired	0.4	0.65
Males younger than 30 years old	1.11	1.85
Males 30-50 years old	0.97	1.62
Males older than 50 years old	0.84	1.4
Males older than 50 years, mobility impaired	0.60	1.0

- FED and Smoke Detectors

In order to calculate the quantity of toxic gases produced during the simulation, several devices were placed in crucial positions, such as close to the exits, near the cabin of initial ignition and in corners where air is not circulating fast enough. Smoke detectors where also used in the cabin of initial ignition in order to start the alarm system. Slices were used throughout the geometry at a height of 1m in order to measure temperature, visibility and HRR. The specific positions of detectors are shown in figure 13.

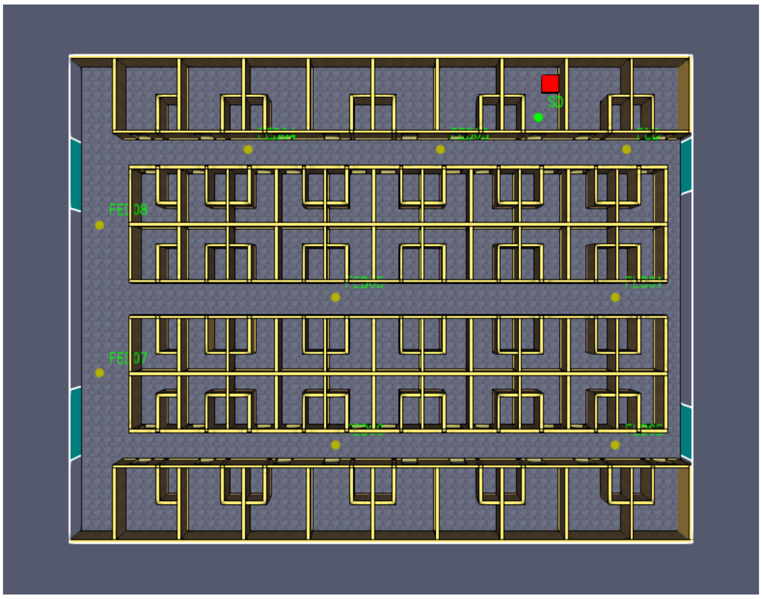

Figure 13 Positions of FED & smoke detectors

- ➢ Location of Fire

For simplicity reasons, the fire locations are represented by numbers, indicating the different scenarios, as shown in the figure 14 below.

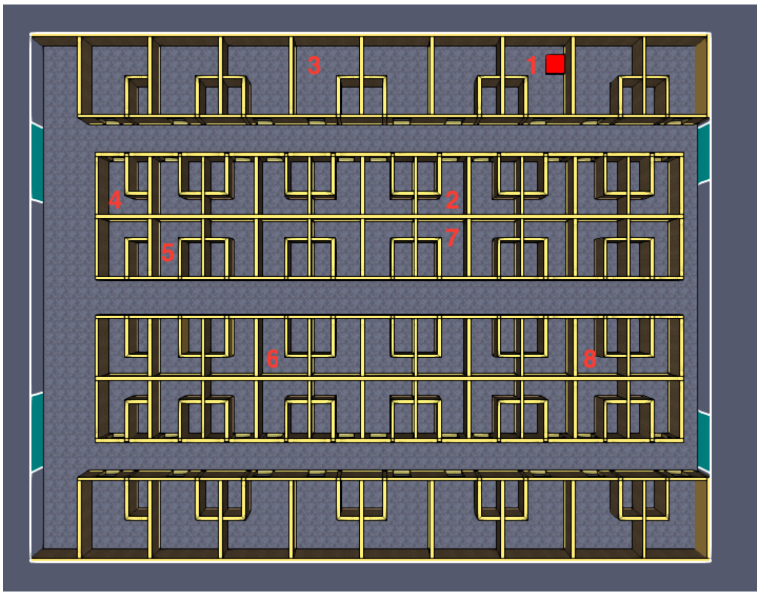

Figure 14 Position of fires

5.2 Assumptions

Certain assumptions were made throughout the simulation, those being:

- All fire extinguishing measures fail to work
- When the smoke detector sets the alarm, all doors open
- Passengers on the cabin where the fire breaks out, have an awareness time of 1 minute less than the others
- Population is randomly placed into cabins, and does not change throughout the different simulations

- All passengers choose the path that leads them to the closest exit, regardless of the presence of smoke or high temperatures
- Smoke or high temperatures does not affect the speed of the passengers

In order to facilitate understanding of the results and space efficiency, images have been used for the presentation. These results were taken out of experimental data and then exported into a different excel file for each passenger, with information about the position, HRR, temperature, visibility and FED values for every second of the simulation.

6. Evaluation of Different Fire Locations

As mentioned above, two different intensities of fire will be simulated. Each fire will be examined in 8 different cabins in order to have a greater understanding of the results to be excluded, summing it up to 16 different cases. Furthermore, in each cabin a standard day evacuation scenario and a standard night evacuation scenario will be simulated. Each simulation needs approximately 400 seconds to complete in the day scenarios and 700 seconds to complete in the night scenarios.

6.1 Moderate fire simulation

For each evacuation scenario visibility and temperature concentration are displayed right before the evacuation starts and before the last passengers have reached the exit, at the heights of 1 m and 1.5 m respectively. As the color scale shows, for the visibility red indicates high visibility while blue indicates zero visibility. For temperature the colors are reversed as blue indicates cold and red indicates hot zones.

On the day scenarios below, the first snapshot is taken 300s after the alarm has gone off (referred as snapshot A) and the second snapshot is taken 1 minute later (referred as snapshot B), which is the time needed for evacuation to be completed. On the night scenarios, the first snapshot is taken 600s after the alarm has gone off and the second one minute later.

6.1.1 Scenario Cabin no 1

In this simulation there is a moderate fire breakout in a 4-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in the following diagrams.

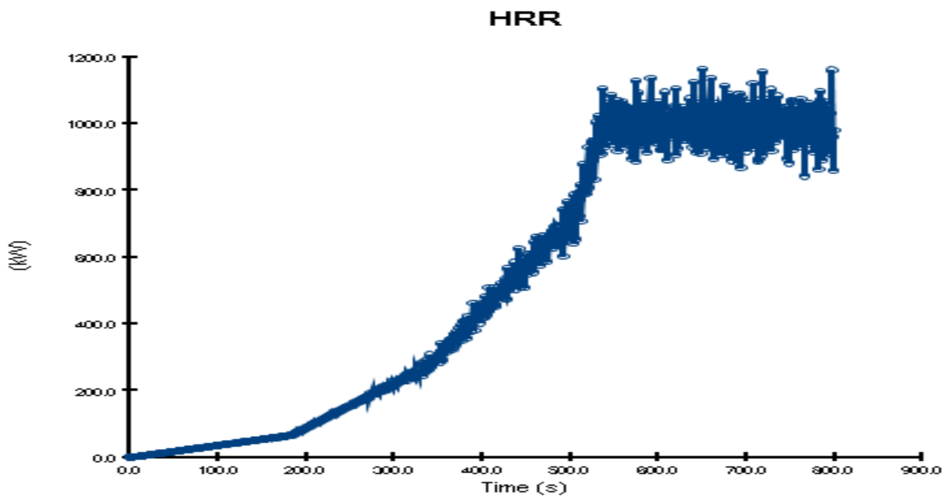

Figure 15 Heat Realease Rate, Moderate Fire, Scenario 1

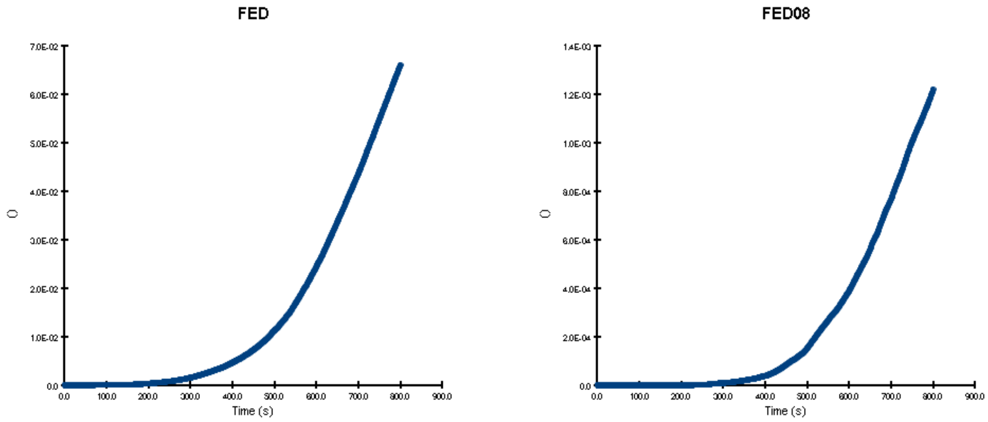

Figure 16 FED Indicators 0 & 8, Moderate Fire, Scenario 1

- Day Scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire breaks through leading to almost zero visibility, and incapacitation of the passengers of that cabin. The cabins close to that one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

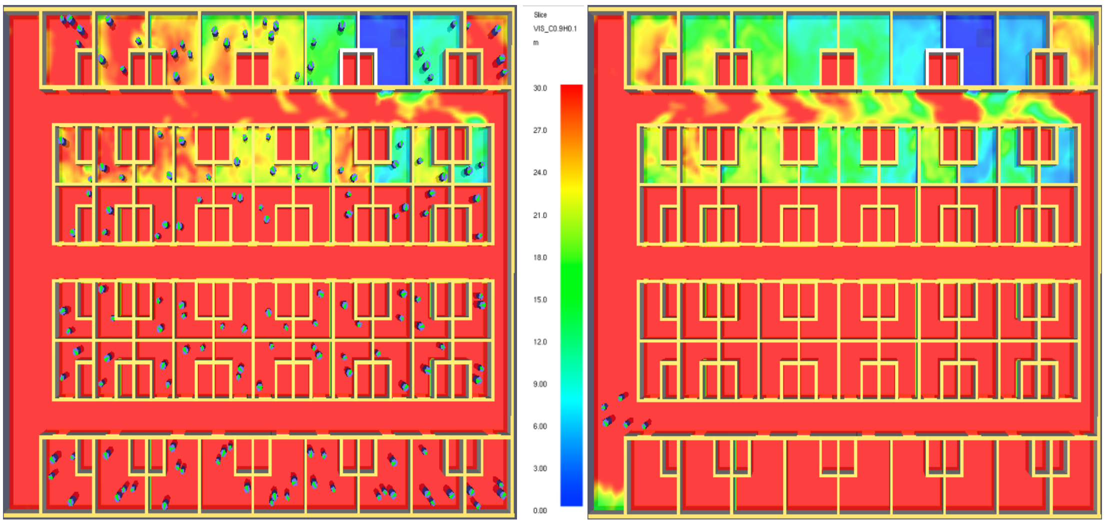

Figure 17 Visibility Day Scenario 1, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to that one but not in a way to cause incapacitation.

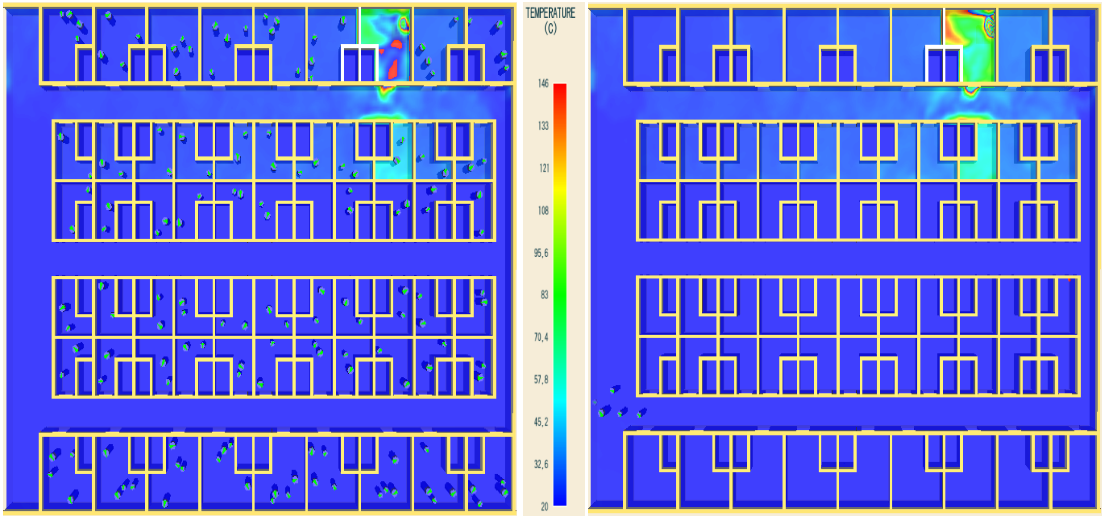

Figure 18 Temperature Day Scenario 1, Moderate Fire, Snapshots A & B

Results
In this scenario, 2 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night Scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 16 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 6 more deaths.

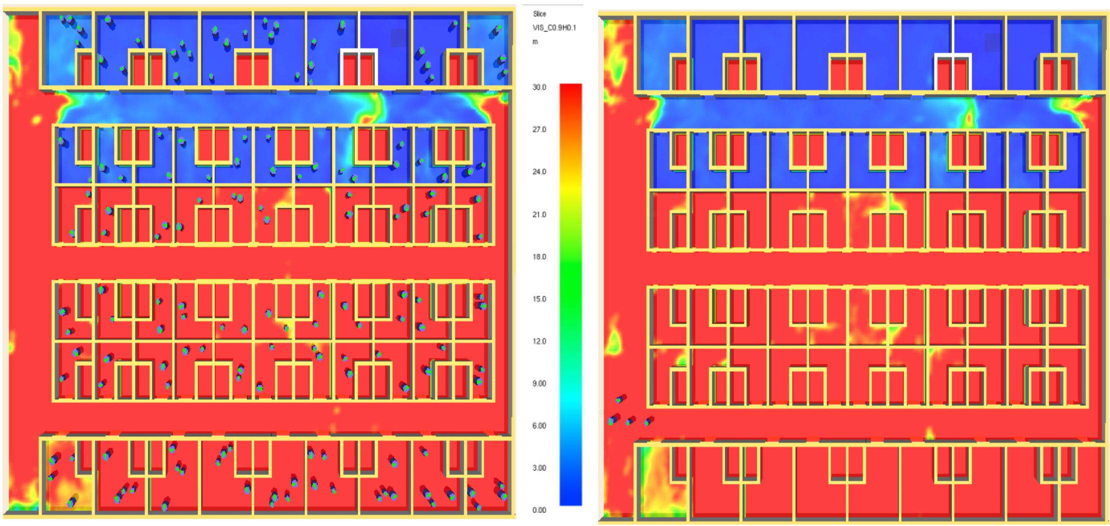

Figure 19 Visibility Night Scenario 1, Moderate Fire, snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire and the cabin opposite to that one but not in a way to cause incapacitation.

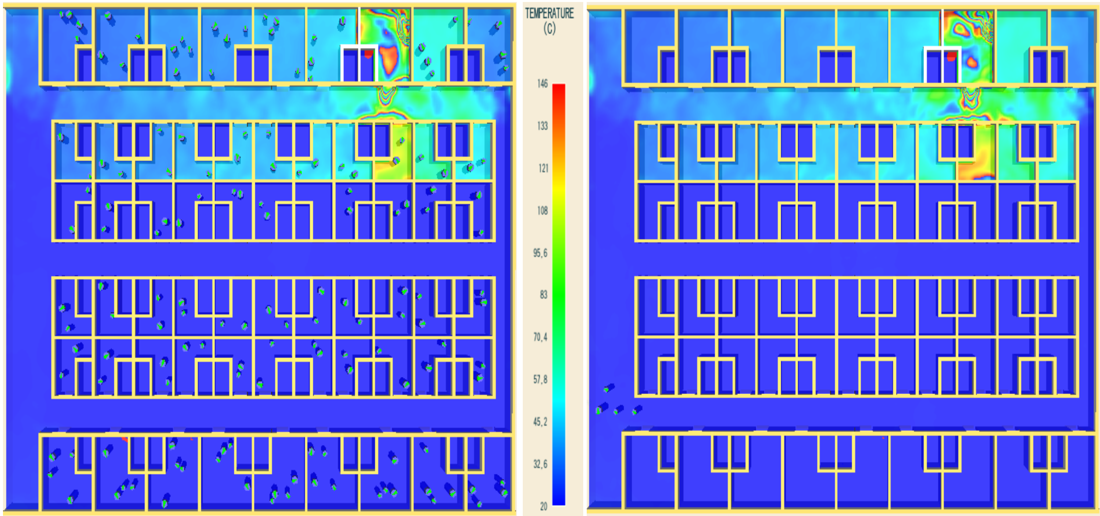

Figure 20 Temperature Night Scenario 1, Moderate Fire, Snapshots A & B

Results

In this scenario, 56 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

6.1.2 Scenario cabin no2

A moderate fire breakout in a 2-passenger cabin is simulated in this case. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below.

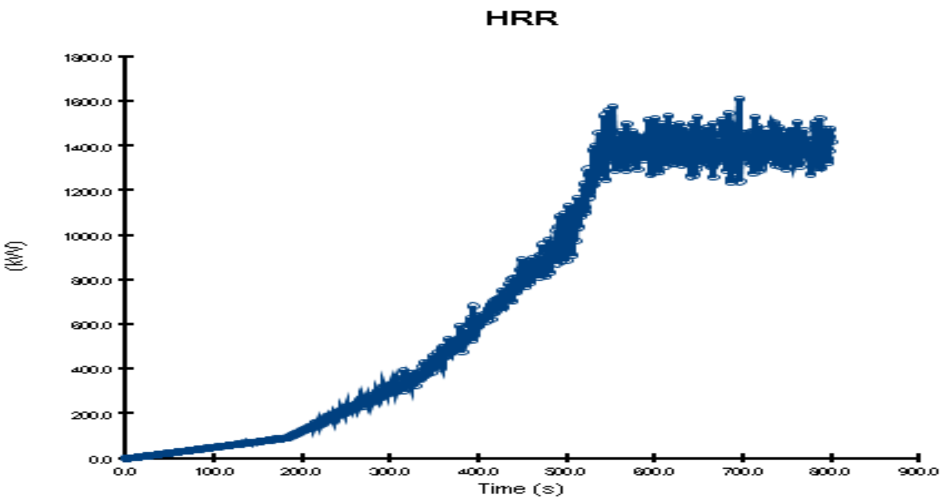

Figure 21 Heat Release Rate, Moderate Fire, scenario 2

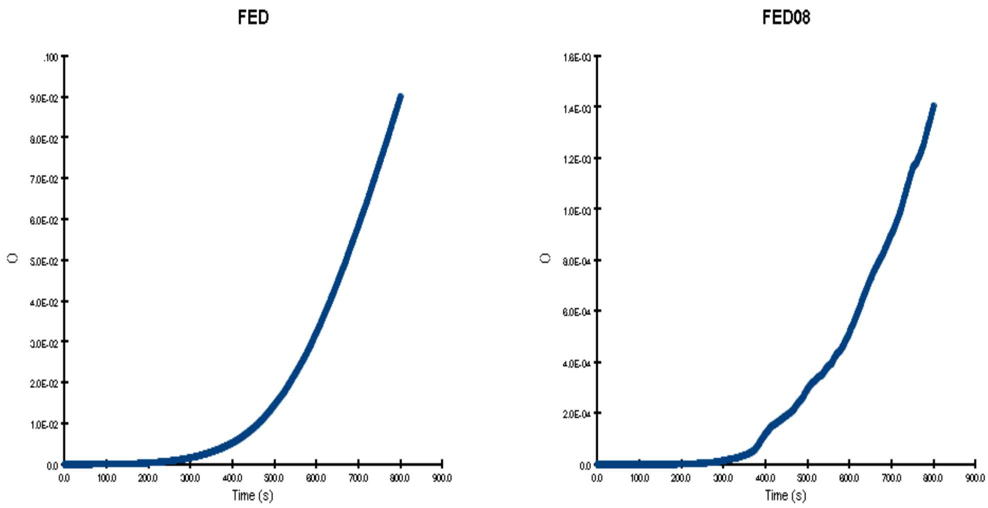

Figure 22 FED 0 & 8, Moderate Fire, Scenario 2

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the cabin opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabin. The cabins close to these ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

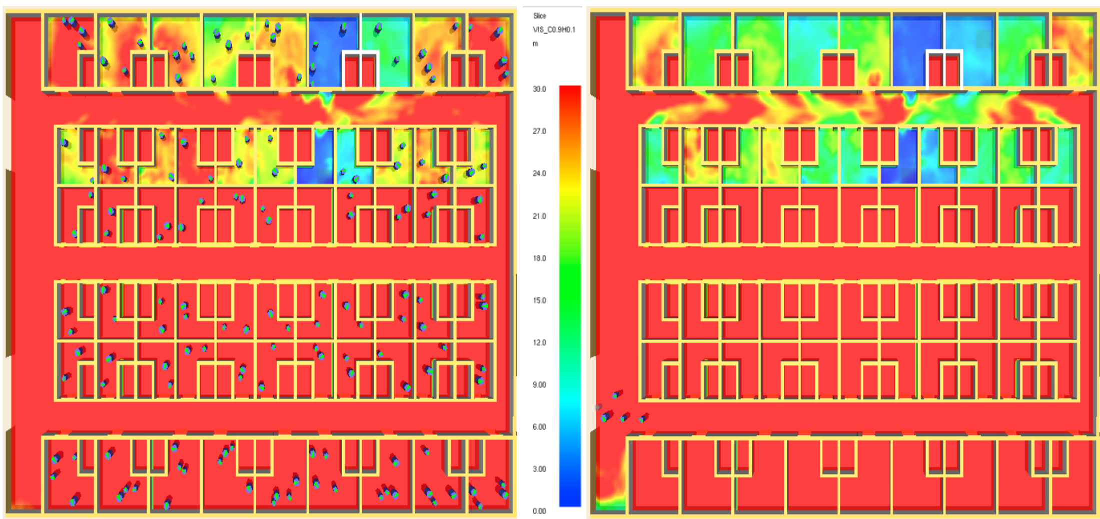

Figure 23 Visibility Day Scenario 2, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to that one but not in a way to cause incapacitation.

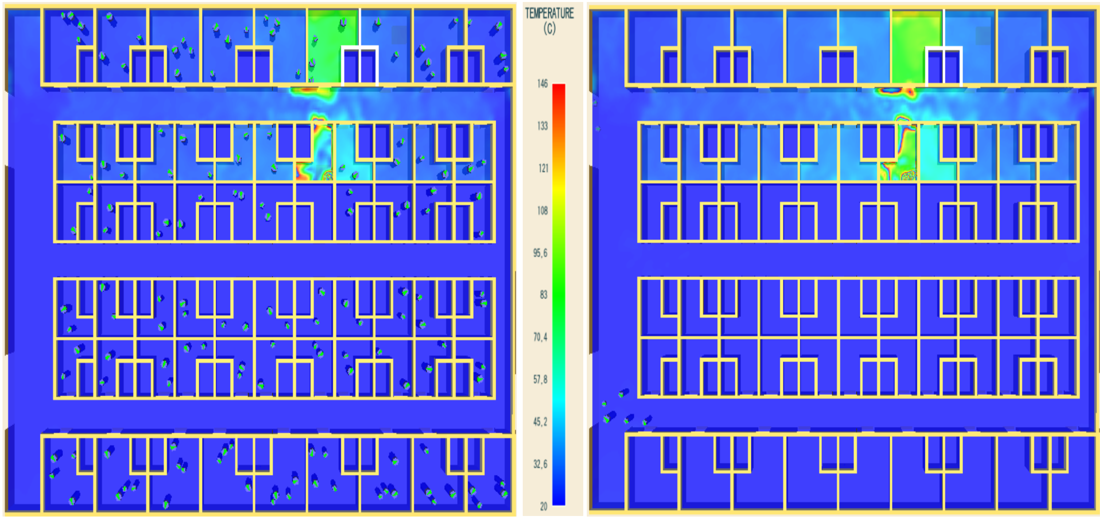

Figure 24 Temperature Day Scenario 1, Moderate Fire, Snapshots A & B

Results

In this scenario, 2 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 16 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 4 more deaths.

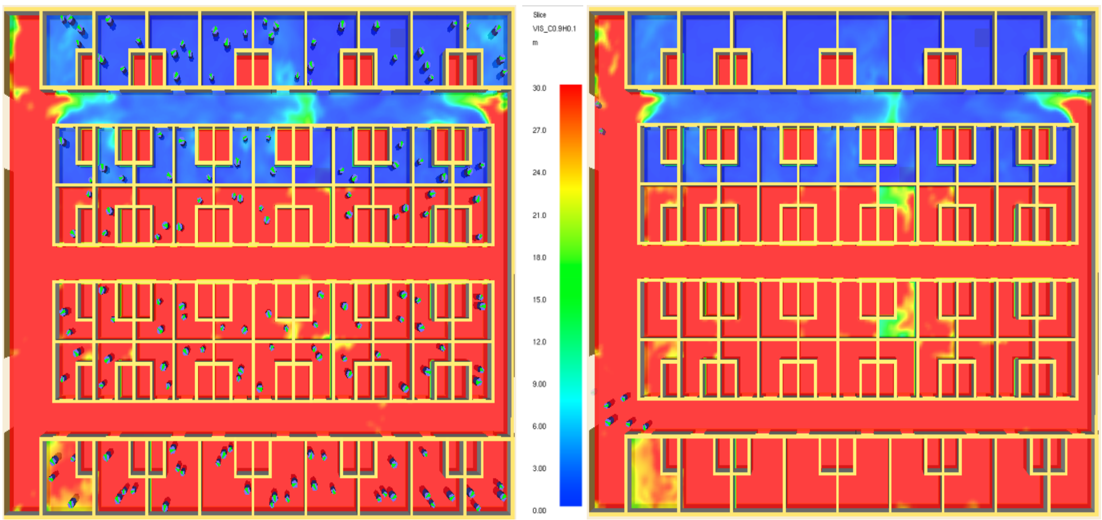

Figure 25 Visibility Night Scenario 1, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to that one but not in a way to cause incapacitation.

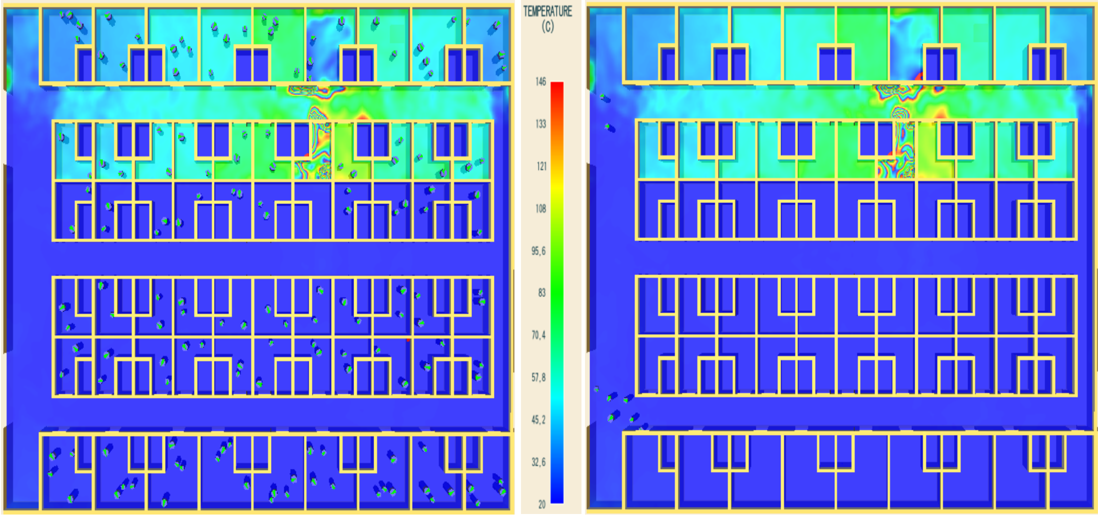

Figure 26 Temperature Night Scenario 1, Moderate Fire, Snapshots A & B

Results

In this scenario, 56 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

6.1.3 Scenario cabin no3

In this case, there is a moderate fire breakout in a 4-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below.

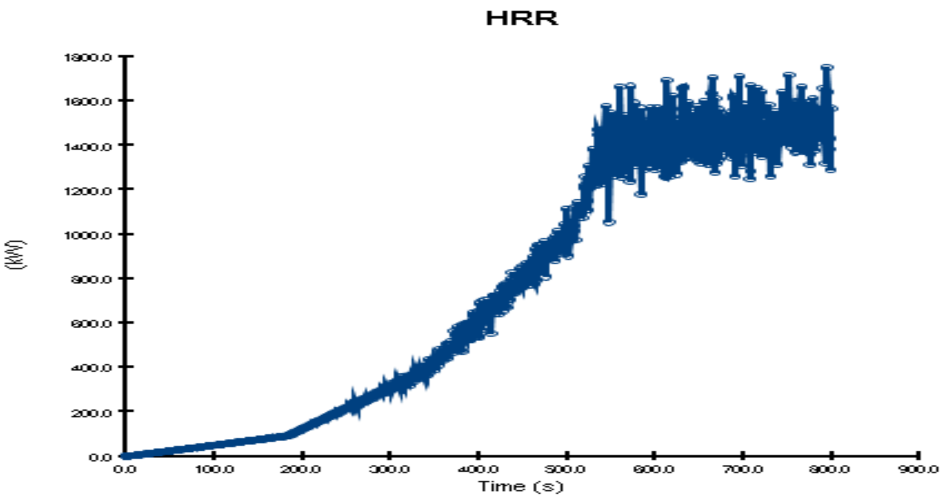

Figure 27 Heat Release Rate, Moderate Fire, scenario 3

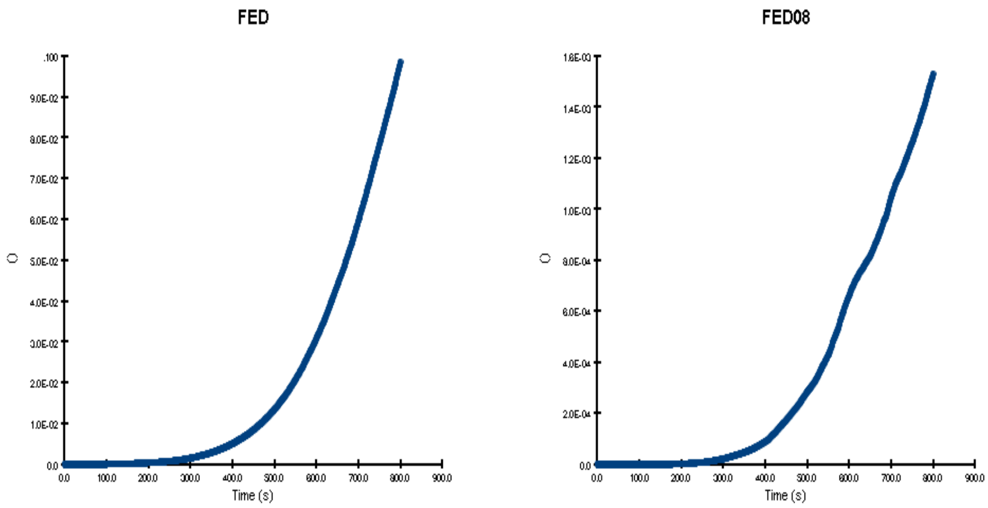

Figure 28 FED 0 & 8, Moderate Fire, Scenario 1

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out, leading to almost zero visibility, and incapacitation of the passengers of the cabin. The cabins close to that one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

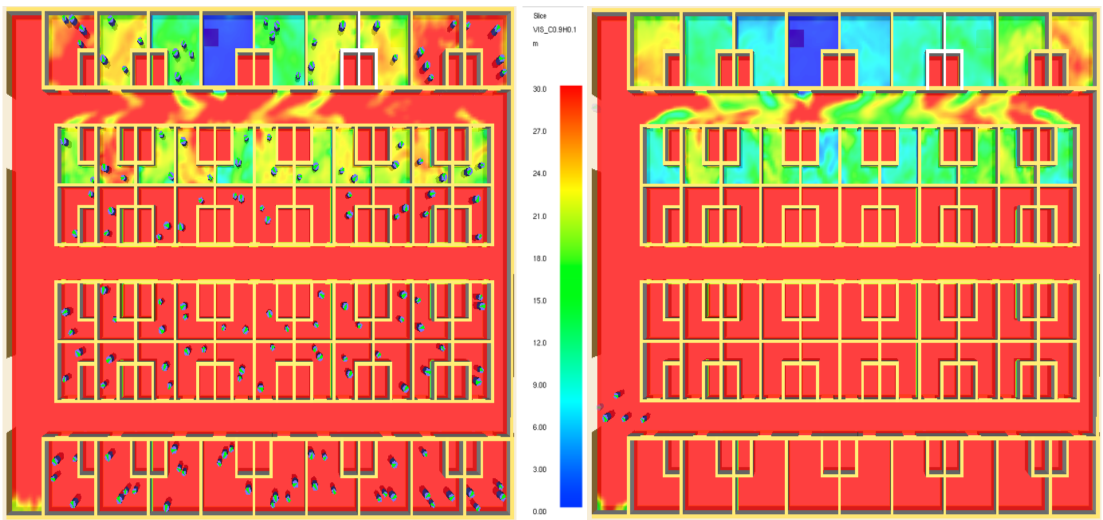

Figure 29 Visibility Day Scenario 3, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to, causing temperatures above 100 ^{0}C which lead to incapacitation.

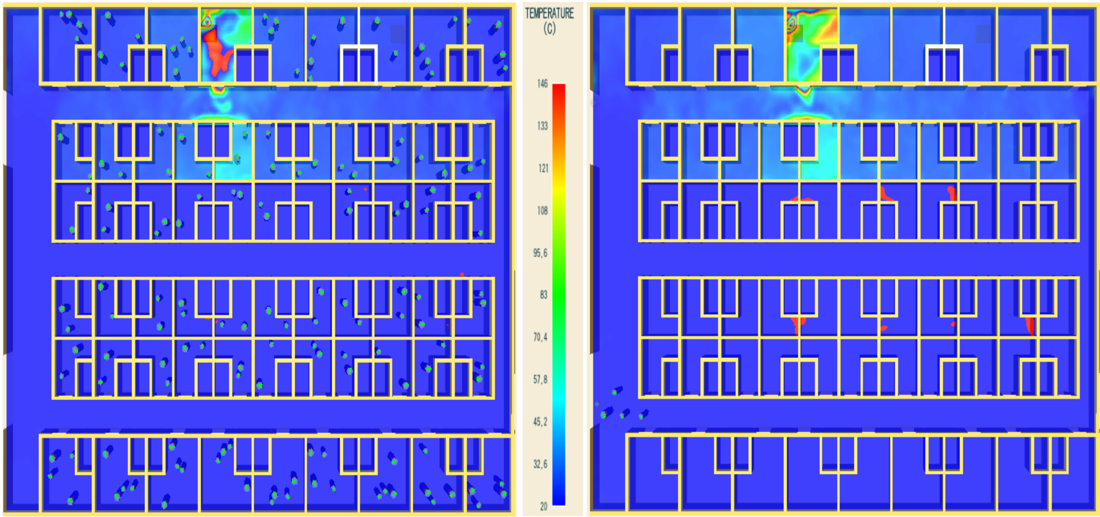

Figure 30 Temperature Day Scenario 3, Moderate Fire, Snapshots A & B

Results
In this scenario, 4 passengers did not manage to escape due to poor visibility and high temperature. FED quantities did not hinder the evacuation process.

- Night scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 16 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 6 more deaths.

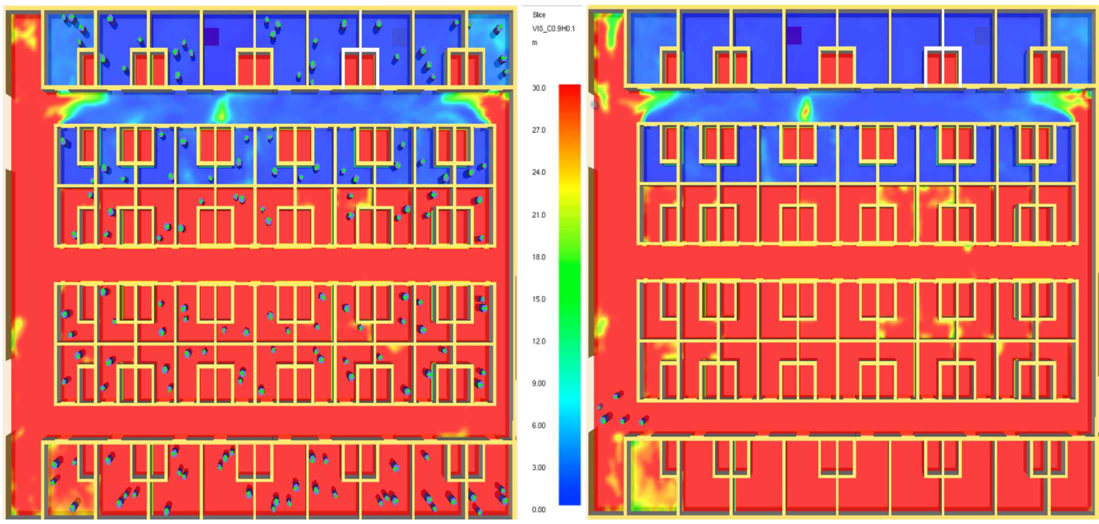

Figure 31 Visibility Night Scenario 3, Moderate Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire and the cabin opposite to, causing temperatures above 100 ^{0}C which lead to incapacitation.

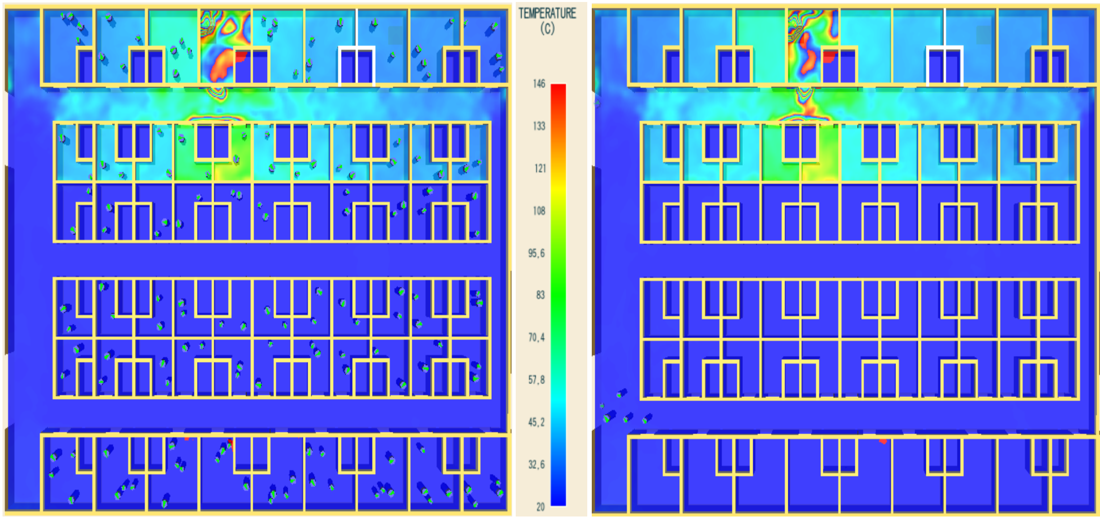

Figure 32 Temperature Night Scenario 3, Moderate Fire, Snapshots A & B

Results
In this scenario, 50 passengers did not manage to escape due to poor visibility, 4 of who were also affected by high temperature. FED quantities did not hinder the evacuation process.

6.1.4 Scenario cabin no4

In this simulation, there is a moderate fire breakout in a 2-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below.

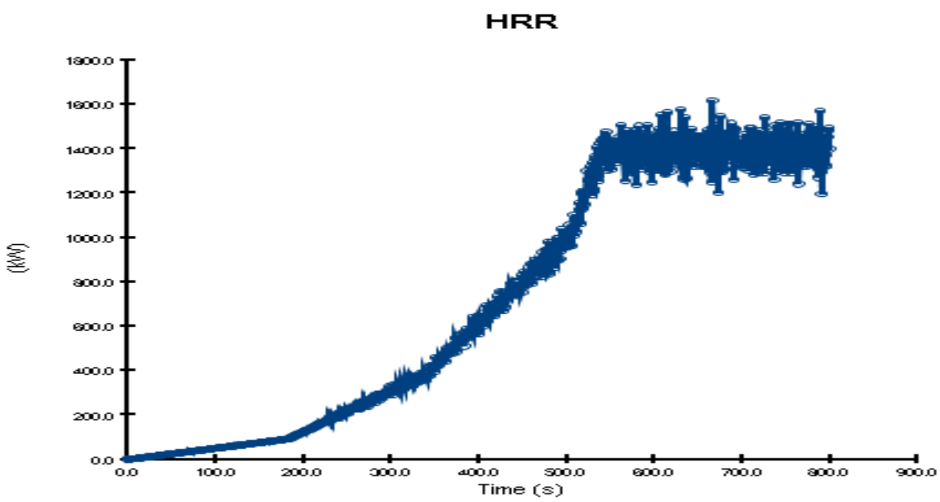

Figure 33 Heat Release Rate, Moderate Fire, Scenario 4

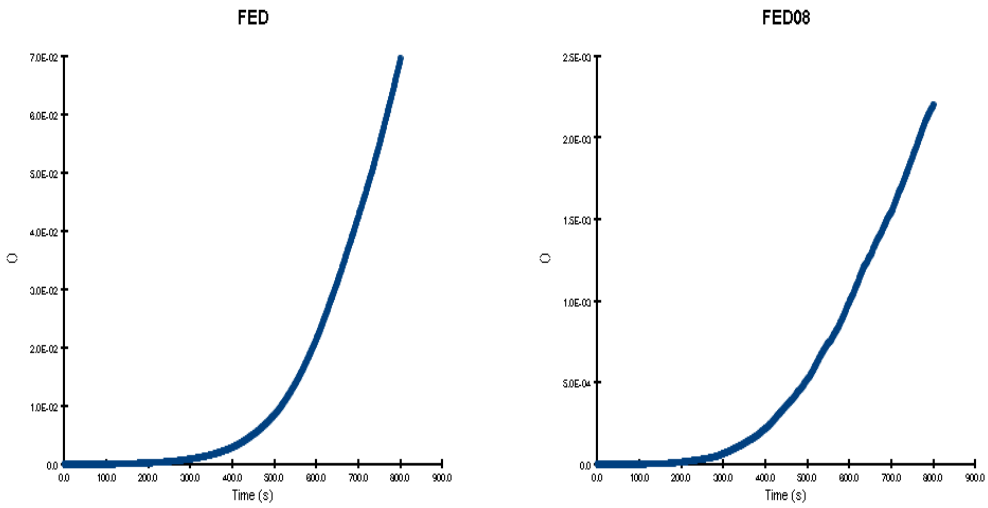

Figure 34 FED 0 & 8, Moderate Fire, Scenario 4

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the fire opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabins. The cabins close to these ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

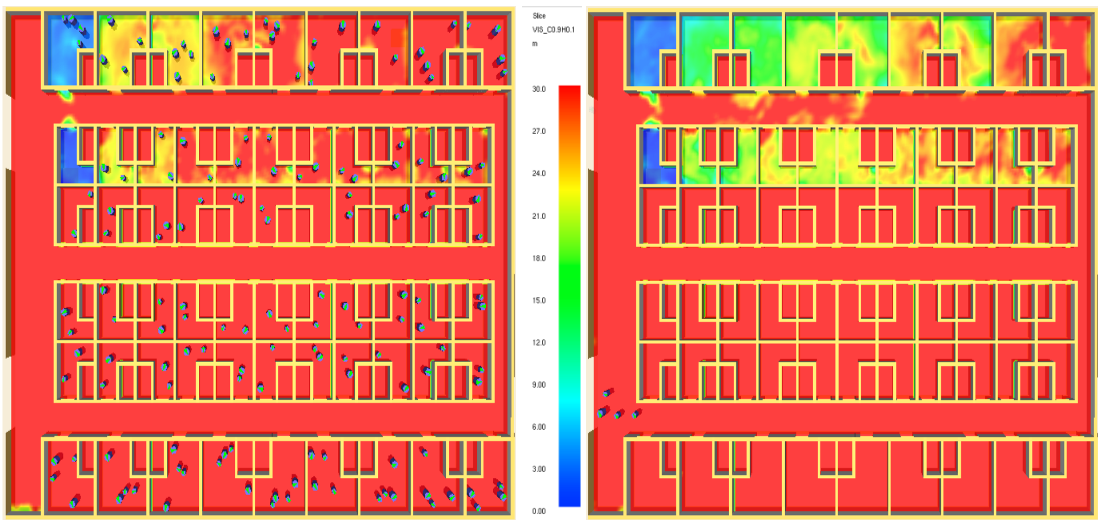

Figure 35 Visibility Day Scenario 4, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to that one but not in a way to cause incapacitation.

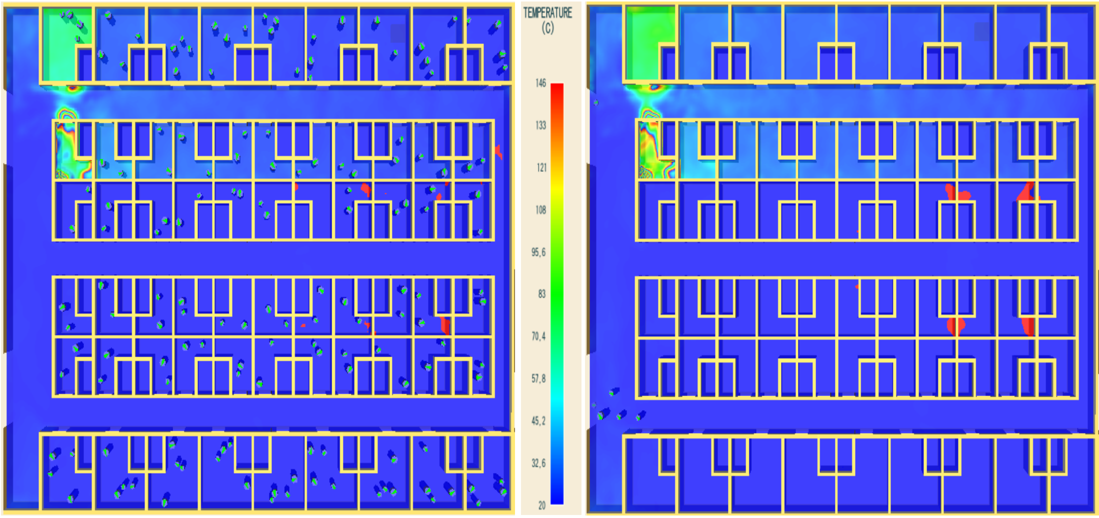

Figure 36 Temperature Day Scenario 4, Moderate Fire, Snapshots A & B

Results

In this scenario, 6 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night Scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 17 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also minimized visibility, which affects the evacuation process leading to 6 more deaths.

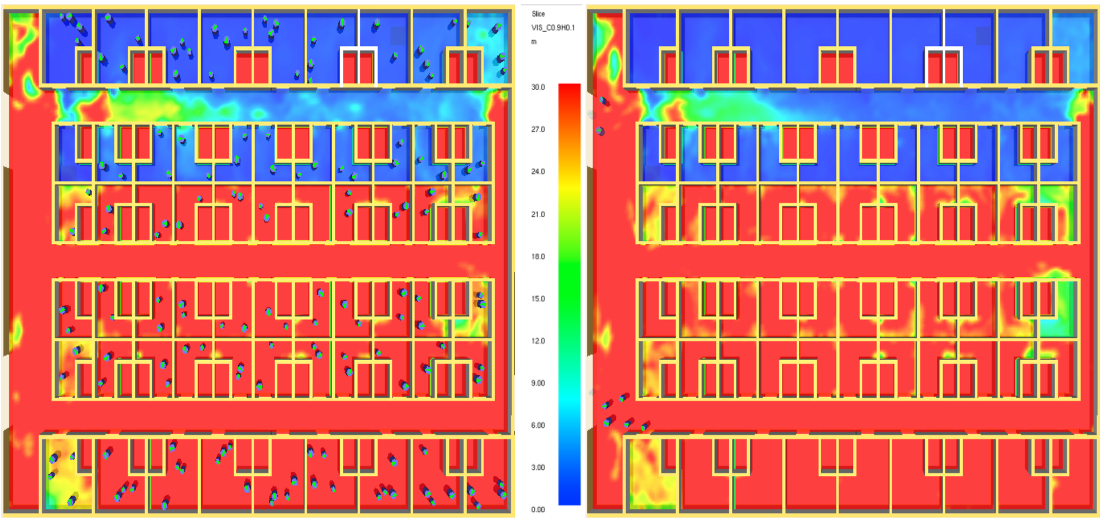

Figure 37 Visibility Night Scenario 4, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to, causing temperatures above 100 ⁰C which lead to incapacitation.

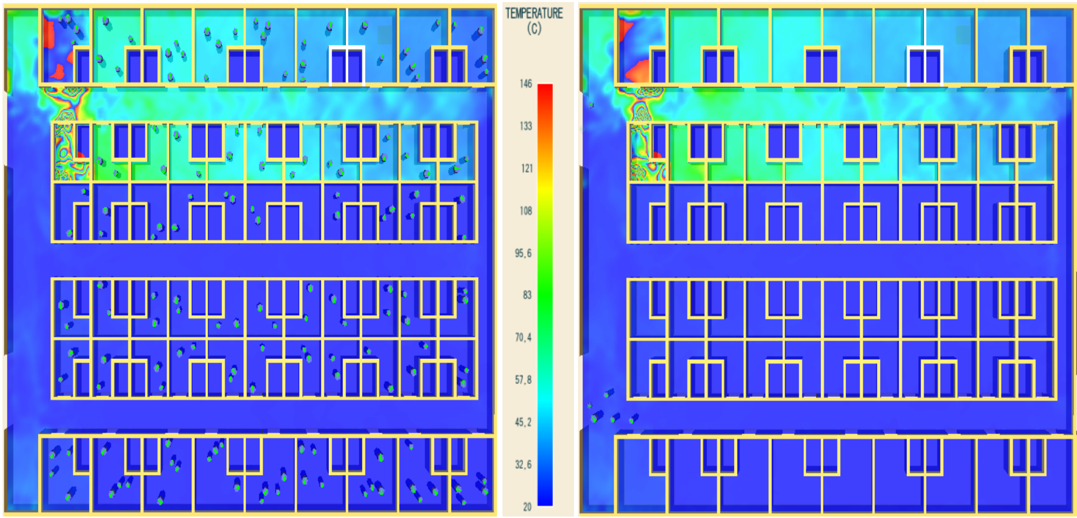

Figure 38 Temperature Night Scenario 4, Moderate Fire, Snapshots A & B

Results
In this scenario, 56 passengers did not manage to escape due to poor visibility, 6 of who were also affected by high temperature. FED quantities did not hinder the evacuation process.

6.1.5 Scenario cabin no5

A moderate fire breakout in a 2-passenger cabin is being simulated in this case. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below.

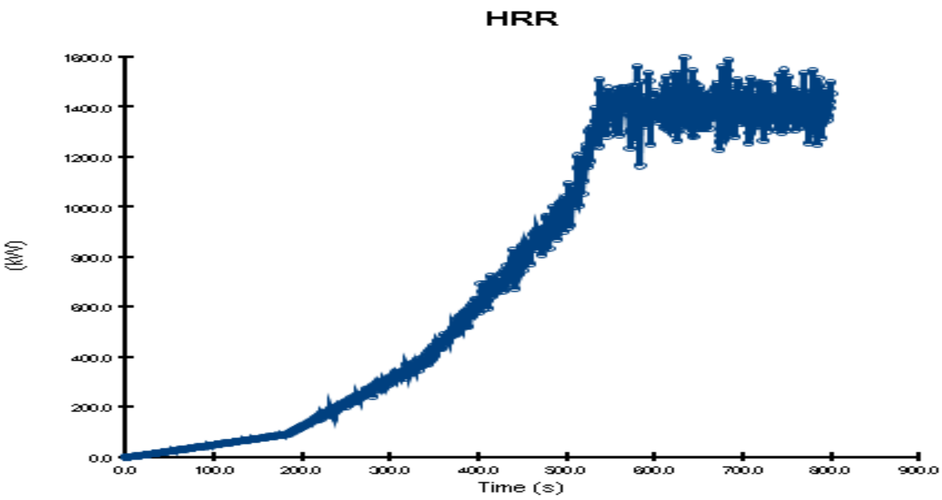

Figure 39 Heat Release Rate, Moderate Fire, Scenario 5

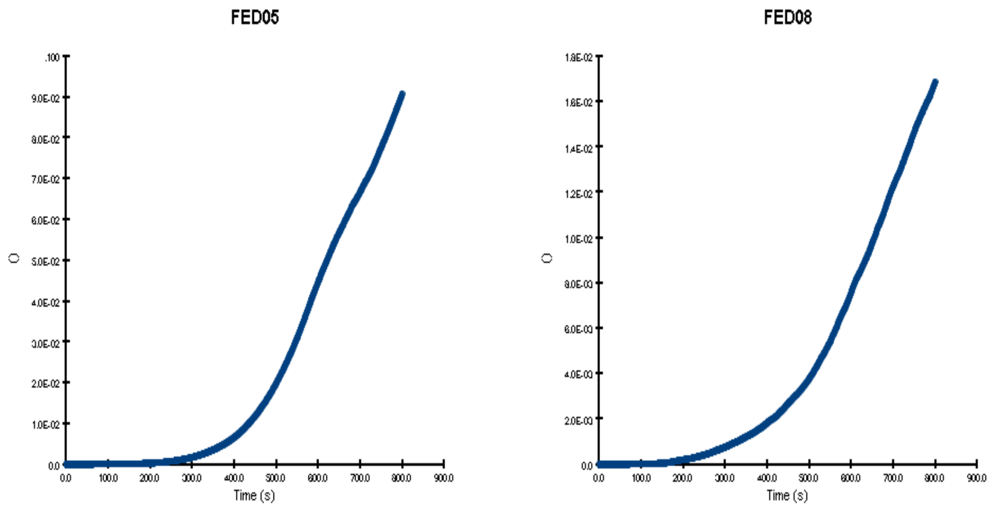

Figure 40 FED 5 & 8, Moderate Fire, Scenario 5

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out leading to almost zero visibility, and incapacitation of the passengers of that cabin. The cabins close to that one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

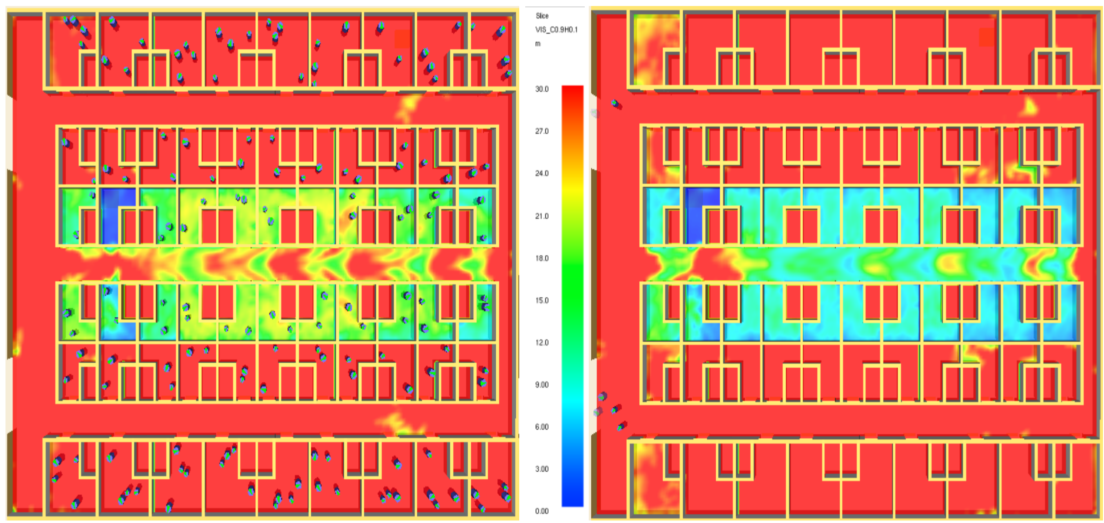

Figure 41 Visibility Day Scenario 5, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to that one but not in a way to cause incapacitation.

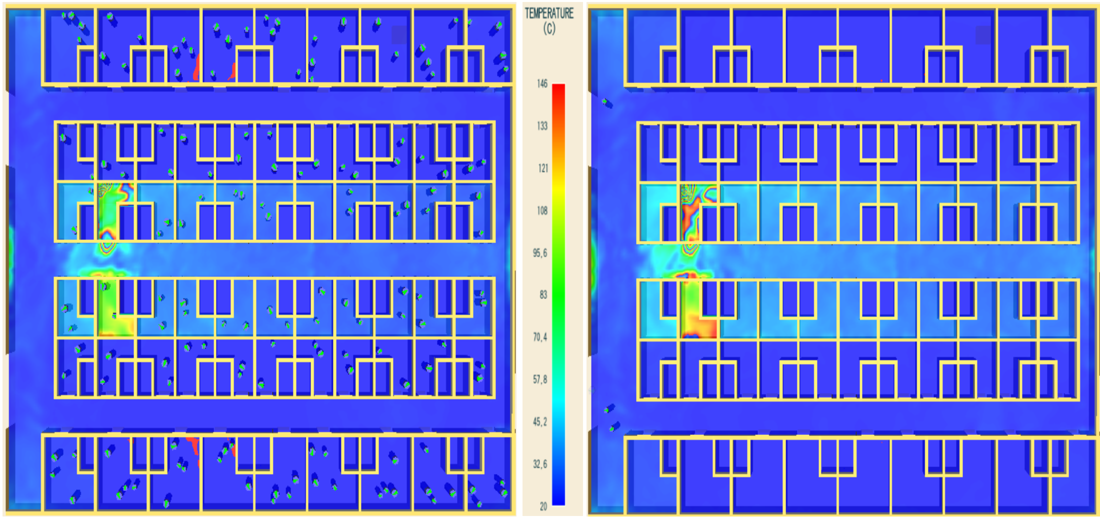

Figure 42 Temperature Day Scenario 5, Moderate Fire, Snapshots A & B

Results
In this scenario, 2 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

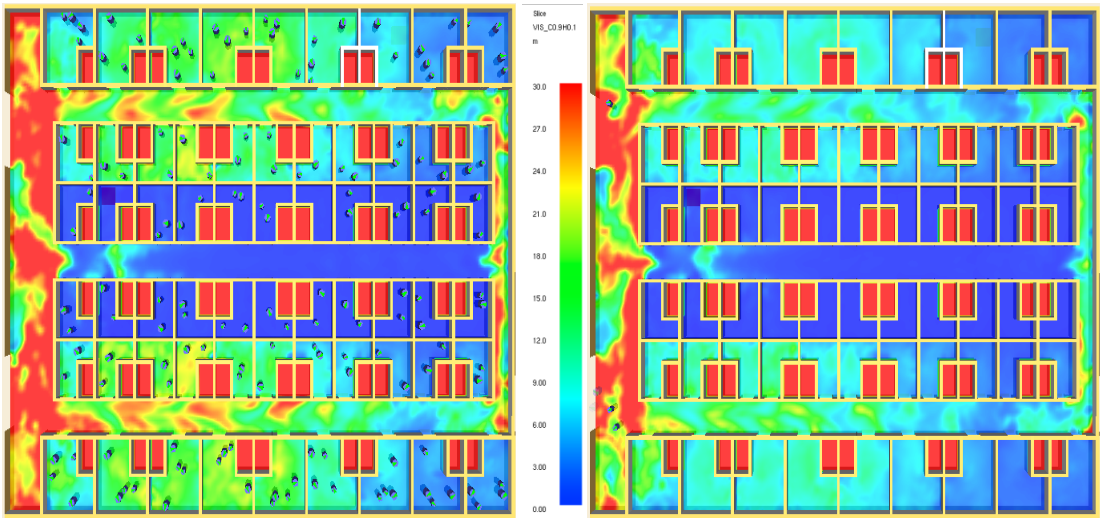

Figure 43 Visibility Night Scenario 5, Moderate Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire and the cabin opposite to, causing temperatures above 100 ^{0}C, which lead to incapacitation.

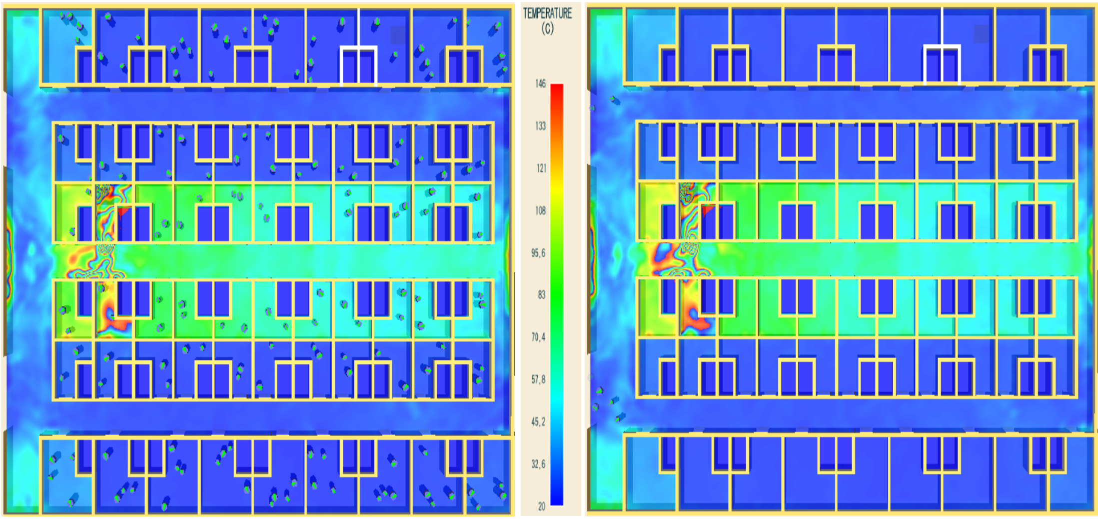

Figure 44 Temperature Night Scenario 5, Moderate Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility, 4 of who were also affected by high temperature. FED quantities did not hinder the evacuation process.

6.1.6 Scenario cabin no6

In this simulation there is a moderate fire breakout in a 2-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below.

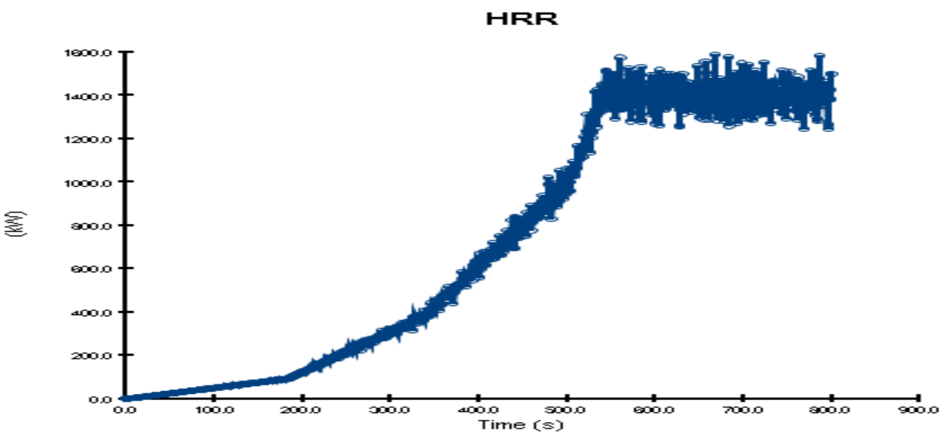

Figure 45 Heat Release Rate, Moderate Fire, Scenario 6

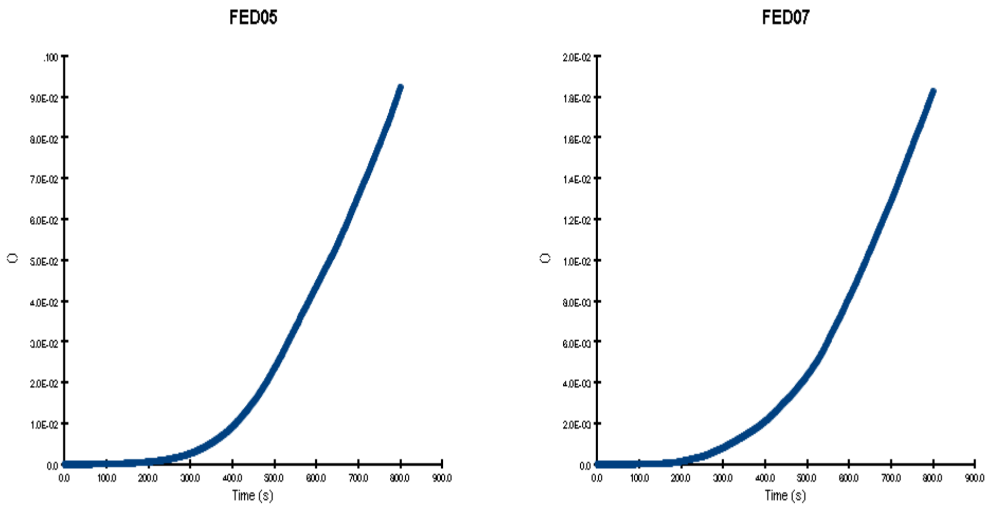

Figure 46 FED 5 & 7, Moderate Fire, Scenario 6

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out leading to almost zero visibility, and incapacitation of the passengers of that cabin. The cabins close to that one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

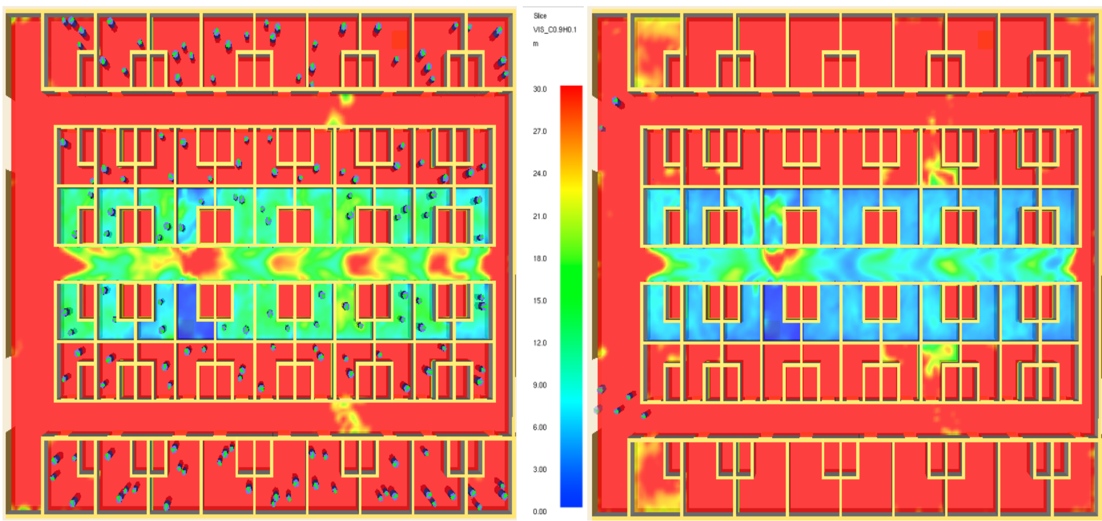

Figure 47 Visibility Day Scenario 6, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire causing incapacitation due to high temperatures. The cabin opposite to that one is also affected but not in a way to cause incapacitation.

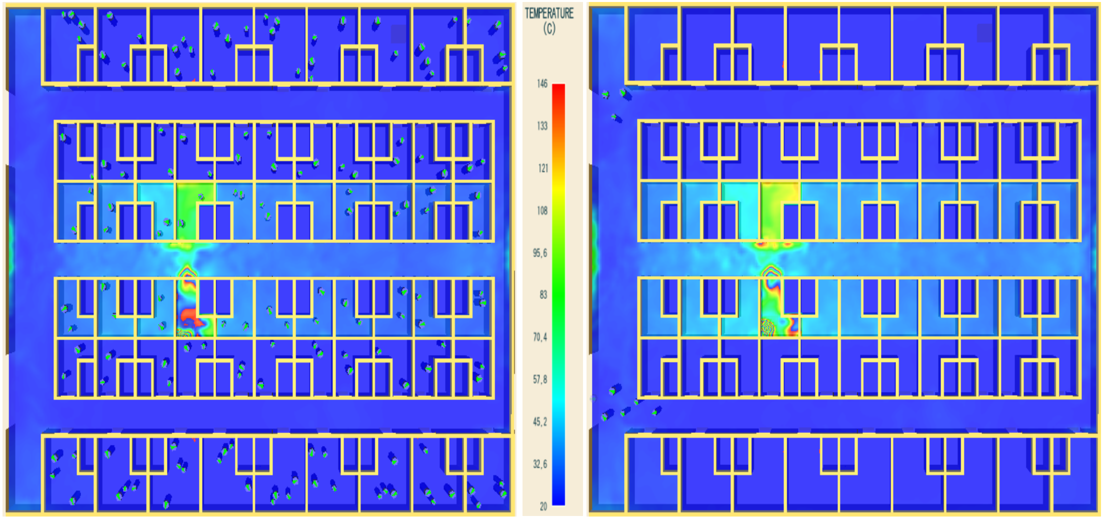

Figure 48 Temperature Day Scenario 6, Moderate Fire, Snapshots A & B

Results

In this scenario, 2 passengers did not manage to escape due to poor visibility and high temperature. FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

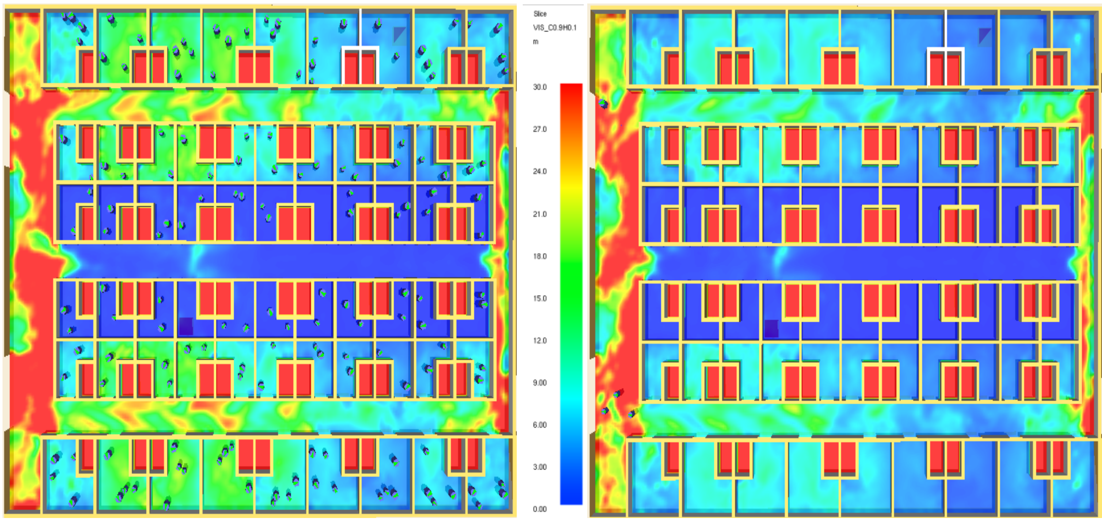

Figure 49 Visibility Night Scenario 6, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire causing incapacitation due to high temperatures. The cabin opposite to that one is also affected but not in a way to cause incapacitation.

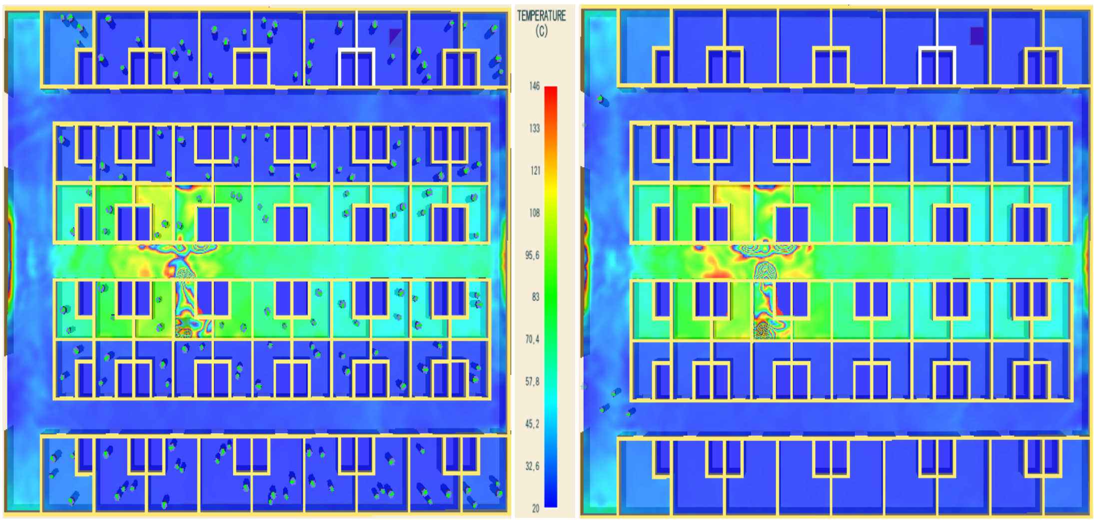

Figure 50 Temperature Night Scenario 6, Moderate Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility, 2 of who were also affected by high temperature. FED quantities did not hinder the evacuation process.

6.1.7 Scenario cabin no7

In this case, there is a moderate fire breakout in a 2-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below

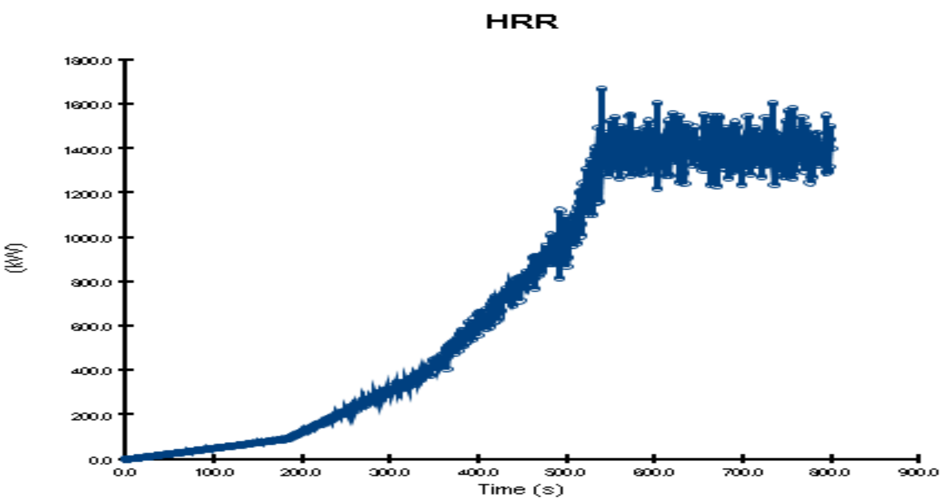

Figure 51 Heat Release Rate, Moderate Fire, Scenario 7

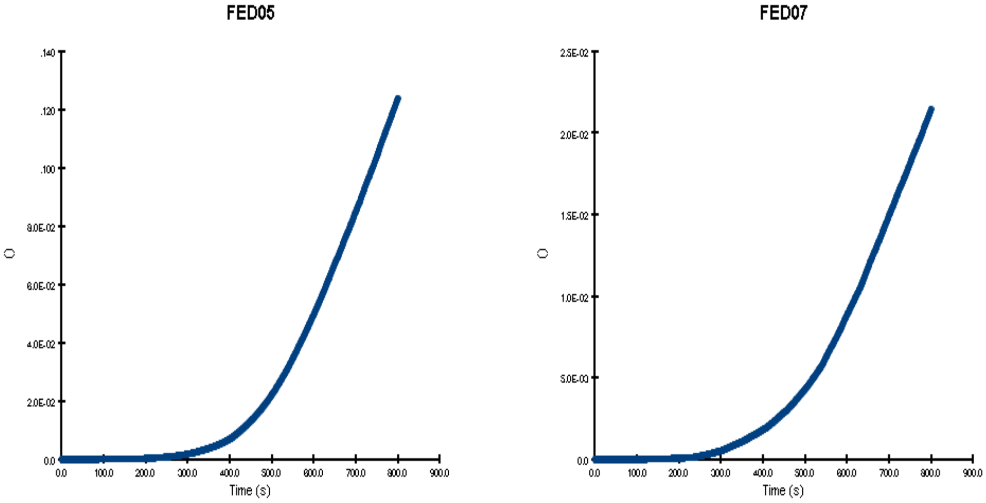

Figure 52 FED 5 & 7, Moderate Fire, Scenario 7

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the one opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabins. The cabins close to these ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

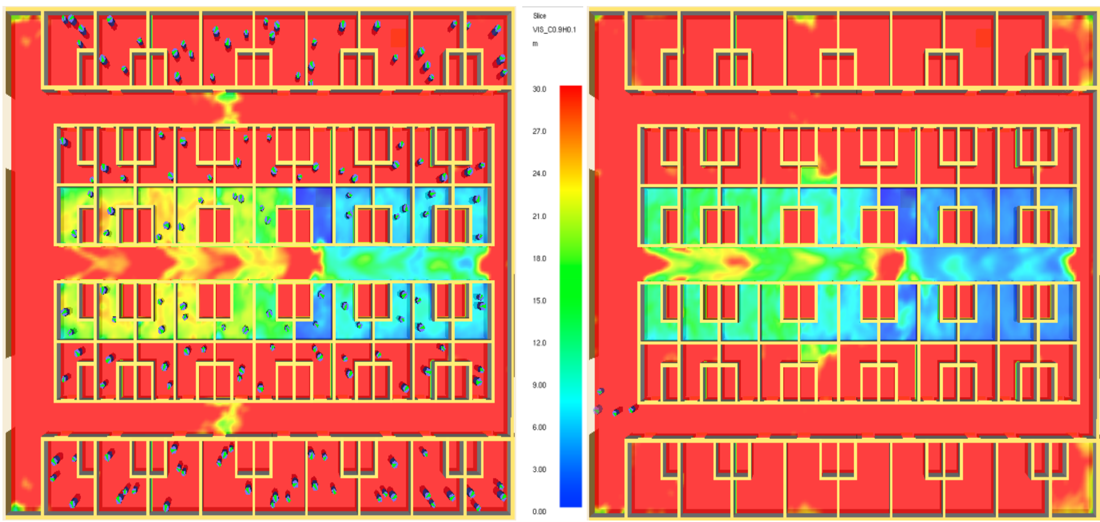

Figure 53 Visibility Day Scenario 7, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire, causing incapacitation due to high temperatures. The cabin opposite to that one is also affected but not in a way to cause incapacitation.

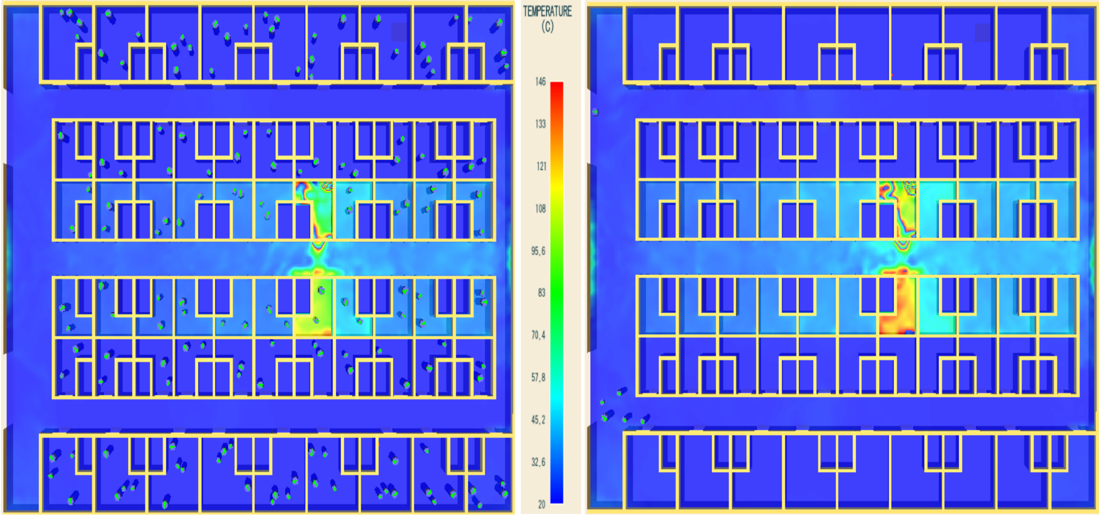

Figure 54 Temperature Day Scenario 7, Moderate Fire, Snapshots A & B

Results

In this scenario, 4 passengers did not manage to escape due to poor visibility, 2 of who were also affected by high temperature. FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

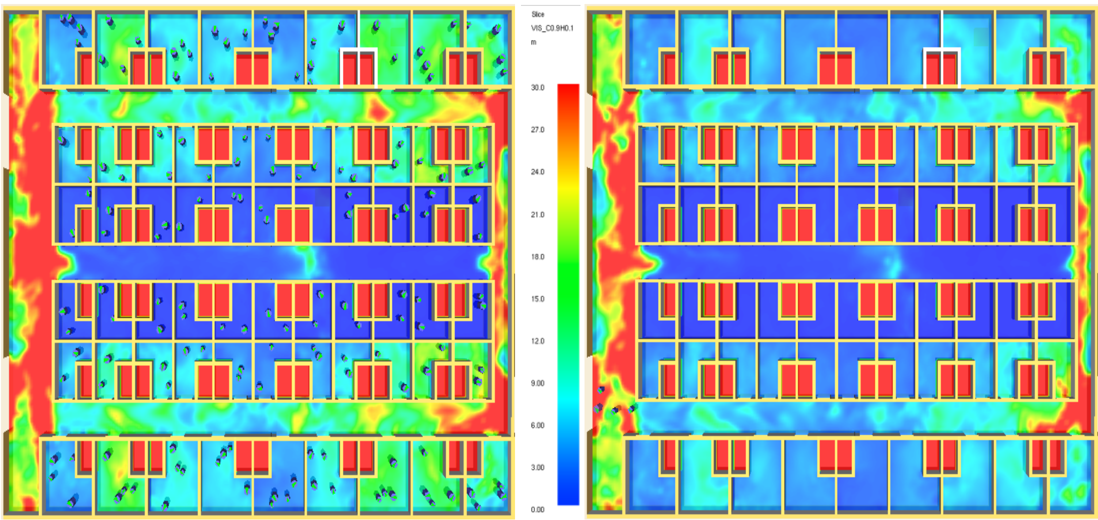

Figure 55 Visibility Night Scenario 7, Moderate Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to, and the two closest cabins, causing temperatures above 100 ^{0}C which lead to incapacitation.

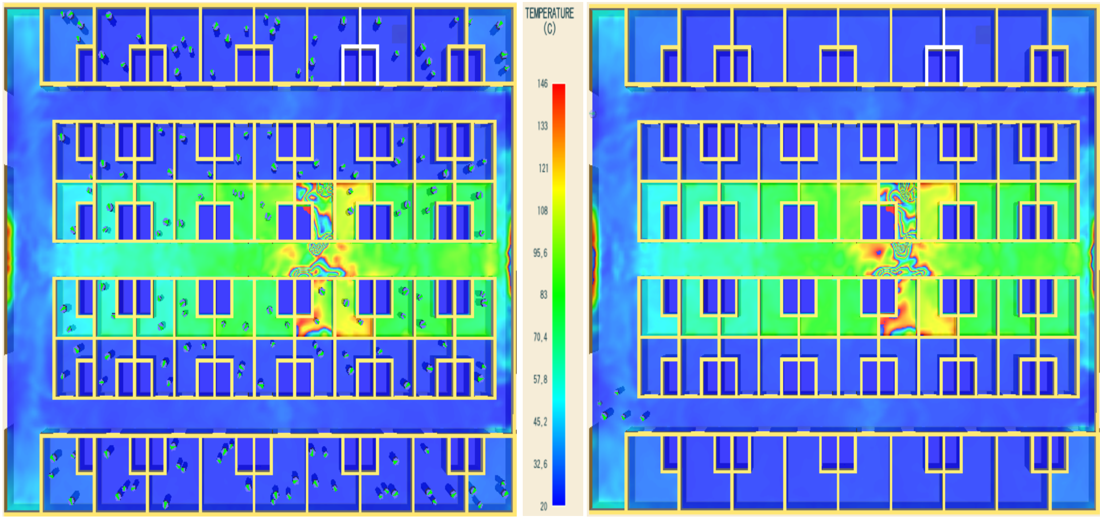

Figure 56 Temperature Night Scenario 7, Moderate Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility, 8 of who were also affected by high temperature. FED quantities did not hinder the evacuation process.

6.1.8 Scenario cabin no8

In this simulation, there is a moderate fire breakout in a 2-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in diagrams below.

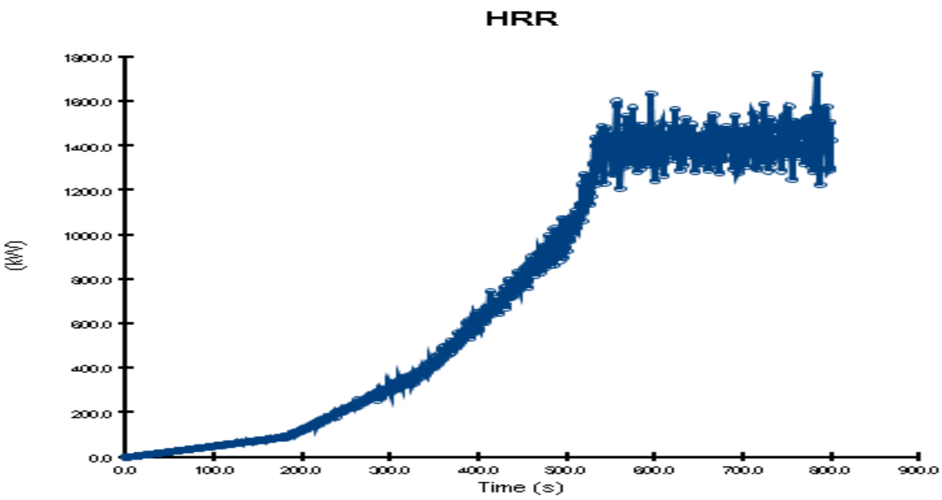

Figure 57 Heat Release Rate, Moderate Fire, Scenario 8

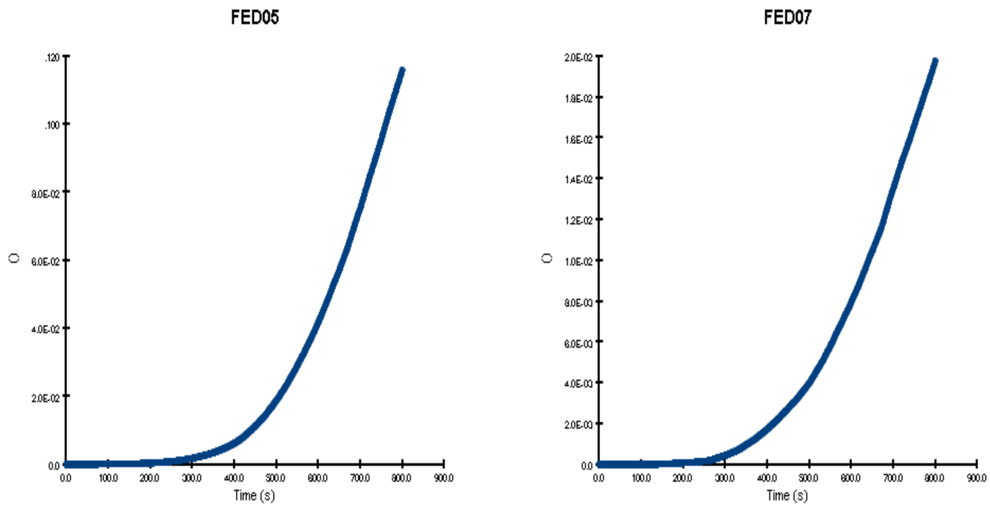

Figure 58 FED 5 & 7, Moderate Fire, Scenario 8

- Day scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the one opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabin. The cabins close to these ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

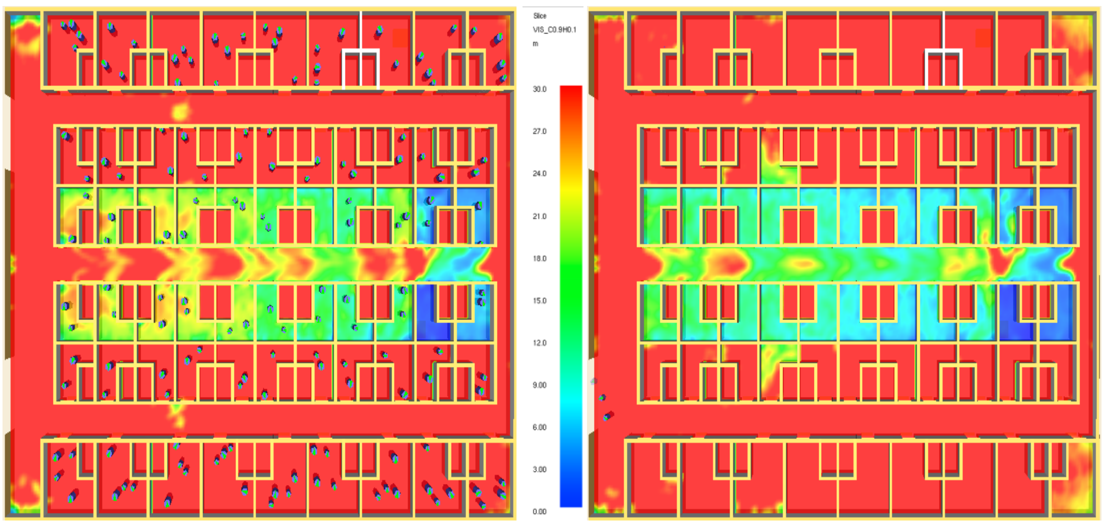

Figure 59 Visibility Day Scenario 8, Moderate Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire, causing incapacitation due to high temperatures. The cabin opposite to that one is also affected but not in a way to cause incapacitation.

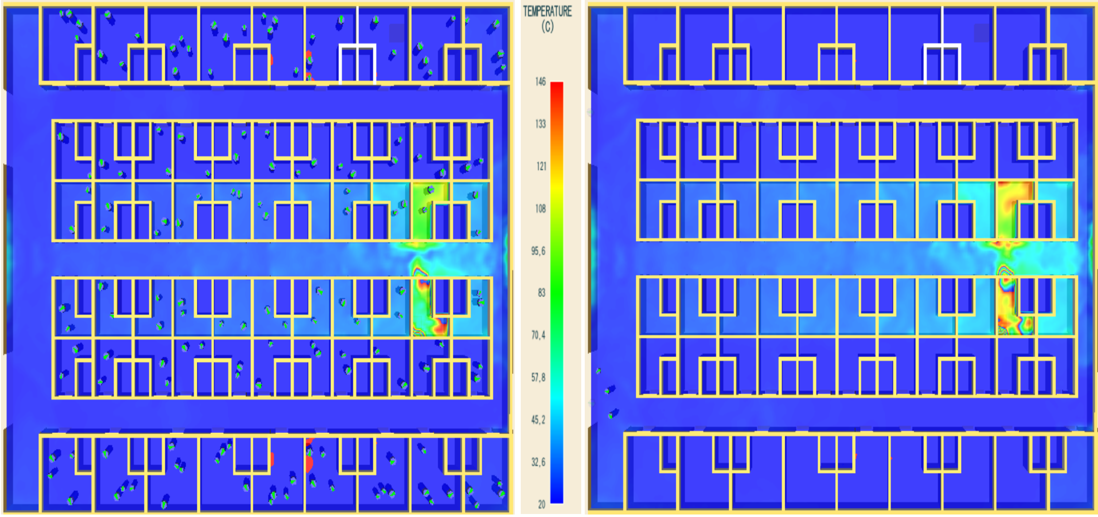

Figure 60 Temperature Day Scenario 8, Moderate Fire, Snapshots A & B

Results
In this scenario, 4 passengers did not manage to escape due to poor visibility, 2 of who were also affected by high temperature. FED quantities did not hinder the evacuation process

- Night scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins. Also the corridors have reduced visibility at the end of the evacuation, but enough for the passengers to escape.

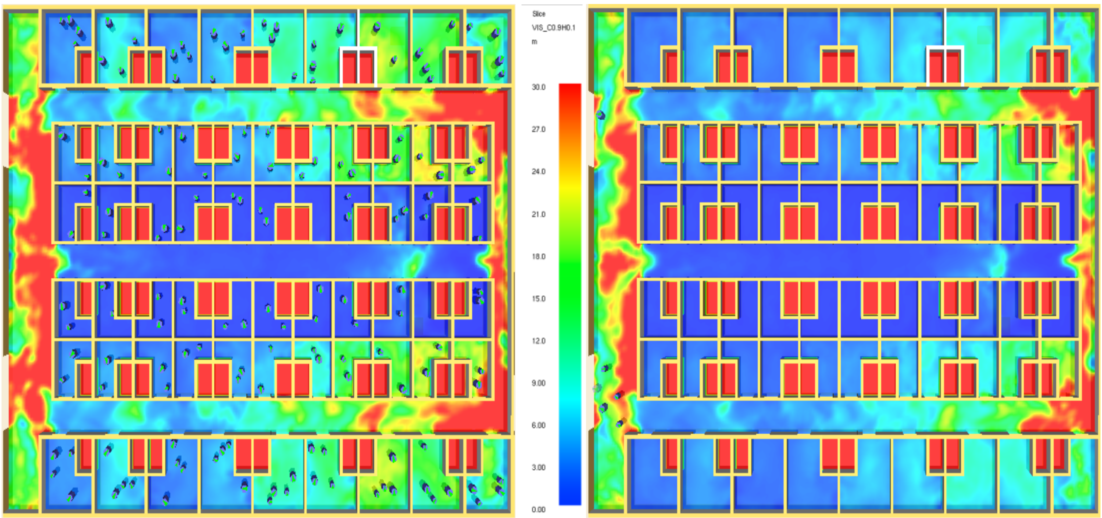

Figure 61 Visibility Night Scenario 8, Moderate Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire, the cabin opposite to and the two closest cabins, causing temperatures above 100 ^{0}C which lead to incapacitation.

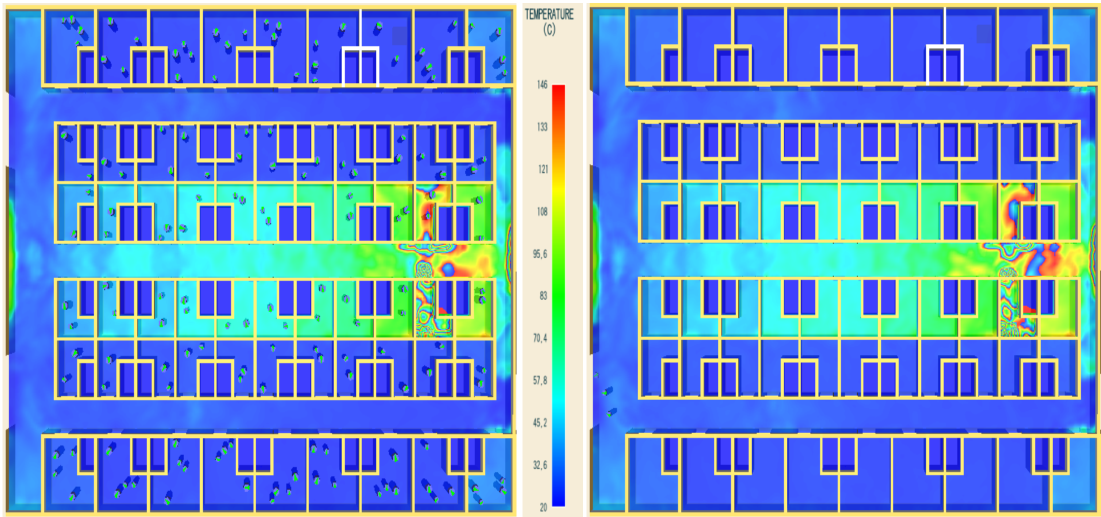

Figure 62 Temperature Night Scenario 8, Moderate Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility, 8 of who were also affected by high temperature. FED quantities did not hinder the evacuation process

6.2 Extreme fire simulation

6.2.1 Scenario cabin no1

An extreme fire breakout in a 4-passenger cabin is being simulated in this scenario. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

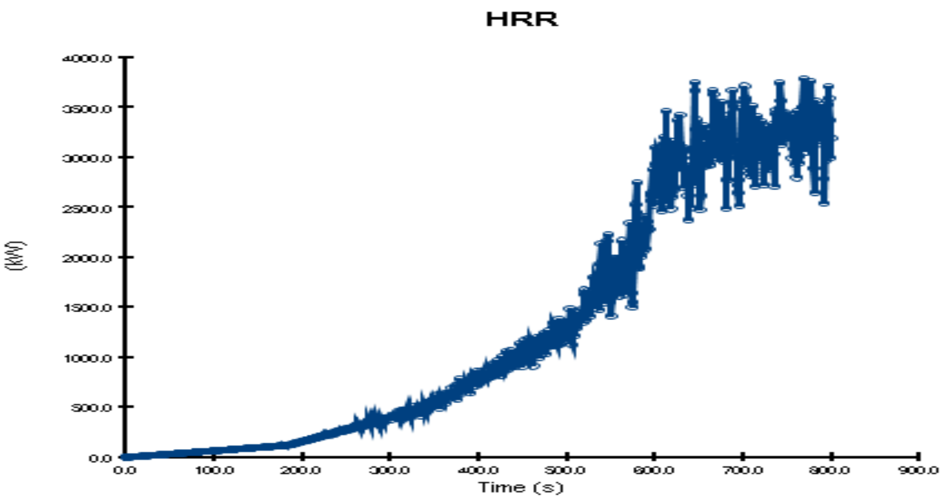

Figure 63 Heat Release Rate, Extreme Fire, Scenario 1

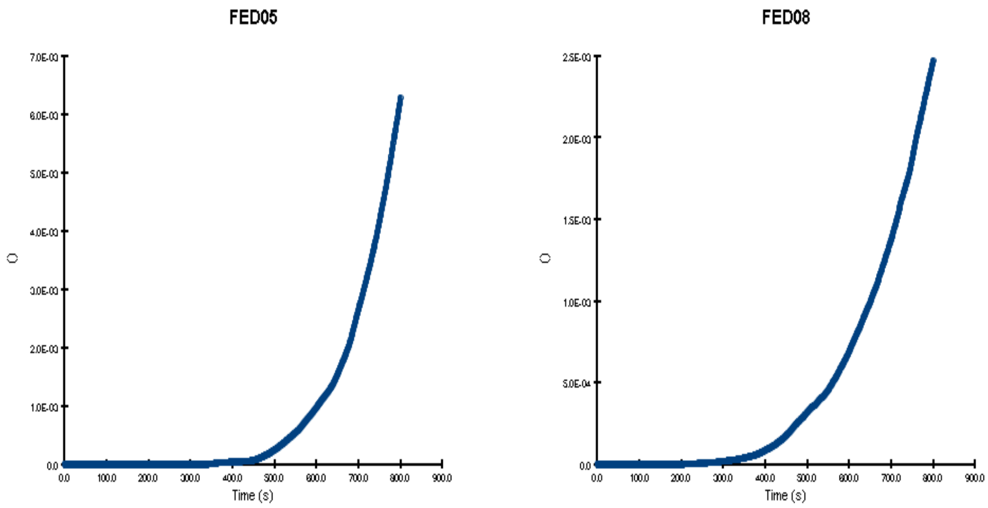

Figure 64 FED 5 & 8, Extreme Fire, Scenario 1

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire breaks through leading to almost zero visibility, and incapacitation of the passengers of that cabin. The cabins close to that one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

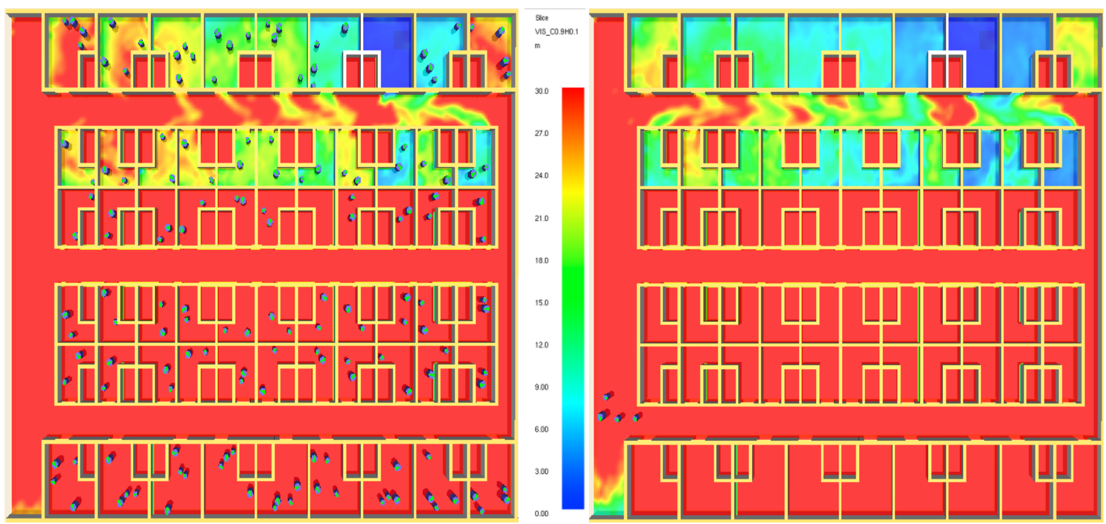

Figure 65 Visibility Day Scenario 1, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire causing temperatures above 100 ^{0}C and incapacitation.

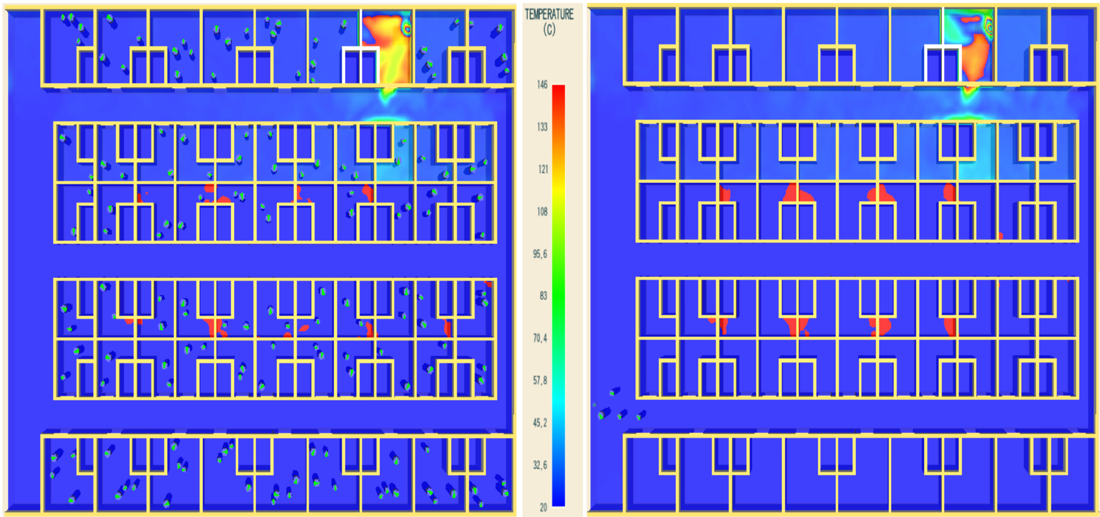

Figure 66 Temperature Day Scenario 1, Extreme Fire, Snapshots A & B

Results

In this scenario, 2 passengers did not manage to escape due to poor visibility and high temperature. FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 16 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 6 more deaths.

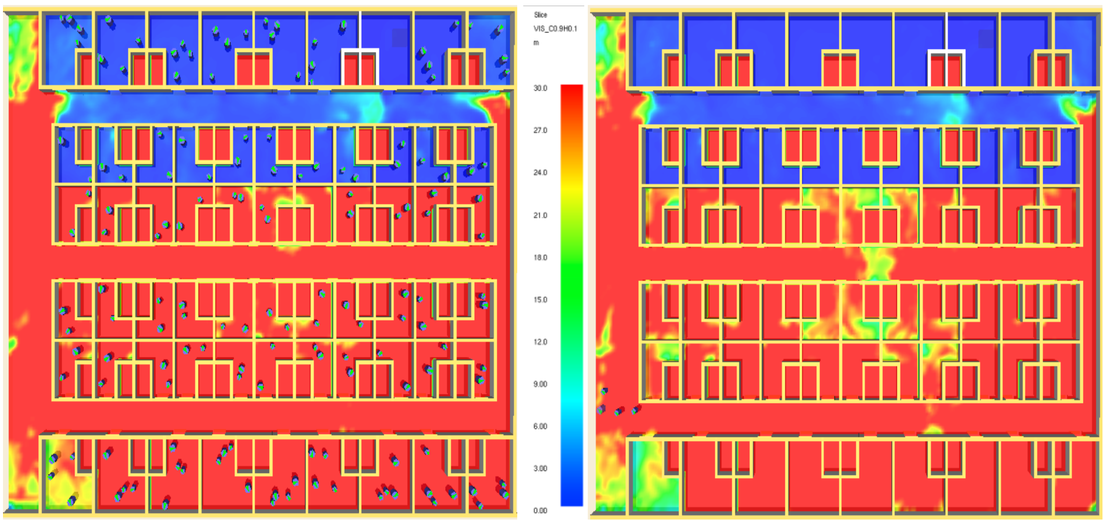

Figure 67 Visibility Night Scenario 1, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite producing temperatures of over 100 ^{0}C and causing incapacitation.

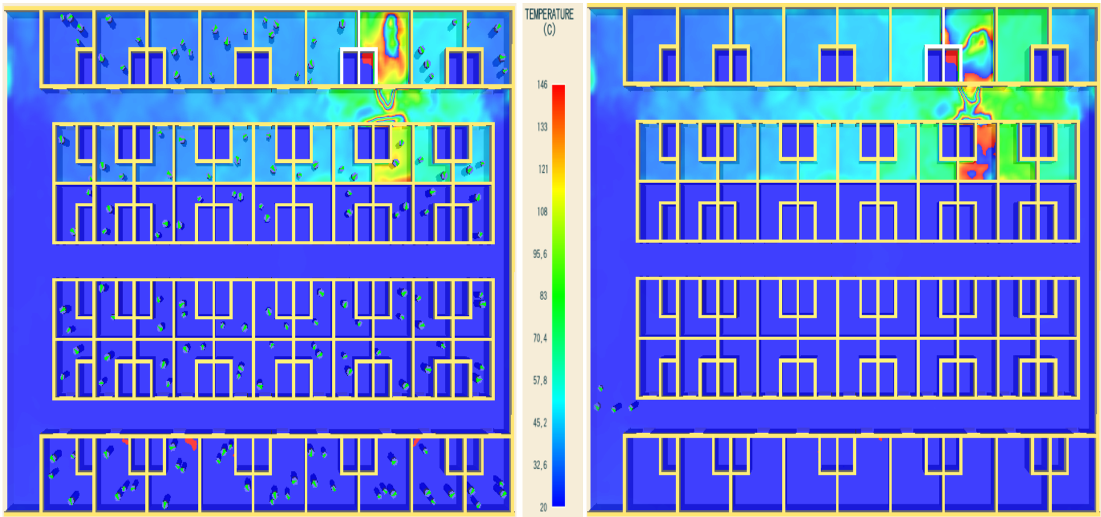

Figure 68 Temperature Night Scenario 1, Extreme Fire, Snapshots A & B

Results
In this scenario, 56 passengers did not manage to escape due to poor visibility, high temperatures affected 6 of them. FED quantities did not hinder the evacuation process.

6.2.2 Scenario cabin no2

In this simulation there is an extreme fire breakout in a 4-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

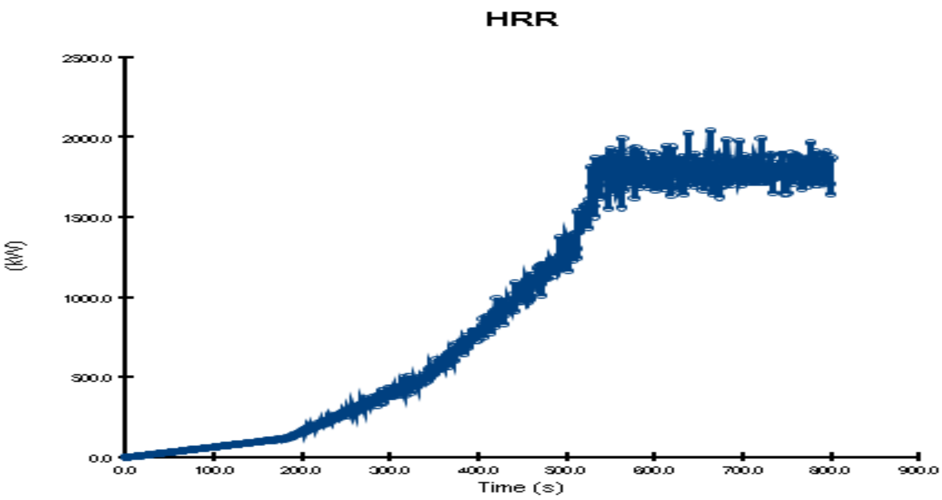

Figure 69 Heat Release Rate, Extreme Fire, Scenario 2

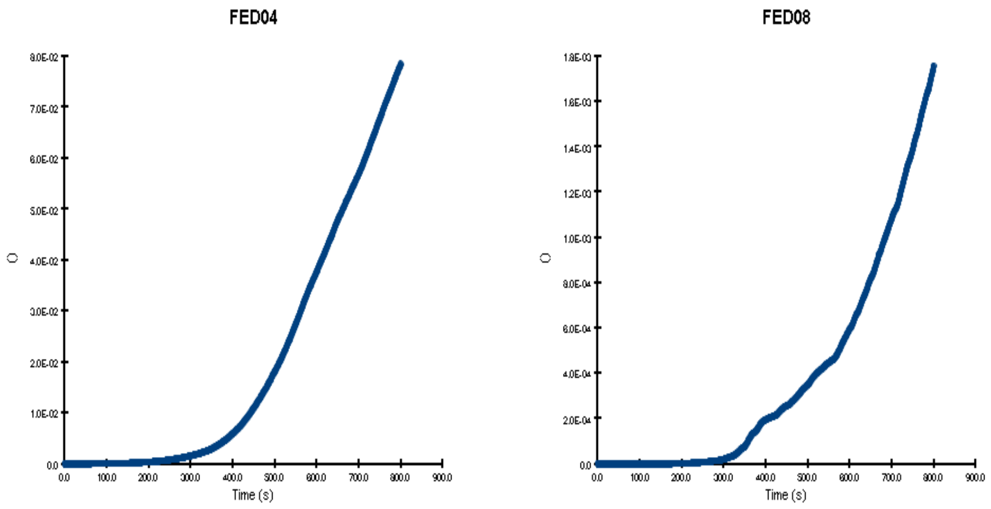

Figure 70 FED 4 & 8, Extreme Fire, Scenario 2

- Day scenario

Visibility

In this simulation, visibility due to smoke is highly reduced in cabin where the fire breaks through and the one opposite of it leading to almost zero visibility, and incapacitation of the passengers of the cabins. The cabins close to those ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

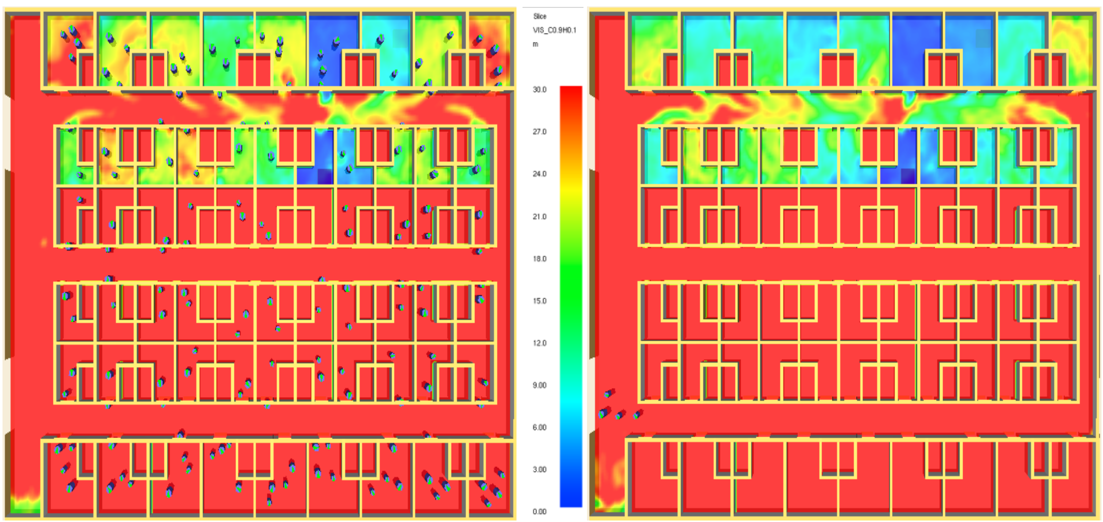

Figure 71 Visibility Day Scenario 2, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire producing temperatures of over 100 ^{0}C and incapacitation.

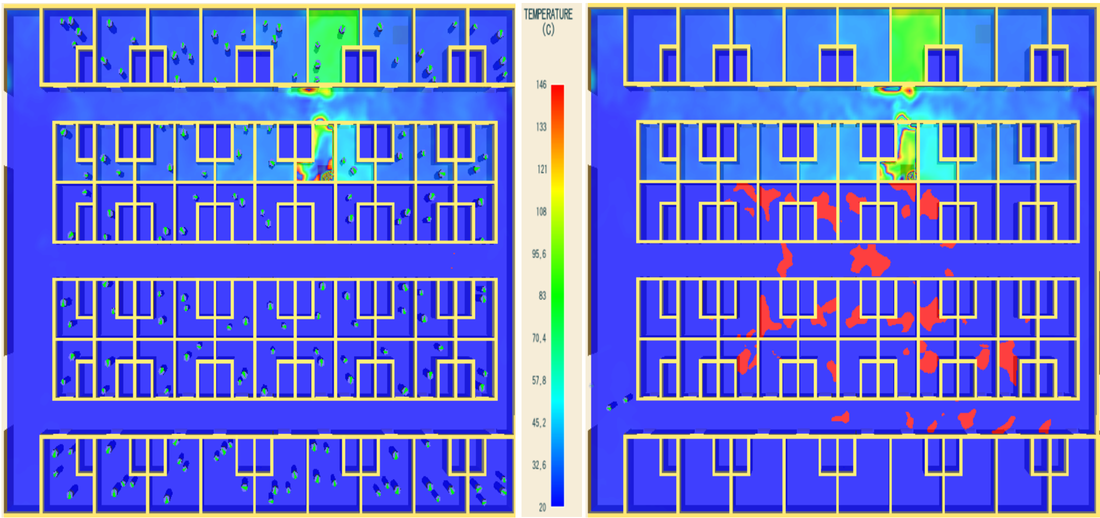

Figure 72 Temperature Day Scenario 2, Extreme Fire, Snapshots A & B

Results

In this scenario, 6 passengers did not manage to escape due to poor visibility. High temperature affected 2 of them but FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 17 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 4 more deaths.

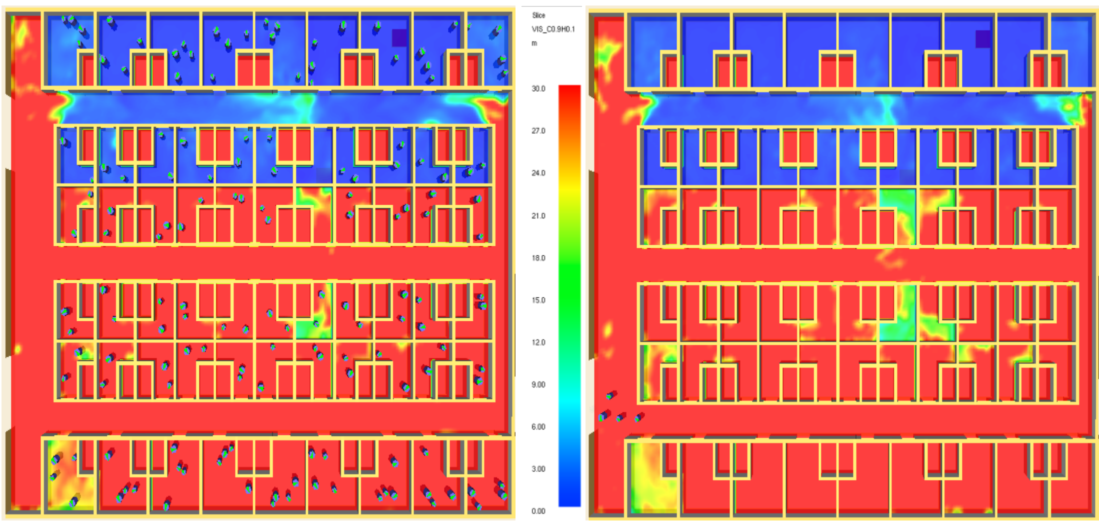

Figure 73 Visibility Night Scenario 2, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite to that but not in a way to cause incapacitation.

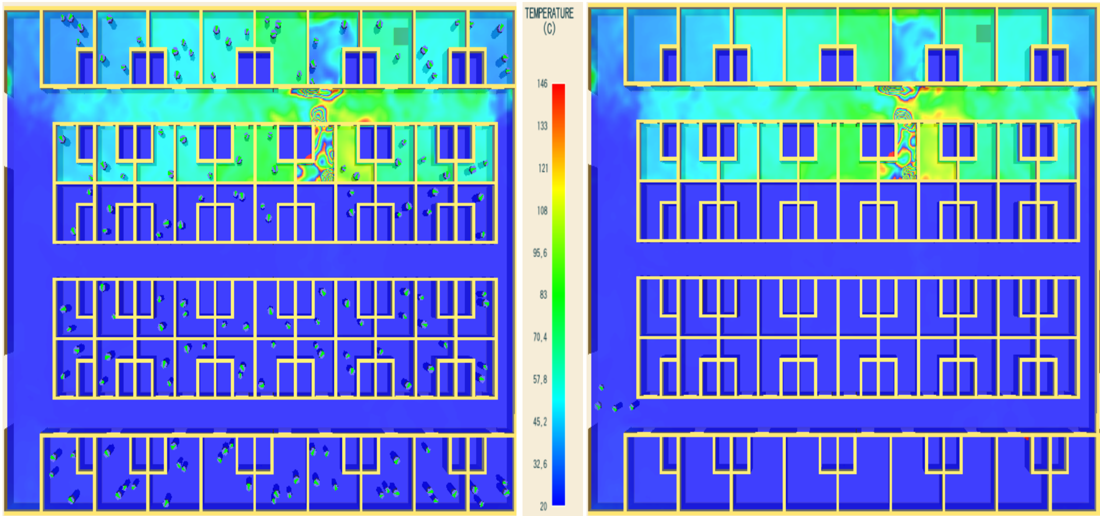

Figure 74 Temperature Night Scenario 2, Extreme Fire, Snapshots A & B

Results

In this scenario, 56 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

6.2.3 Scenario cabin no3

In this case, an extreme fire breakout in a 4-passenger cabin is being simulated. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

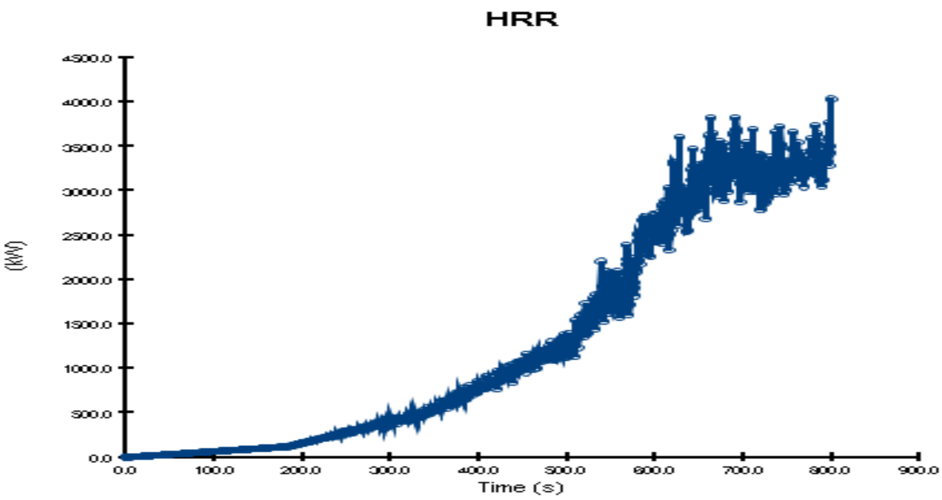

Figure 75 Heat Release Rate, Extreme Fire, Scenario 3

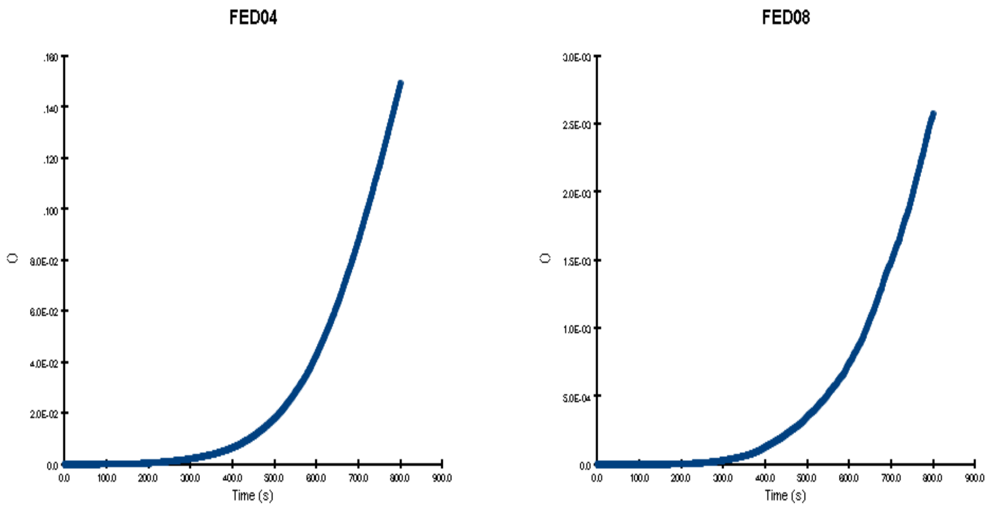

Figure 76 FED 4 & 8, Extreme Fire, Scenario 3

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire breaks through leading to almost zero visibility, and incapacitation of the passengers of that cabin. The cabins close to that one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

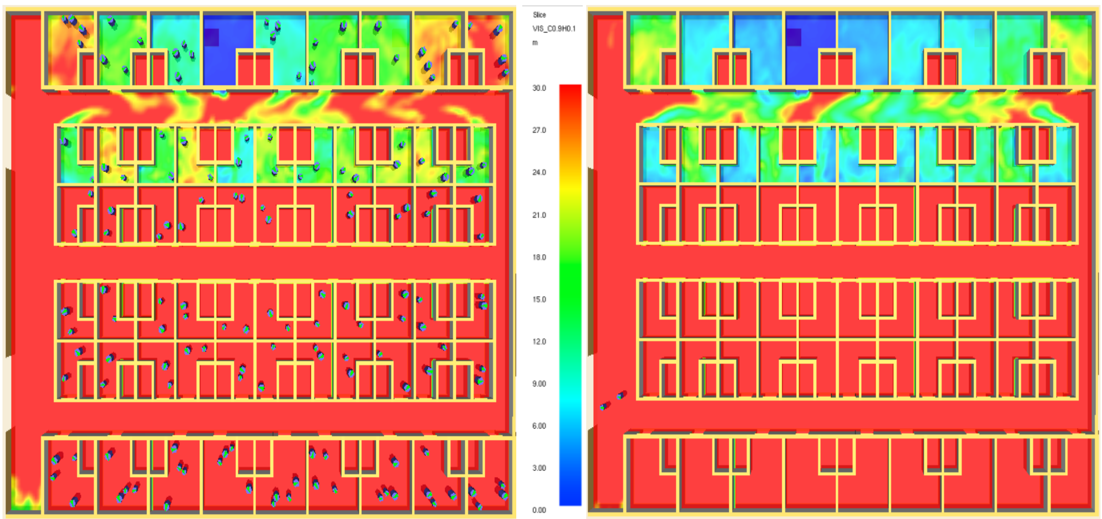

Figure 77 Visibility Day Scenario 3, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire producing temperatures of over 100 ^{0}C and incapacitation.

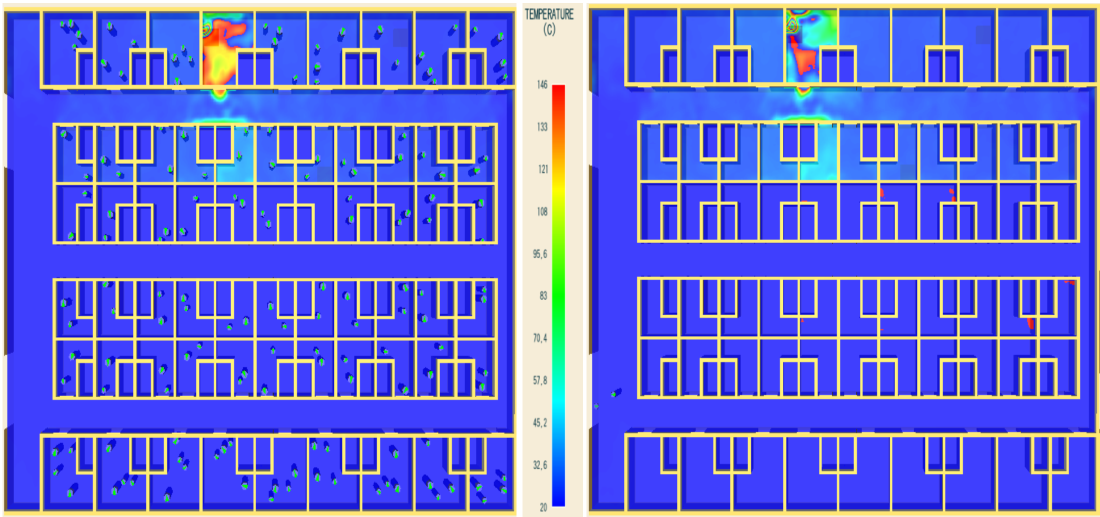

Figure 78 Temperature Day Scenario 3, Extreme Fire, Snapshots A & B

Results
In this scenario, 4 passengers did not manage to escape due to poor visibility and high temperature. FED quantities did not hinder the evacuation process.

- Night scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 17 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 4 more deaths.

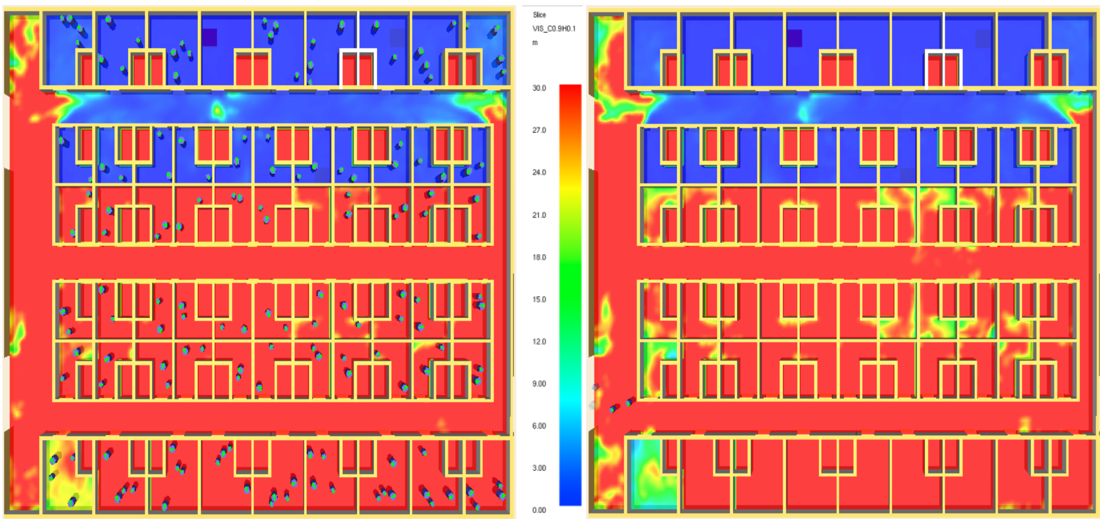

Figure 79 Visibility Night Scenario 3, Extreme Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire producing temperatures of over 100 ^{0}C and incapacitation. Cabin opposite to that one and cabins close to that are affected by high temperatures but not in a way to cause incapacitation during evacuation.

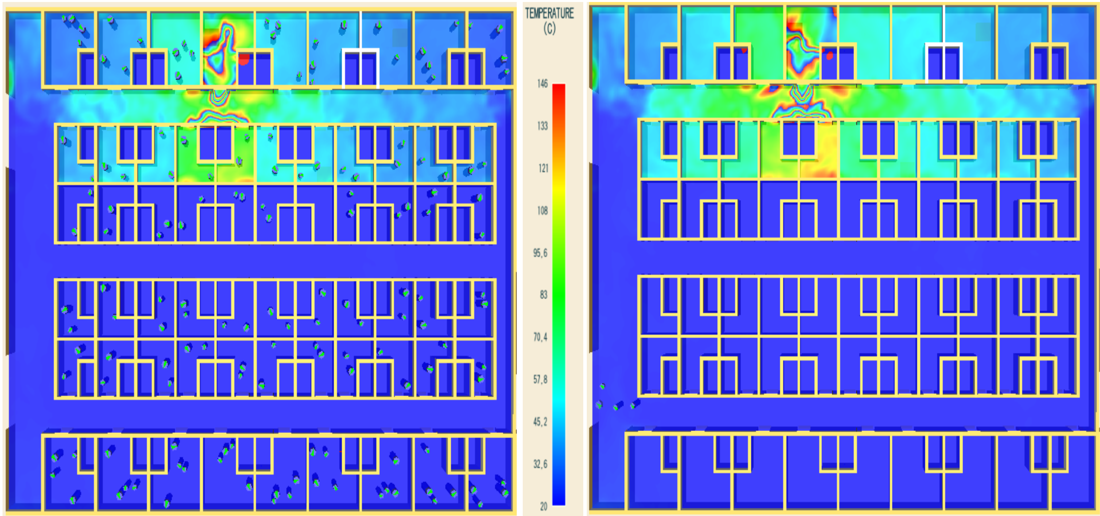

Figure 80 Temperature Night Scenario 3, Extreme Fire, Snapshots A &

Results
In this scenario, 56 passengers did not manage to escape due to poor visibility. High temperature affected 4 of them and FED quantities did not hinder the evacuation process.

6.2.4 Scenario cabin no4

In this simulation there is an extreme fire breakout in a 4-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

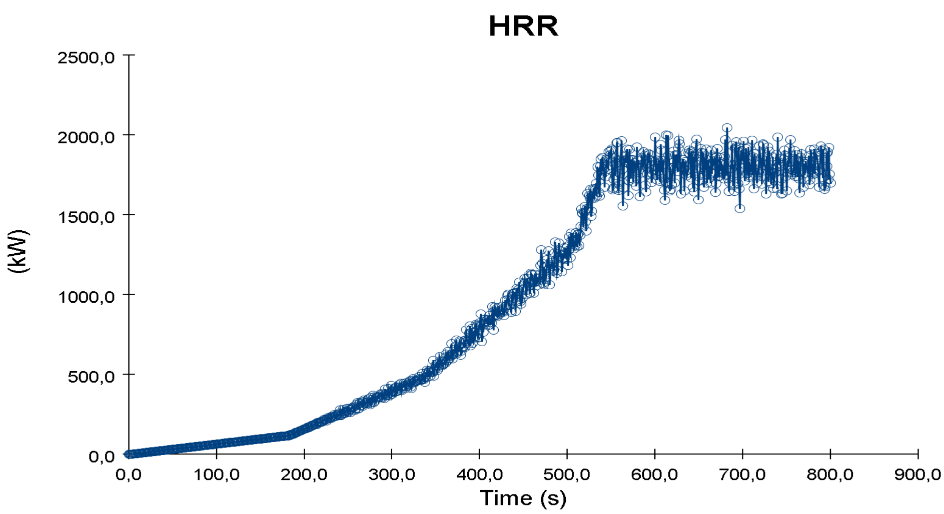

Figure 81 Heat Release Rate, Extreme Fire, Scenario 4

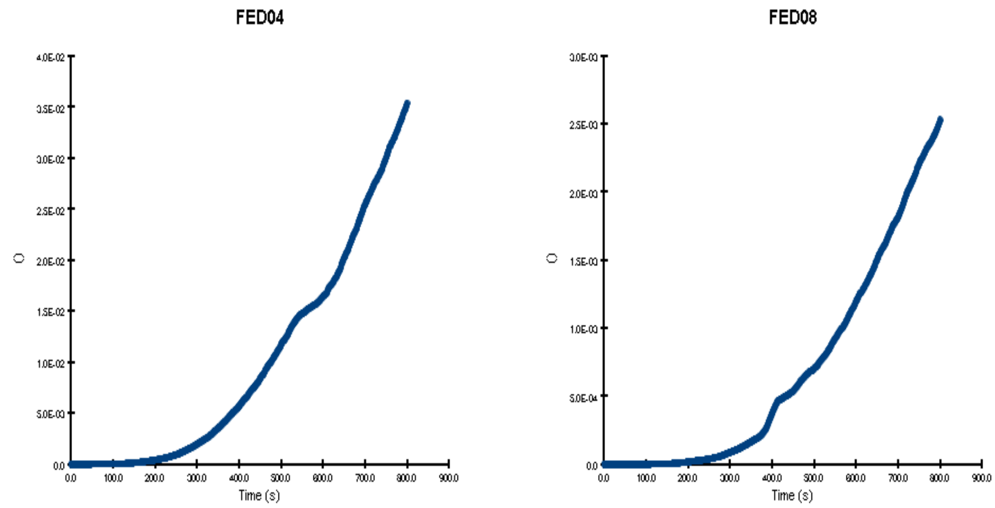

Figure 82 FED 4 & 8, Extreme Fire, Scenario 4

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the fire opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabins. The cabins close to these ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

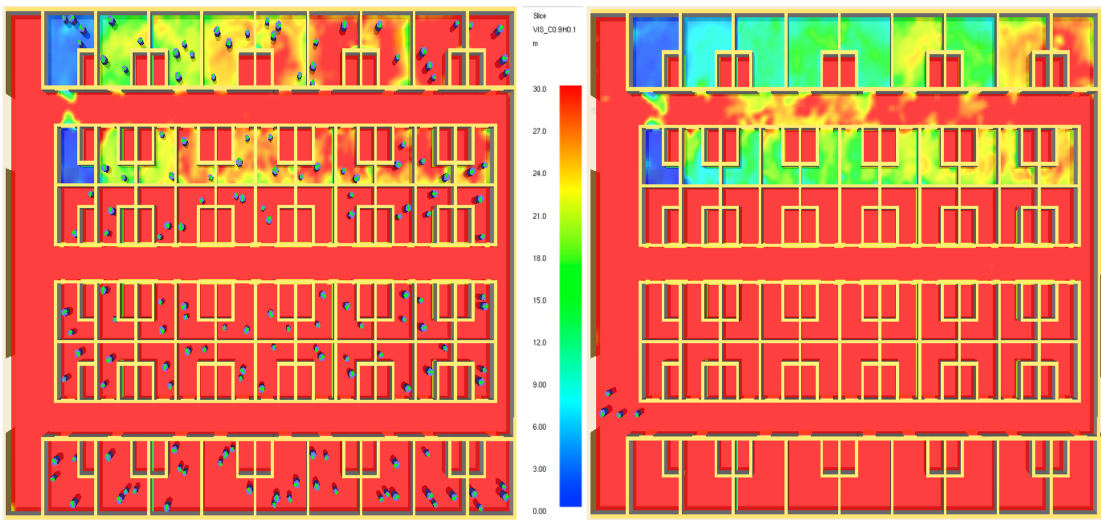

Figure 83 Visibility Day Scenario 4, Extreme Fire, snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire producing temperatures of over 100 ^{0}C and incapacitation.

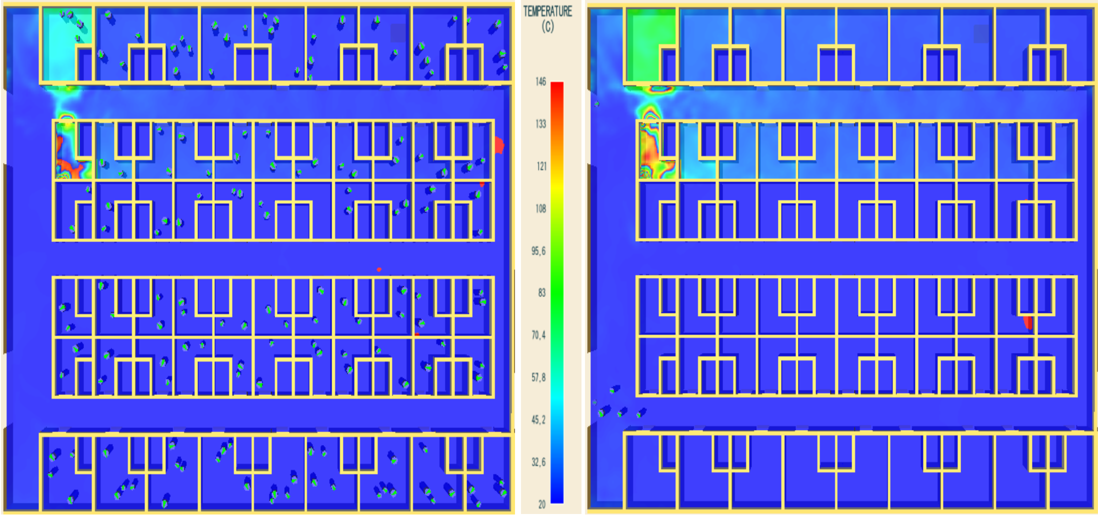

Figure 84 Temperature Day Scenario 4, Extreme Fire, Snapshots A & B

Results

In this scenario, 6 passengers did not manage to escape due to poor visibility. 2 of them were also affected by high temperature. FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility at 16 cabins, leading to incapacitation of the passengers before the evacuation begins. At the end of the evacuation procedure the corridor has also zero visibility, which affects the evacuation process leading to 6 more deaths.

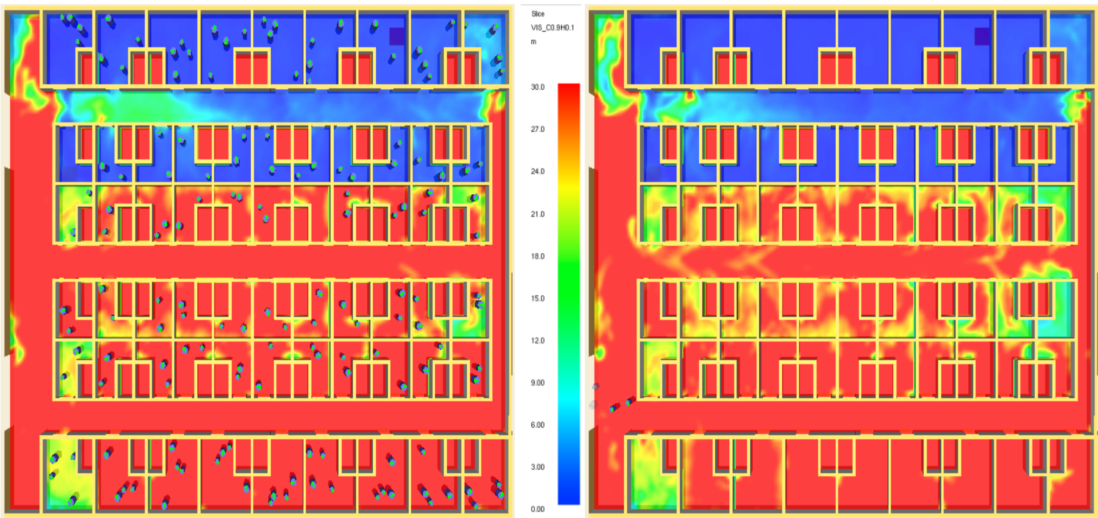

Figure 85 Visibility Night Scenario 4, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire producing temperatures of over 100 ^{0}C and causing incapacitation.

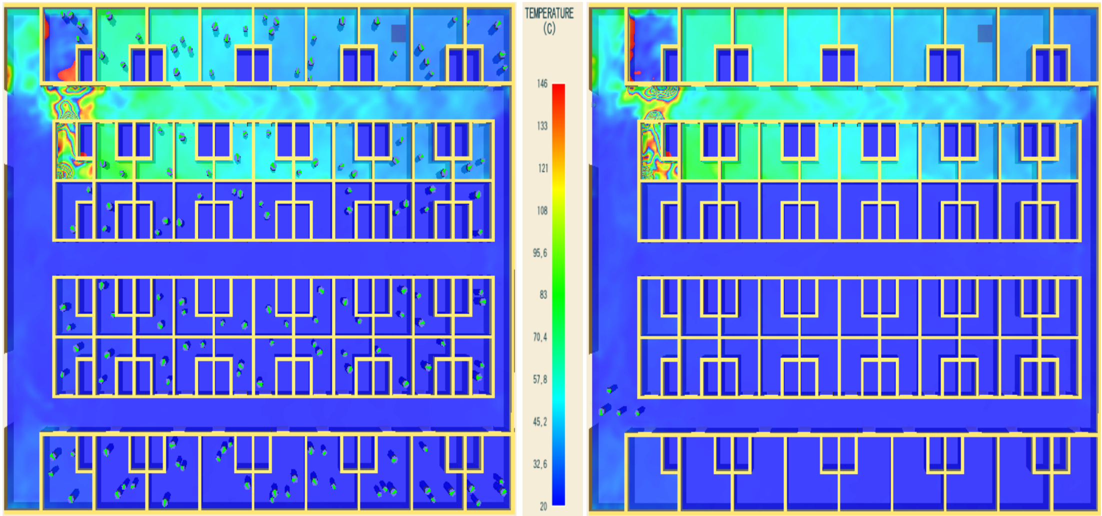

Figure 86 Temperature Night Scenario 4, Extreme Fire, Snapshots A & B

Results

In this scenario, 56 passengers did not manage to escape due to poor visibility, high temperature affected 6 of them. FED quantities did not hinder the evacuation process.

6.2.5 Scenario cabin no5

An extreme fire breakout in a 2-passenger cabin is being examined in this simulation. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

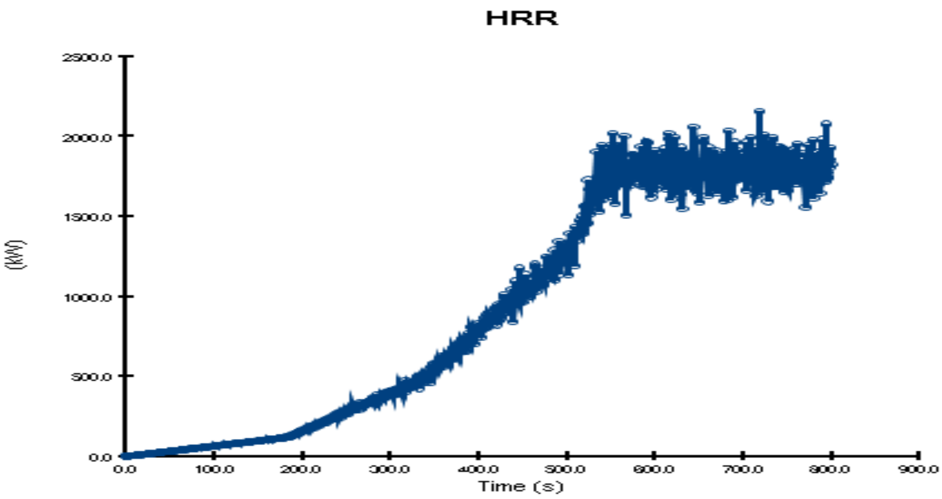

Figure 87 Heat Release Rate, Extreme Fire, Scenario 5

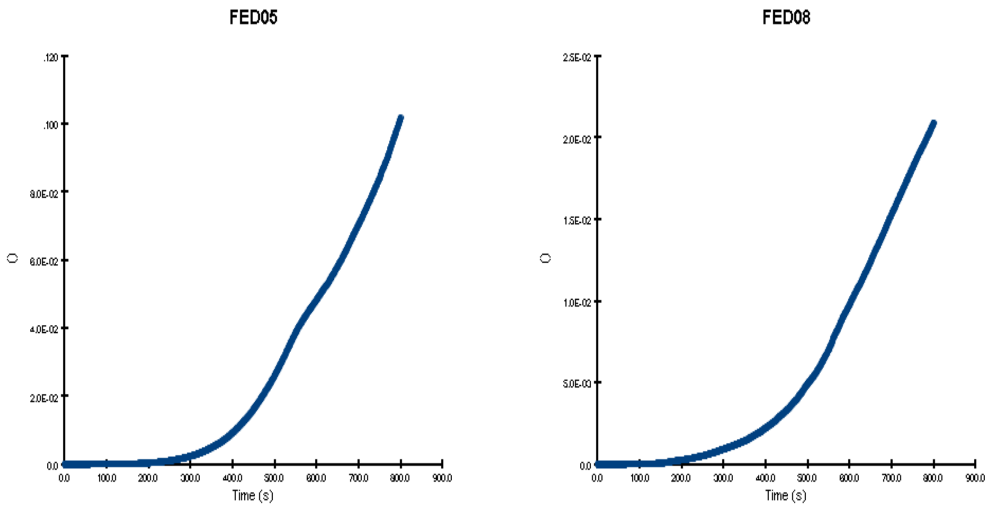

Figure 88 FED 5 & 8, Extreme Fire, Scenario 5

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out, leading to almost zero visibility, and incapacitation of the passengers of the cabin. The cabins close to this one reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

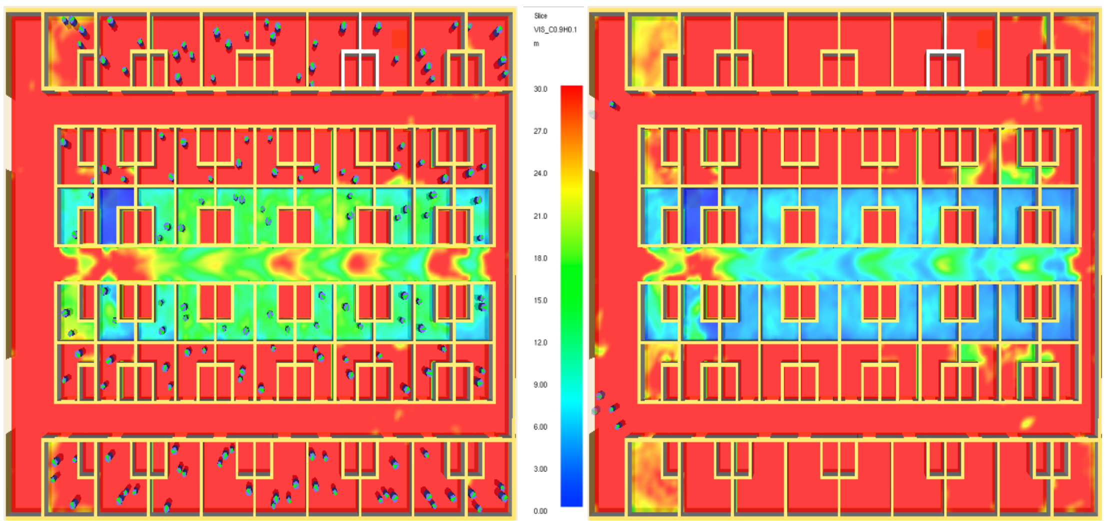

Figure 89 Visibility Day Scenario 5, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite but not in a way to cause incapacitation.

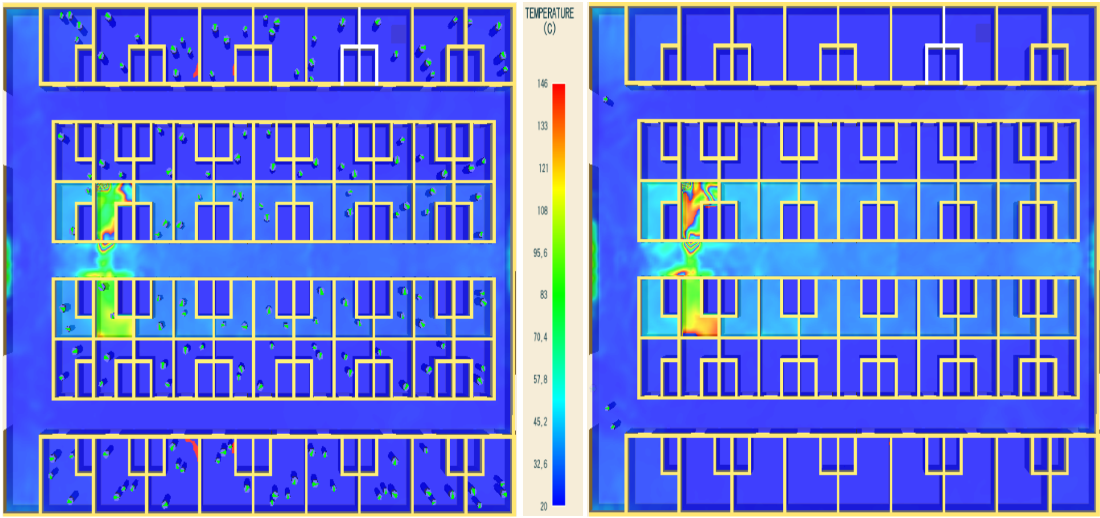

Figure 90 Temperature Day Scenario 5, Extreme Fire, Snapshots A & B

Results
In this scenario, 2 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

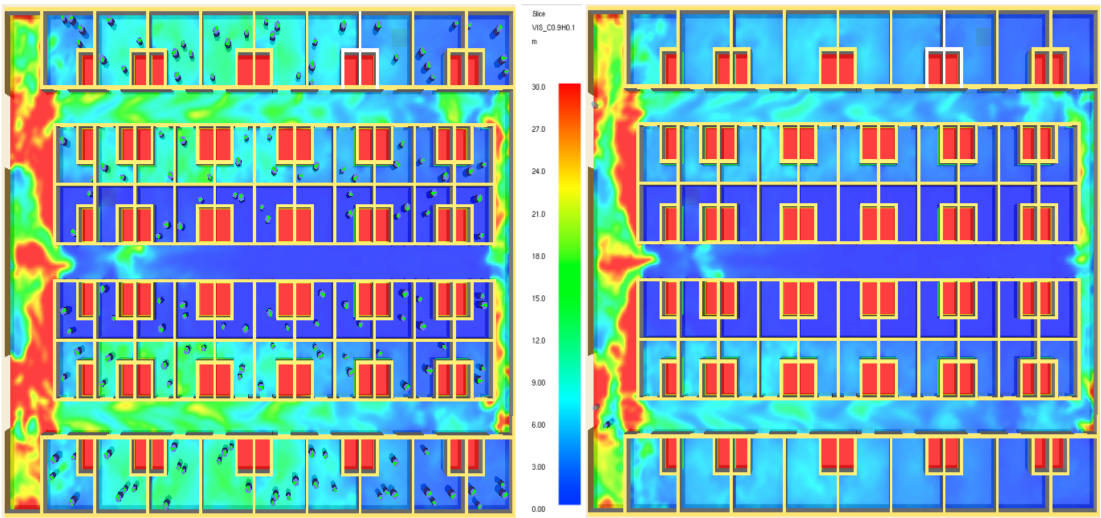

Figure 91 Visibility Night Scenario 5, Extreme Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire and the cabin opposite but not in a way to cause incapacitation.

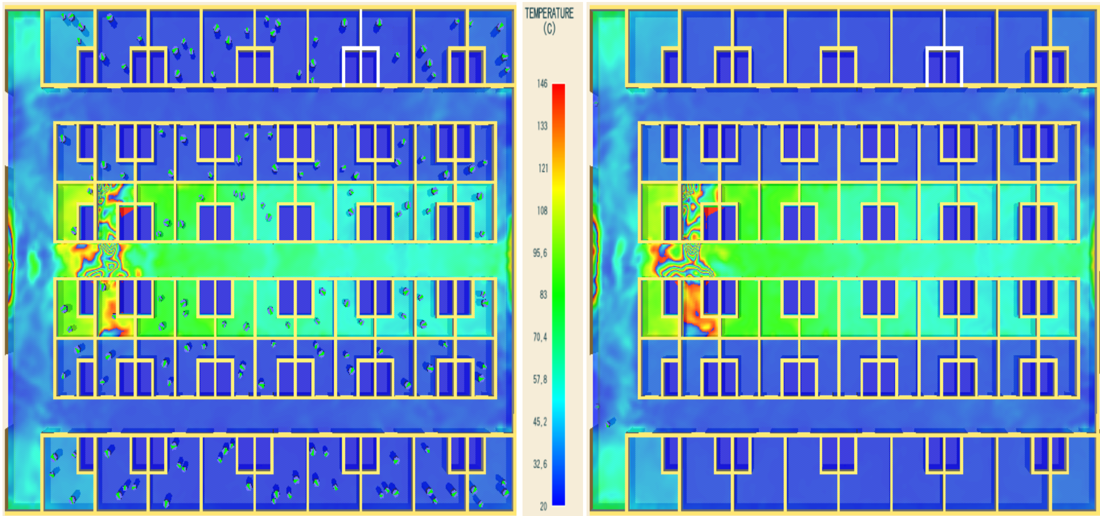

Figure 92 Temperature Night Scenario 5, Extreme Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

6.2.6 Scenario cabin no6

In this case, there is an extreme fire breakout in a 2-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

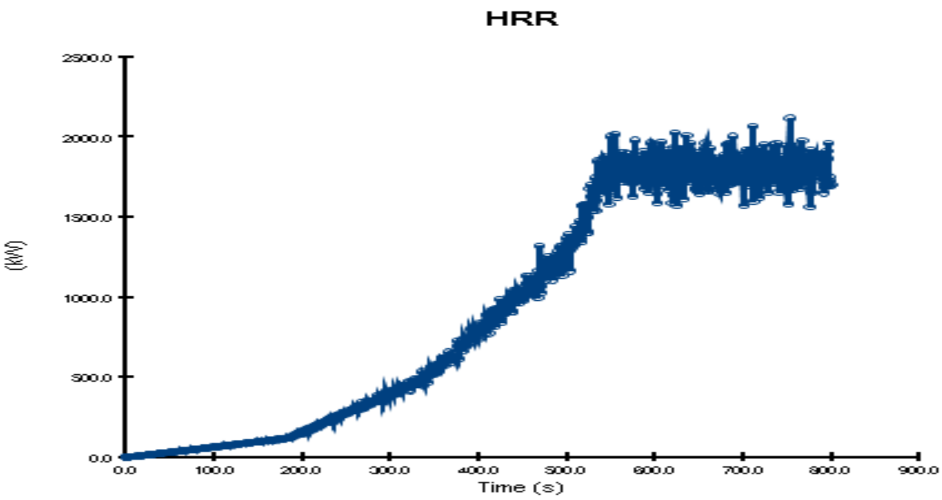

Figure 93 Heat Release Rate, Extreme Fire, Scenario 6

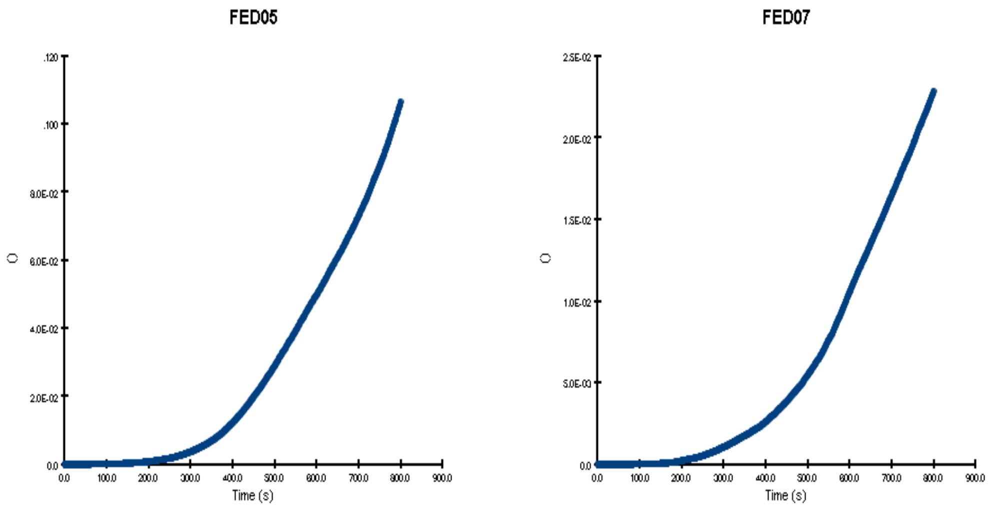

Figure 94 FED 5 & 7, Extreme Fire, Scenario 6

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out, leading to almost zero visibility, and incapacitation of the passengers of the cabin. The cabins close to it are highly affected but only reach a visibility of less than 10m at the end of the evacuation process, which is considered enough for passengers to escape.

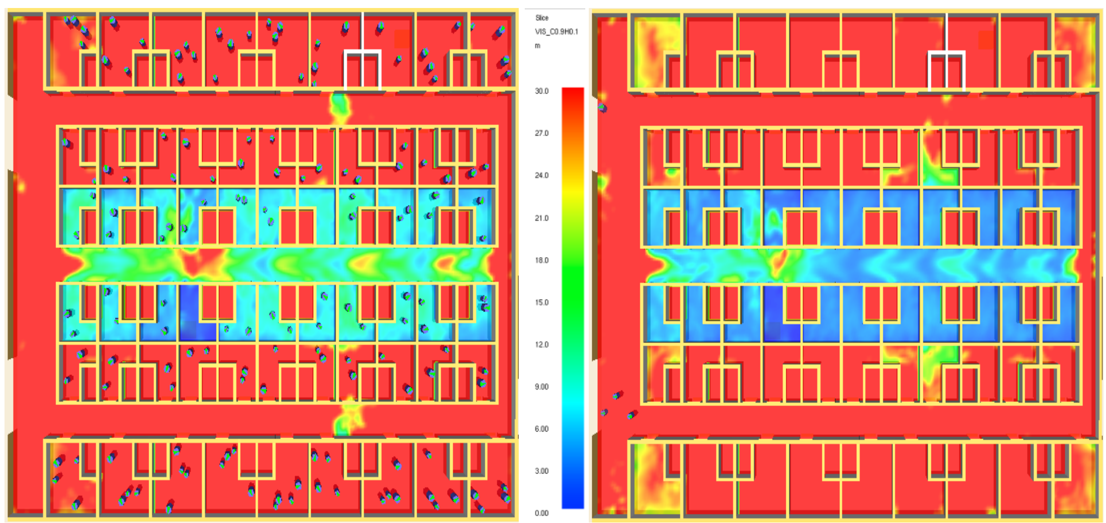

Figure 95 Visibility Day Scenario 6, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite but not in a way to cause incapacitation.

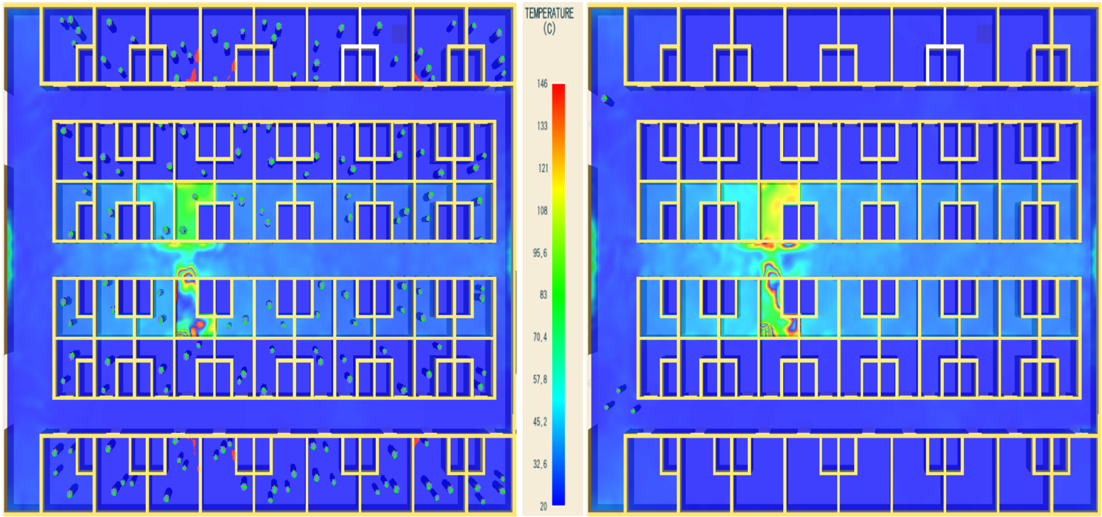

Figure 96 Temperature Day Scenario 6, Extreme Fire, Snapshots A & B

Results

In this scenario, 2 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

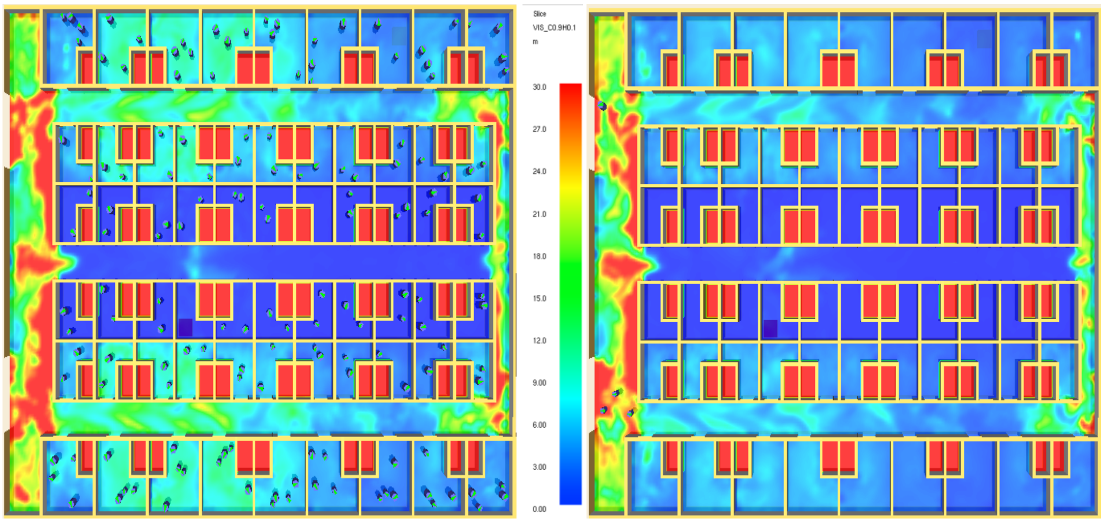

Figure 97 Visibility Night Scenario 6, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite producing temperatures of over 100 ^{0}C and incapacitation. Cabins near to them are also affected during evacuation as well as the corridor.

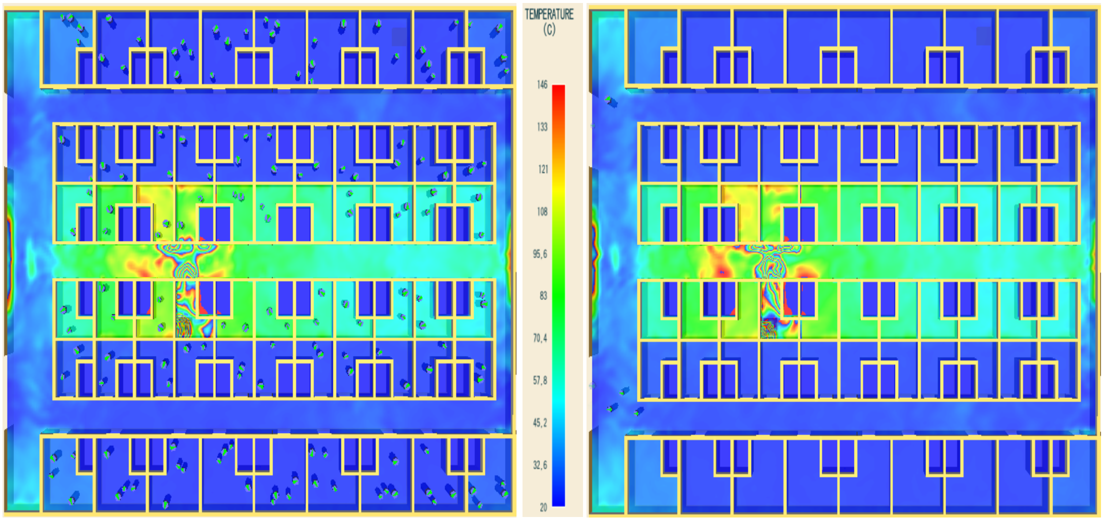

Figure 98 Temperature Night Scenario 6, Extreme Fire, Snapshots A & B

Results
In this scenario, 44 passengers did not manage to escape due to poor visibility. High temperature affected 4 of them and FED quantities did not hinder the evacuation process.

6.2.7 Scenario cabin no7

In this case, an extreme fire breakout in a 2-passenger cabin is being simulated. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

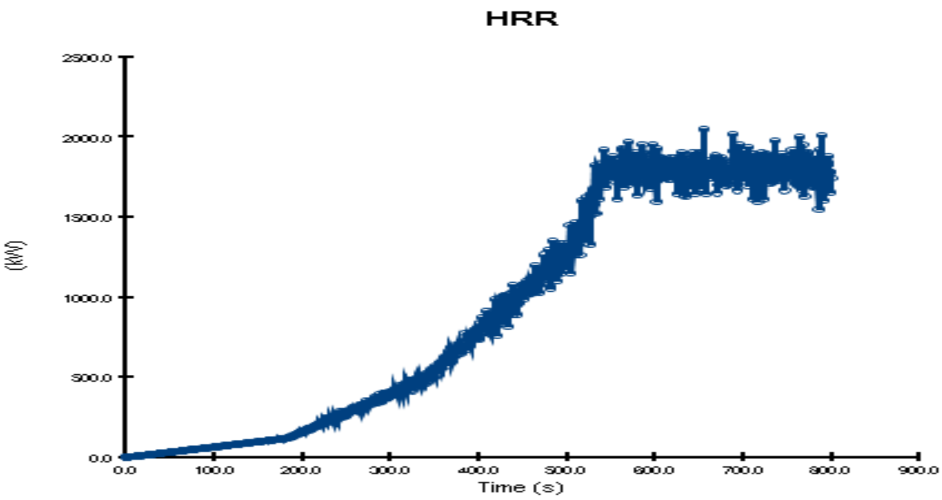

Figure 99 Heat Release Rate, Extreme Fire, Scenario 7

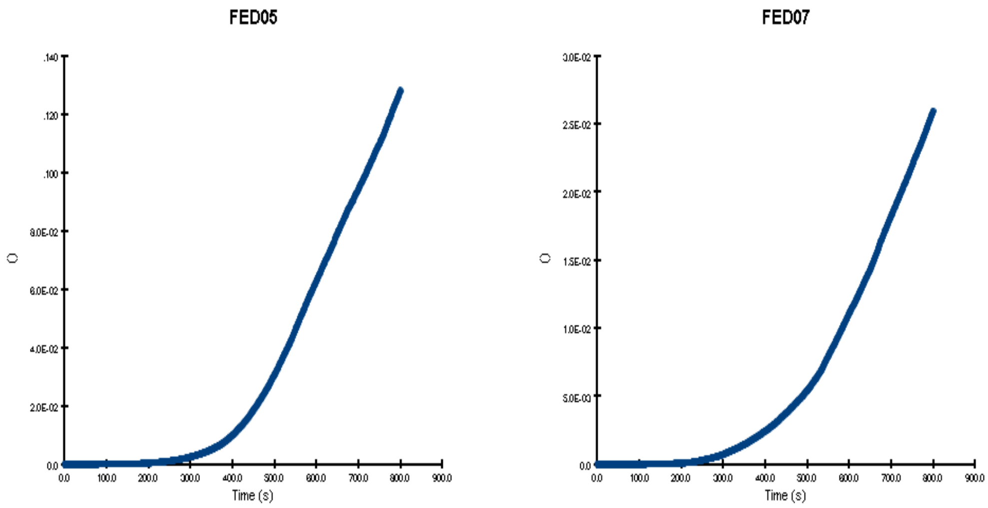

Figure 100 FED 5 & 7, Extreme Fire, Scenario 7

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the fire opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabins. The cabins close to these ones reach a visibility of 10m at the time of evacuation, which is considered enough for passengers to escape.

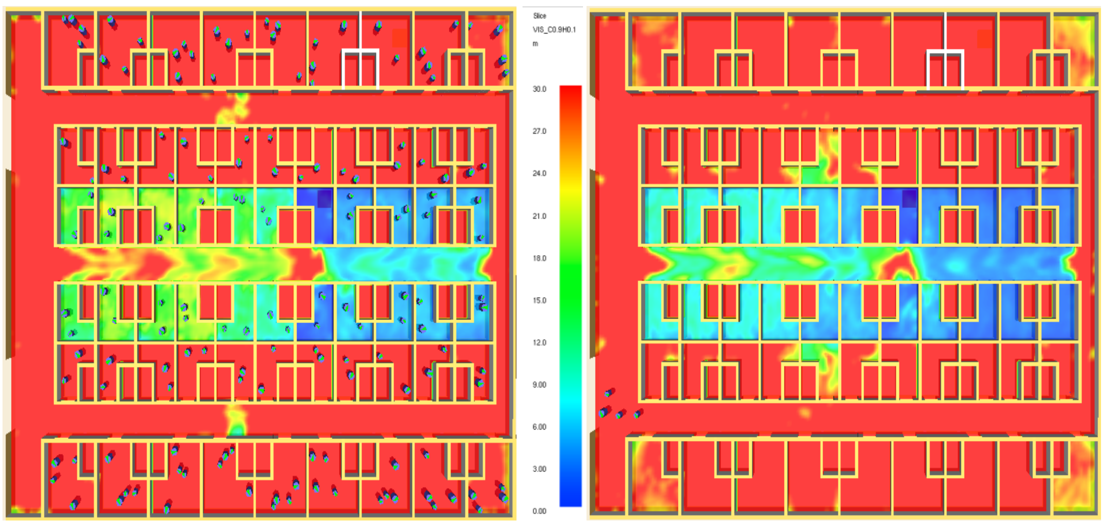

Figure 101 Visibility Day Scenario 7, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite but not in a way to cause incapacitation.

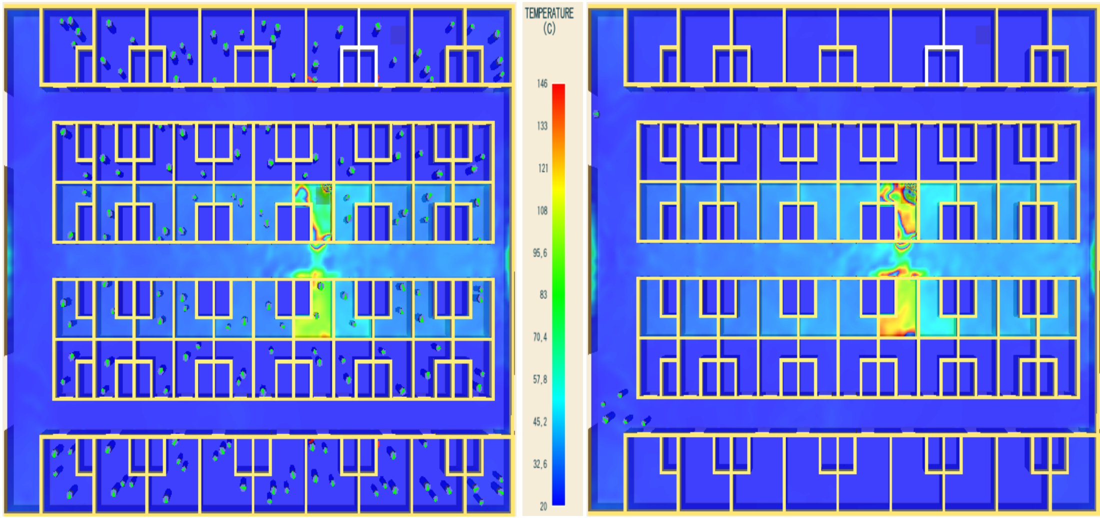

Figure 102 Temperature Day Scenario 7, Extreme Fire, Snapshots A & B

Results
In this scenario, 4 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night scenario

Visibility
In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

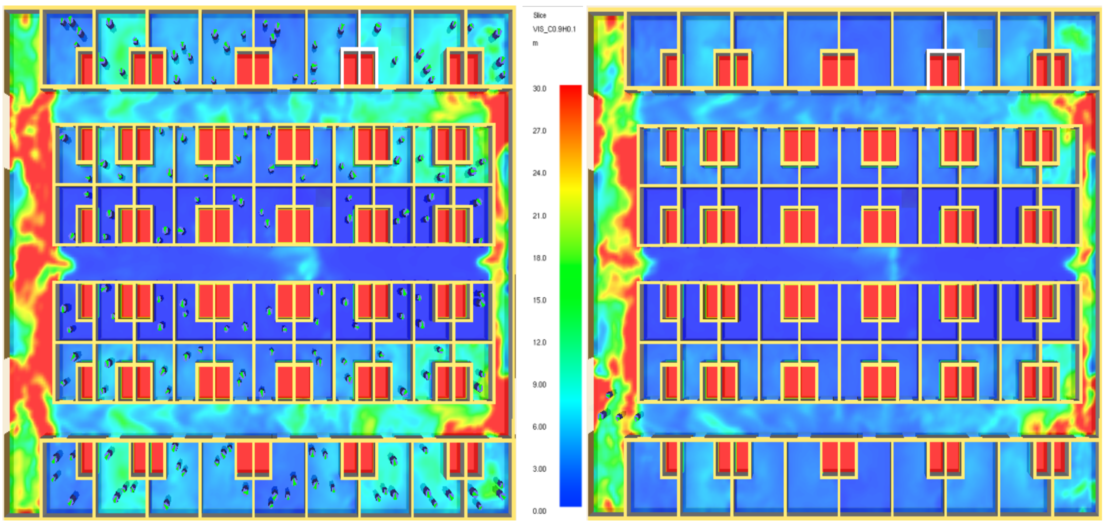

Figure 103 Visibility Night Scenario 7, Extreme Fire, Snapshots A & B

Temperature
In this scenario, temperature only affects the cabin of fire and the cabin opposite producing temperatures of over 100 ^{0}C and incapacitation. Cabins near to them are also affected during evacuation as well as the corridor.

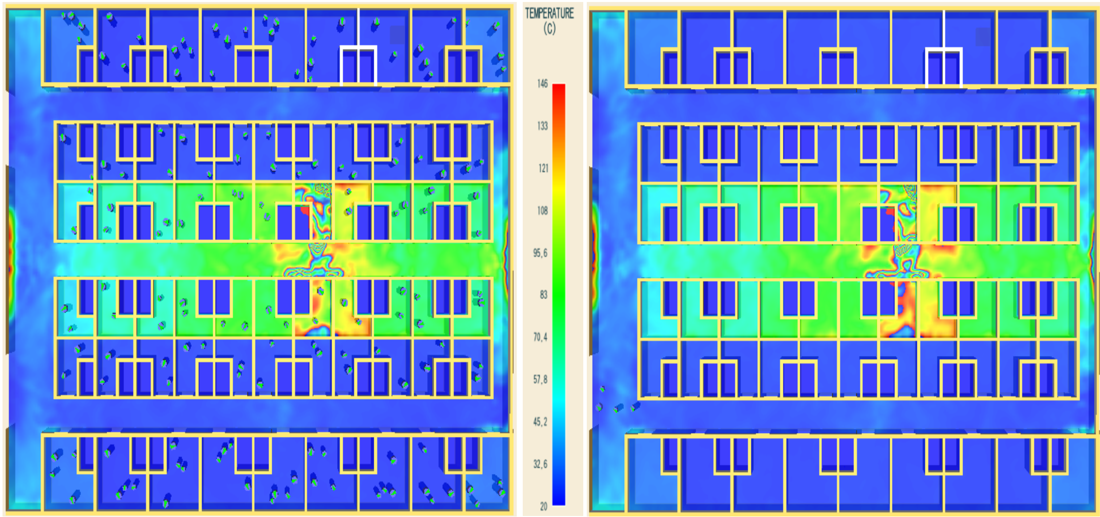

Figure 104 Temperature Night Scenario 7, Extreme Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility. High temperature affected 8 of them and FED quantities did not hinder the evacuation process.

6.2.8 Scenario cabin no8

In this simulation there is an extreme fire breakout in a 2-passenger cabin. Heat release rate and FED values of the detectors near the fire and the exits are presented in tables below.

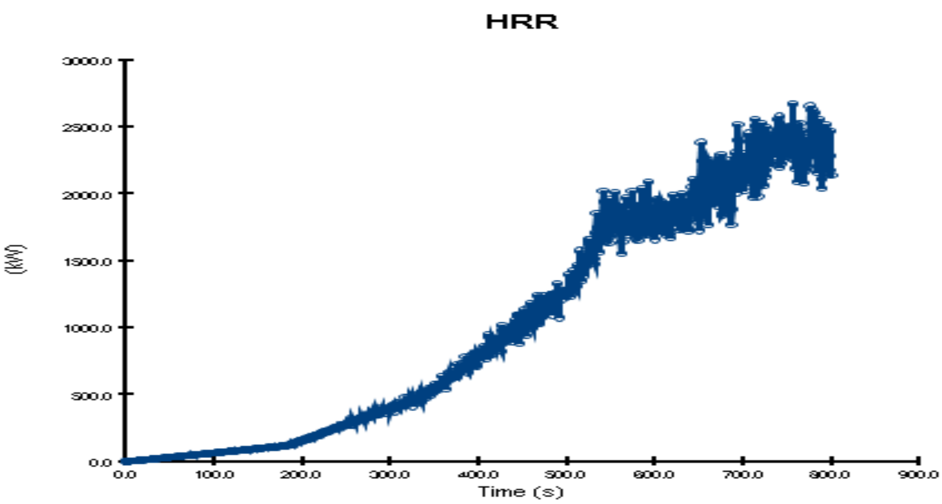

Figure 105 Heat Release Rate, Extreme Fire, Scenario 8

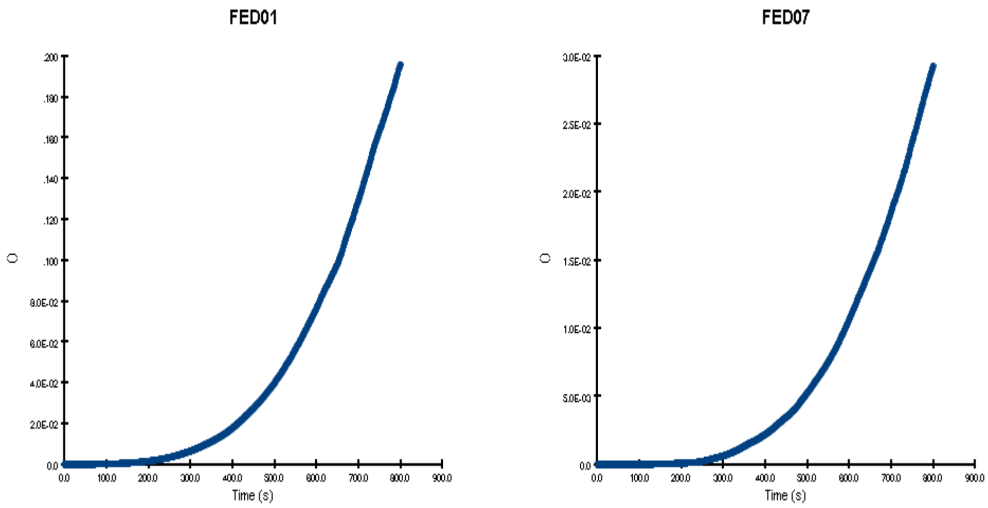

Figure 106 FED 1 & 7, Extreme Fire, Scenario 8

- Day scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in cabin where the fire broke out and the fire opposite of it, leading to almost zero visibility, and incapacitation of the passengers of the cabins. The cabins close to these ones reach a visibility of less 5m during the evacuation process, leading 2 more passengers to incapacitation but for the rest is considered enough to escape.

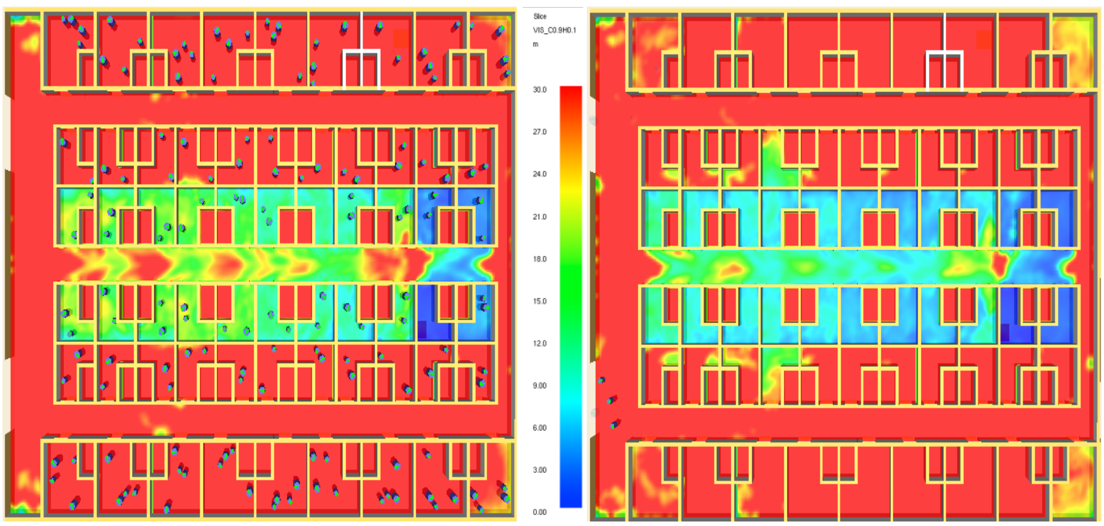

Figure 107 Visibility Day Scenario 8, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite but not in a way to cause incapacitation.

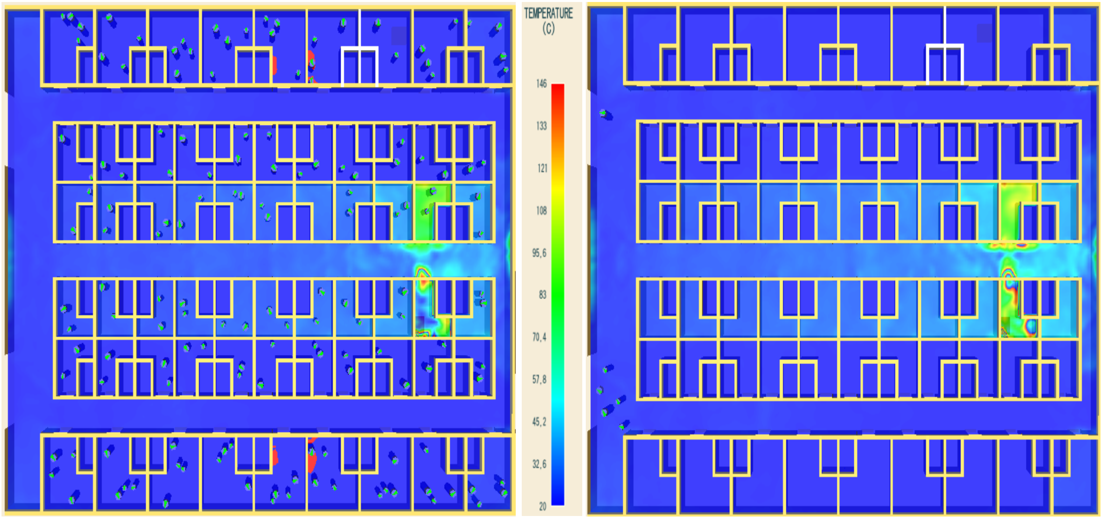

Figure 108 Temperature Day Scenario 8, Extreme Fire, Snapshots A & B

Results

In this scenario, 6 passengers did not manage to escape due to poor visibility. Temperature and FED quantities did not hinder the evacuation process.

- Night scenario

Visibility

In this scenario, visibility due to smoke is highly reduced in the cabins of the same corridor as the one the fire broke out. There is almost zero visibility in 22 cabins, leading to incapacitation of the passengers before the evacuation begins.

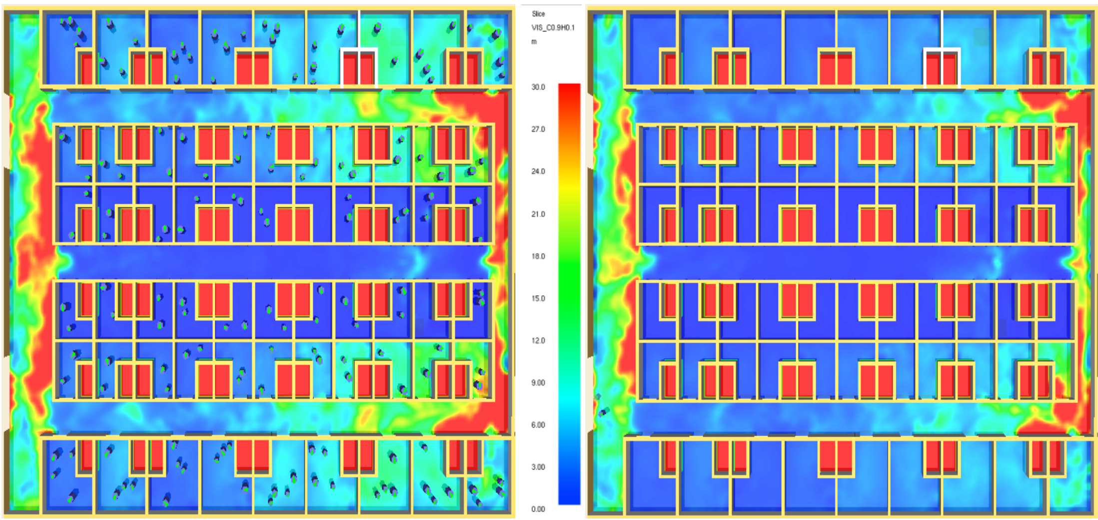

Figure 109 Visibility Night Scenario 8, Extreme Fire, Snapshots A & B

Temperature

In this scenario, temperature only affects the cabin of fire and the cabin opposite producing temperatures of over 100 ^{0}C and incapacitation. Cabins near to them are also affected during evacuation as well as the corridor.

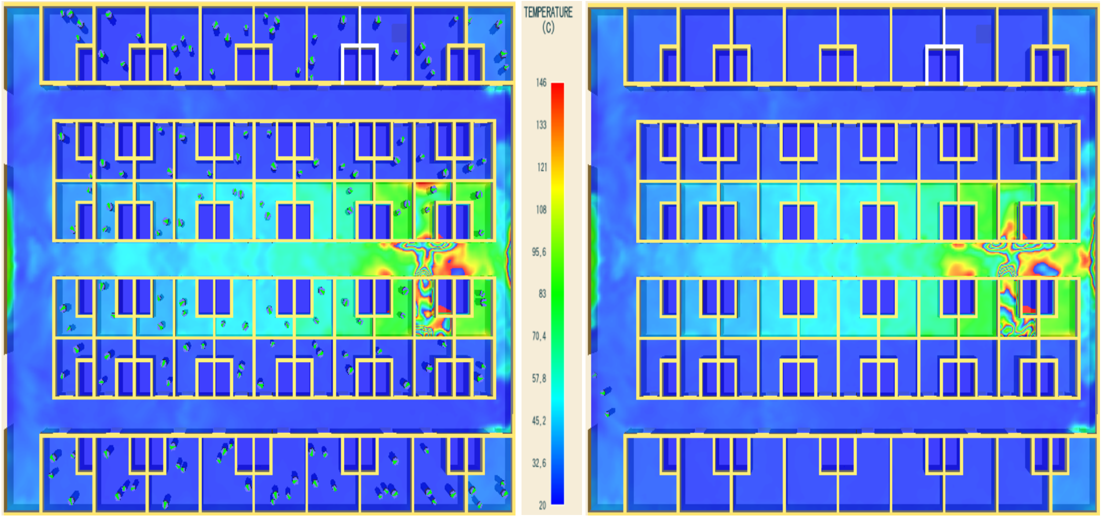

Figure 110 Temperature Night Scenario 8, Extreme Fire, Snapshots A & B

Results

In this scenario, 44 passengers did not manage to escape due to poor visibility. High temperature affected 8 of them and FED quantities did not hinder the evacuation process.

6.3 Summary

Throughout the different simulations, it has been observed that there is not a noteworthy difference regarding the number of people incapable to evacuate between moderate and extreme fire scenarios. On the other hand, there is a great variation as far as day and night scenarios are concerned. The main reason is the large variance in the awareness time between day and night.

Another significant alteration to the results has been spotted for the multiple positions of the fire. Fire in cabins closer to the exit provides better chances of escape for the passengers of the nearby cabins than a fire at a greater distance to the exits. On the contrary, when a fire is in a cabin closer to the exit, visibility is highly reduced as soot is creating an "obstacle" in front of the exits, eventually leading to a greater percentage of incapacitation. Results of passenger fatalities derived from each scenario are briefly presented in table 9.

Table 8 Summary of Fatalities

	Moderate		Extreme	
Cabin	Day	Night	Day	Night
1	2	56	2	56
2	2	56	6	56
3	4	50	4	56
4	6	56	6	56
5	2	44	2	44
6	2	44	2	44
7	4	44	4	44
8	4	44	6	44

7. Evaluation of Time to Egress

In order to examine a possible evacuation scenario in depth, the first case of moderate fire has been selected to simulate different evacuation situations.

7.1 Evacuation Scenarios at Different Speeds

In this part of the case study, 8 different scenarios (4 days – 4 nights) are tested, each one with different speed for each category of the passenger, so as to simulate special movements, such as fast walking or crawling. The speeds are shown in the table following. The variation of the speeds is due to the fact that there is an initial speed and a maximum speed that a passenger can reach.

Table 9 Examined Evacuation Speeds

Scenario	Man 1 (m/s)	Woman 1 (m/s)	Man 2 (m/s)	Woman 2 (m/s)
1	0.8-1.34	0.8-1.3	0.8-1.1	0.8-1.05
2	0.67-1.16	0.67-1.14	0.67-0.97	0.67-0.97
3	0.54-0.98	0.54-0.97	0.54-0.84	0.54-0.84
4	0.4-0.8	0.4-0.8	0.4-0.7	0.4-0.7

Man 1: Man with no mobility problems or young
Woman 1: Woman with no mobility problems or young
Man 2: Man with mobility problems or older
Woman 2: Woman with no mobility problems or older

In every scenario there are 2 different behaviors for the passengers evacuating. The first behavior is the "go to any exit behavior" which is assigned to every passenger, setting an awareness time of 5 minutes for day and 10 minutes for night after the alarm sets off. The second behavior is the "fire room behavior" which is assigned to the passengers of the cabin where the fire broke out and gives them a decreased awareness time of 4 minutes for day and 9 minutes for night after the alarm sets off.

Day Scenario 1

In the first scenario examined, after the simulation the results show a total of 2 deaths due to low visibility, while temperature and FED did not hinder the evacuation process.

In Table 11 below travel times for the passengers regarding different profiles and behaviors can be seen. An average of the time needed to evacuate is an important tool while examining the consequences of speed during evacuation.

Table 10 Evacuation completion time, by behavior and profile. Day Scenario 1

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	306.1	355.5	329.6
Fire room behavior	2	271	278.3	274.6
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	278.3	347.1	328
Man-old	31	306.2	352.4	328.8
Woman-young	48	271	354.1	329.4
Woman-old	31	308	355.5	329.6

Night Scenario 1

In the night scenario, visibility caused the incapacitation of 42 passengers, temperature caused the incapacitation of 2 passengers, while FED did not hinder the evacuation process.

Table 11 Evacuation completion time, by behavior and profile. Night Scenario 1

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	606.1	655.5	629.6
Fire room behavior	2	571	578.3	574.6
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	578.3	647.1	628
Man-old	31	606.2	652.4	628.8
Woman-young	48	571	654.1	629.4
Woman-old	31	608	655.5	629.6

Day Scenario 2

In the second scenario examined, the results exported show a total of 2 deaths due to low visibility, while temperature and FED did not hinder the evacuation process.

Table 12 Evacuation completion time, by behavior and profile. Day Scenario 2

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	307	362.1	333.8
Fire room behavior	2	276.2	285.5	280.8
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	285.5	355.7	332.4
Man-old	31	307.1	361	332.5
Woman-young	48	276.2	362.1	333.9
Woman-old	31	309.2	359.6	333.8

Night Scenario 2

In this night scenario, visibility caused the incapacitation of 42 passengers, temperature caused the incapacitation of 2 passengers, while FED did not hinder the evacuation process.

Table 13 Evacuation completion time, by behavior and profile. Night Scenario 2

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	607	662.1	633.8
Fire room behavior	2	576.2	585.5	580.8
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	585.5	655.7	632.4
Man-old	31	607.1	661	632.5
Woman-young	48	576.2	662.1	633.9
Woman-old	31	609.2	659.6	633.8

Day Scenario 3

In the third scenario examined, the results exported show a total of 2 deaths due to low visibility, while temperature and FED did not hinder the evacuation process.

Table 14 Evacuation completion time, by behavior and profile. Day Scenario 3

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	308	372.7	339.9
Fire room behavior	2	283.8	296	289.9
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	296	368.9	339.4
Man-old	31	308	369.1	337.7
Woman-young	48	283.8	372.7	340
Woman-old	31	309.8	371.1	339.4

Night Scenario 3

In this night scenario, visibility caused the incapacitation of 46 passengers, temperature caused the incapacitation of 2 passengers, while FED did not hinder the evacuation process.

Table 15 Evacuation completion time, by behavior and profile. Night Scenario 3

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	608	672.7	639.9
Fire room behavior	2	583.8	596	589.9
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	596	668.9	639.4
Man-old	31	608	669.1	637.7
Woman-young	48	583.8	672.7	640
Woman-old	31	609.8	671.1	639.4

Day Scenario 4

In the fourth scenario examined, the results exported show a total of 2 deaths due to low visibility, while temperature and FED did not hinder the evacuation process.

Table 16 Evacuation completion time, by behavior and profile. Day Scenario 4

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	309.4	391.7	349.2
Fire room behavior	2	296.1	315.7	305.9
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	310.2	386.4	349.4
Man-old	31	311.7	386.5	347
Woman-young	48	296.1	391.7	349.2
Woman-old	31	309.4	389	348.1

Night Scenario 4

In the last night scenario, visibility caused the incapacitation of 48 passengers, temperature caused the incapacitation of 2 passengers, while FED did not hinder the evacuation process.

Table 17 Evacuation completion time, by behavior and profile. Night Scenario 4

Completion Times by Behavior (s):				
Behavior	Count	Min	Max	Avg
Go to Any Exit	156	609.4	691.7	649.2
Fire room behavior	2	596.1	616	606
Completion Times by Profile (s):				
Profile	Count	Min	Max	Avg
Man-young	48	610.2	687.1	649.3
Man-old	31	611.7	686.5	647
Woman-young	48	596.1	691.7	649.3
Woman-old	31	609.4	689	648.2

7.1.1 Summary

By evaluating the outcomes of the multiple simulations, the difference in the time needed to evacuate is evident. Specifically, there is a 20 second increase on the average evacuation time, which, in turn, results in an increase to the number of passengers unable to escape safely. More specifically, in the last night scenario, 6 passengers have been added to the number of casualties, in addition to the casualties in the first night scenario. Another interesting outcome is the fact that the difference in speed seems to affect the younger passengers more than the older ones.

7.2 Evacuation Scenarios at Different Reaction time

A more detailed analysis on how time affects the survivability is also conducted. In order to examine the safe time for reaction, measurements of fatalities have been taken every 30 seconds for all the cases (8) of the moderate fire scenario.

A total of 1264 passengers were examined and the results are given in the time chart presented in figure 111. After 400 seconds, a great increase on the rhythm casualties occur is shown. That increase results in a great difference on the number of passengers unable to evacuate safely between day and night scenarios. To be more specific, the day scenario evacuation starts at 300 seconds after the alarm and finishes at approximately 380 seconds, resulting in a total of 42 casualties, while the night evacuation scenario starts at 600 seconds and finishes at approximately 680 seconds resulting in a total of 394 casualties. What is of great importance is the fact that the time span, at which the rhythm of casualties is the greatest, is right after the day evacuation scenario ends, and until 30 seconds before the night evacuation scenario begins. In conclusion to this, more passengers deceased before the evacuation begins than during the evacuation process.

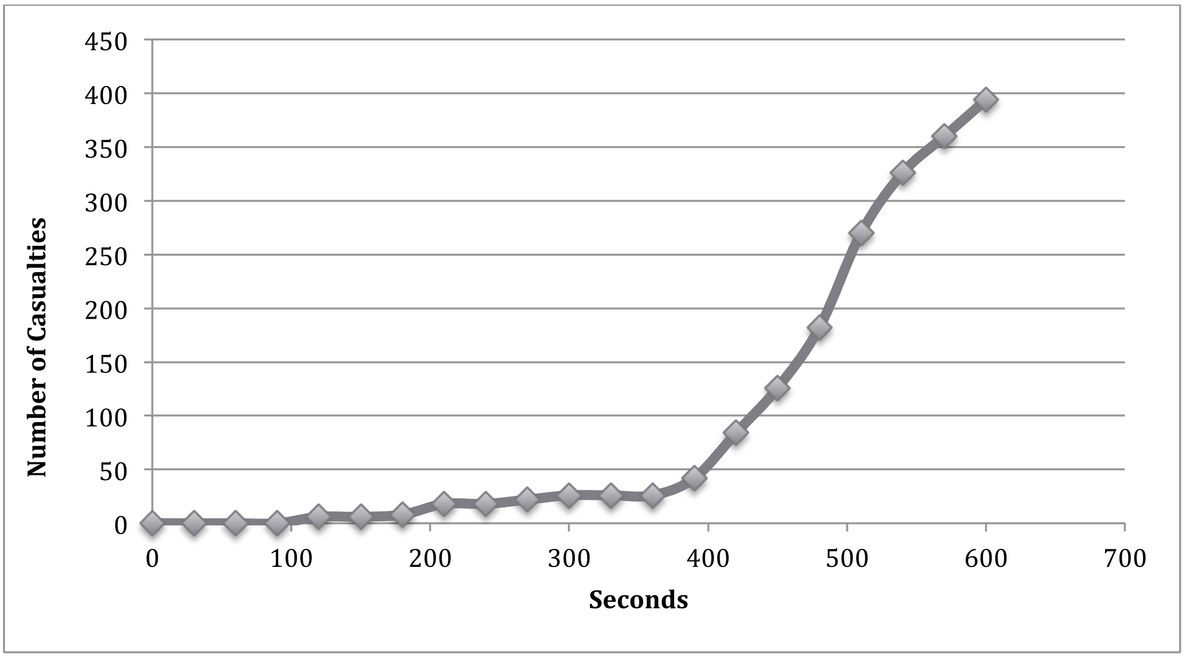

Figure 111 Casualties Over Time

8. Conclusion and Recommendations

Ship evacuation and fire simulation models have a profound impact on safety at sea. The combination of these modern simulation tools can give a detailed analysis on both human and materialistic behavior under emergency situations. Such analysis can be used in order to assess the design of a vessel, the procedures that need to be followed, the impact of a fire scenario and as a suggestion for potential solutions on problems that may occur.

This research has dealt with the issue of two fire scenarios and multiple evacuation simulations at a cabin area within a passenger ship. In general, a shipboard evacuation is a complicated procedure, and the involvement of fire is forcing the engineer to take into consideration the multiple effects fire has on evacuees.

The demonstration cases performed have shown that response time, location of the fire and speed of the passengers result in differences to the number of casualties. The delayed response to fire alarms can be fatal, especially during the night scenarios when the awareness time is considered greater than the day scenarios. The location of the fire has a significant role to the distribution of the fatalities, as fires closer to the exit are more convenient in day scenarios while the opposite is happening for the night scenarios. The speed of the passengers hugely affects the number of survivors as low speeds increase the incapacitation. In defense to all of the above, the decisions made by the passengers in order to evacuate are modeled using a simplified approach and without the aid of the crew.

Further additions are required to model more realistically the evacuation process in a fire scenario, such as the ability for the passenger to choose the most preferable root to the exit instead of the shortest one or the use of measures able to extinguish fire after a certain period of time. The use of observations on actual evacuations from burning ships or buildings would also be a helpful ad-on.

References

Amor, H. B., Murray, J., Obst, O. (2003). Fast, Neat and Under Control: Inverse Steering Behaviors for Physical Autonomous Agents. Research report. Intitut fur Informatik, Universitat Koblenz-Landau.

ANEK Lines. (2014). Press release 29-12-2014. ANEK Lines.Retrieved 10 April 2017.

Atreya, A. (2016). Convection Heat Transfer. In: The SFPE Handbook of Fire Protection Engineering, by Morgan J. Jurley (Eds), Chapter 3, pp.53-102.

Apte, V., Edwards, A., Fleischmann, C.M., Brian, J., Wade, C., Young, E. and Yung, D. (2005). Design Fires for Apartment Buildings - Literature Review. BRANZ Study Report No. 136, BRANZ Ltd, Porirua City, New Zealand.

Azzi, C. , Pennycott, A., Mermiris, G. & Vassalos, D. (2011). Evacuation Simulation of Shipboard Fire Scenarios. Proceedings, Fire and Evacuation Modeling Technical Conference 2011, Baltimore, Maryland.

Babrauskas, V. (2008). Quantifying the Combustion Product Hazard on the Basis of Test Results. Proceedings of Hazards of Combustion Products: Toxicity, Opacity, Corrosivity and Heat Release Conference. Interscience Communications Limited. London, England.

Babrauskas, V. (2016). Heat Release Rates. In: The SFPE Handbook of Fire Protection Engineering, by Morgan J. Jurley (Eds), Chapter 26, pp.799-905.

Brown, R. (1939). Chapter Four: The Morro Castle Disaster. *Men, Wind and Sea*. New York: Carlyle House, pp. 87-104

Ezekoye, O. A. (2016). Conduction of Heat in Solids. In: The SFPE Handbook of Fire Protection Engineering, by Morgan J. Jurley (Eds), Chapter 2, pp.25-53.

FSS (2007). International Code for Fire Safety Systems (FSS Code). In: I.M.O. (Editor).

Galea, E.R., Lawrence, P., Gwynne, S., Filippidis, L., Blackshields, D., Sharp, G., Hurst, N., Wang, Z. & Ewer, J. (2003). Simulating ship evacuation under fire conditions. In Proceedings of the 2nd International Pedestrian and Evacuation Dynamics Conference, Greenwich.

Galliano, M. & Watson, F. F. (2008). TSMS Lakonia Disaster 50th Anniversary. Gibraltar Heritage Trust.

Gann, R.J., Babrauskas, V., Peacock, R.D. and Hall, J. R. Jr. (1994). Fire Conditions for Smoke Toxicity Measurements. Fire and Materials, Vol. 18, No. 3, pp 193-199.

Glasa, J.,Valasek, L., Weisenpacher, P. & Halada, L. (2012). Use of PyroSim for simulation of cinema fire. International Journal on Recent Trends in Engineering and Technology, Vol. 7, No. 2, pp. 51–56.

Glassman, I. (1986). Soot Formation in Combustion Processes. Twenty-Second Symposium (International) on Combustion, pp.295-311. Combustion Institute, Pittsburgh.

Hall, J. R. Jr. (2005). Characteristics of Home Fire Victims. NFPA Fire Analysis and Research, Quincy, MA.

Hottel, H. C. (1984). Stimulation of Fire Research in the United States, after 1940 (A Historical Account). Combustion Science and Technology, Vol. 39, Issue 1-6, pp. 1-10.

Jin, T. (2002). Visibility and Human Behavior in Fire Smoke. In: The SFPE Handbook of Fire Protection Engineering. DiNenno, P. J., Drysdale, D., Beyler, C. L., Walton, W. D., Custer, R. L. P., Watts, J. M. Jr., Hall, J. R. Jr. (Eds). National Fire Protection Association, Quincy, MA, Chapter 2, pp.42-53.

Jones, W. W., Quintiere, J. G. (1984). Prediction of corridor smoke filling by zone models. Center for Fire Research, National Engineering Laboratory, National Bureau of Standards. Reprinted from: Combustion Science and Technology, Vol. 35, No. 5&6, pp.239-253. Washington, DC.

Manum, I. A. (1994). Developments into the 21st Century. Keynote address. In Institute of Marine Engineers Conference Proceedings on Fire Safety on Ships, pp. 5-6. London: Institute of Marine Engineers.

Marine Board of Investigation. (1966). Treasury Department United States Coast Guard.

McGrattan, K., Baum, H., Rehm, R., Mell, W., McDermott, R., Hostikka, S., & Floyd, J. (2010). Fire Dynamics Simulator (version 5), technical reference guide. NIST Special Publication 1018-5, National Institute of Standards and Technology, Gaithersburg, Maryland, USA.

McGrattan, K. & Miles, S. (2016). Modeling Fires Using Computational Fluid Dynamics (CFD). In: The SFPE Handbook of Fire Protection Engineering, by Morgan J. Jurley (Eds), Chapter 32, pp.1034-1066.

MSC Circ. 1238 (2002). Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships International Maritime Organization.

Mulholland, G. W. (2002). Smoke Production and Properties. In: The SFPE Handbook of Fire Protection Engineering. DiNenno, P. J., Drysdale, D., Beyler, C. L., Walton, W. D., Custer, R. L. P., Watts, J. M. Jr., Hall, J. R. Jr. (Eds), Chapter 2, pp.258-268. National Fire Protection Association, Quincy, MA.

Pillai, J. P. (2014). Fires on Ships. In International Conference on Fire at Sea, Organized by RINA, London.

Purser, D. A. & Berrill, K. R. (1983). Effects of carbon monoxide on behaviour in monkeys in relations to human fire hazard. Arch. Environ. Health. Vol. 38, pp.308-315.

Purser, D. A. (1984). A Bioassay Model for Testing the Incapacitating Effects of Exposure To Combustion Product Atmospheres Using Cynomolgus Monkeys. Journal of Fire Sciences. Vol. 2, No. 1, pp.20-36.

Purser, D. A. (2002). Toxicity Assessment of Combustion Products. In: The SFPE Handbook of Fire Protection Engineering. DiNenno, P. J., Drysdale, D., Beyler, C. L., Walton, W. D., Custer, R. L. P., Watts, J. M. Jr., Hall, J. R. Jr. (Eds). National Fire Protection Association, Quincy, MA, pp.83-171.

Salem, A.M. (2016). Use of Monte Carlo Simulation to assess uncertainties in fire consequence calculation. Ocean Engineering. Vol. 117, pp. 411-430.

Salgueiro, O. P., Jönson, J. & Vigne, G. (2012). Sensitivity analysis for modelling parameters used for advanced evacuation simulations. JVVA Fire & Risk. Madrid, Spain.

Zhang, S., (2000). Fire protection onboard: enhance fire safety by design. World Maritime University Dissertations. Paper 56.

SOLAS (2009). The International Convention for the Safety of Life at Sea (SOLAS). In: I.M.O. (Editor).

Solheim, T., Lorentsen, M., Sundnes, P.K., Bang, G. & Bremnes, L. (1992). The "Scandinavian Star" ferry disaster 1990 – a challenge to forensic odontology. International Journal of Legal Medicine. Vol. 104, Issue 6, pp 339-345.

Spyrou, K. J., Themelis, N. & Nikolaou, N. (2013). Towards risk - based fire safety assessment of passenger ships. In Proceedings of IMAM 2013.

Tewarson, A. (2002). Generation of Heat and Chemical Compounds in Fires. In: The SFPE Handbook of Fire Protection Engineering. DiNenno, P. J., Drysdale, D., Beyler, C. L., Walton, W. D., Custer, R. L. P., Watts, J. M. Jr., Hall, J. R. Jr. (Eds), Chapter 3, pp. 82-161. National Fire Protection Association, Quincy, MA.

Tien, C.L., Lee, K.Y., & Stretton, A.J. (2016). Radiation Heat Transfer. In: The SFPE Handbook of Fire Protection Engineering, by Morgan J. Jurley (Eds), Chapter 4, pp.102-138.

Themelis,N., Spyrou, K.J. (2012). Probabilistic fire safety assessment of passenger ships. Journal of Ship Research. Vol. 56, No. 3, pp. 1-23

Thunderhead Engineering, (2010). PyroSim: a model construction tool for fire dynamics simulator (FDS). PyroSim User Manual, Vol. 2, Thunderhead Engineering, Manhattan, USA, 2010.

Thunderhead Engineering (2016). Pathfinder User Manual.

Wikman, J., Evergren, F., Rahm, M., Leroux, J, Breuillard, A. Kjellberg, M. Gustin, L. & Efframsson, F. (2015). FIRESAFE Report: Study investigating cost effective measures for reducing the risk from fires on Ro-Ro passenger ships. European Maritime Safety Agency.

Wikman, J., Evergren, F., Rahm, M., Leroux, J, Breuillard, A. Kjellberg, M. Gustin, L. & Efframsson, F. (2017). FIRESAFE Report: Study investigating cost effective measures for reducing the risk from fires on Ro-Ro passenger ships. European Maritime Safety Agency.

Yamada, T. & Akizuki, Y. (2016). Visibility and Human Behavior in Fire Smoke. In: The SFPE Handbook of Fire Protection Engineering, by Morgan J. Jurley (Eds), Chapter 61, pp.2181-2206.

Appendix A

Pyrosim Software

A brief analysis is indicated below through images, on how Pyrosim user interface (UI) is set and what options are provided to an engineer regarding the structure of a fire.

Pyrosim has a user-friendly interface, giving the user the chance to instantly watch any changes made on the FDS code.

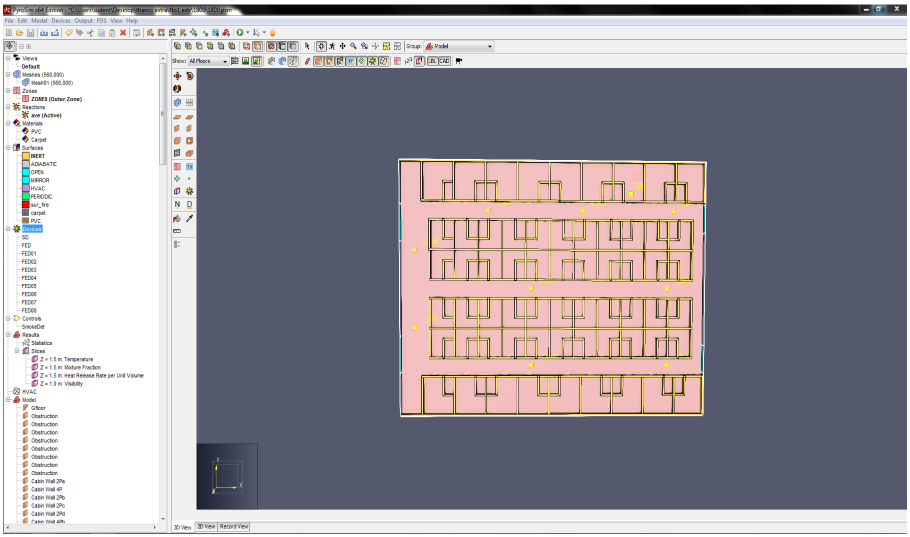

Figure 112 Geometry used in the research

As shown in the figure above, the user can react directly without the need for coding. The main features include an easy accessible panel from which one can modify the main characteristics of the simulation such as:

- ➢ The stoichiometry of the reaction

A reaction can be set by the use of four elements (C, H, O, N) and their compositions on a simple model or by more parameters in the advanced mode of the reaction table.

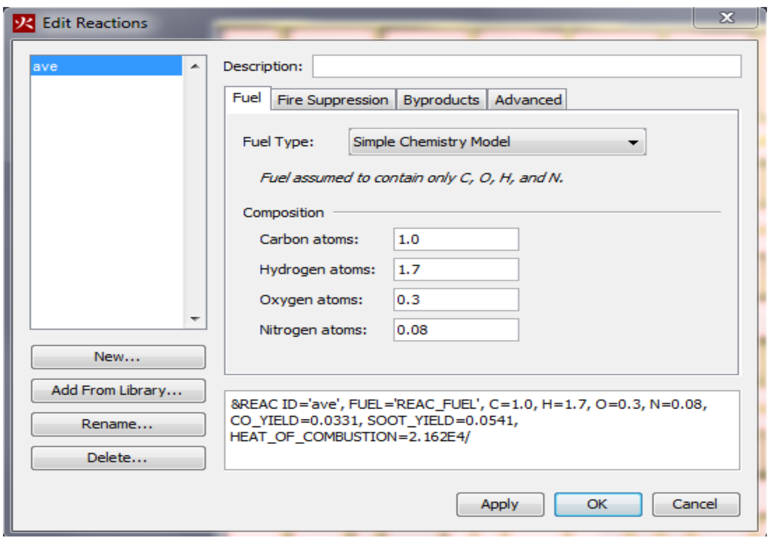

Figure 113 Reaction used in the research

➢ The properties of the materials used

Pyrosim offers a option of pre-arranged properties for a variety of materials, such as PVC, or the option to use the properties desired by the user.

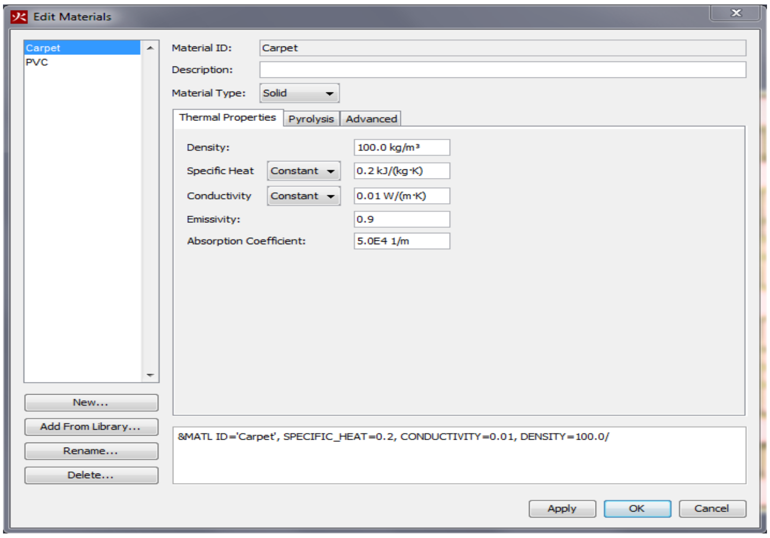

Figure 114 Properties of carpet used in research

➢ The surface of the objects

Surfaces are the part of the object that reacts with the fire and therefore Pyrosim allows an in deep variety of parameters that can be established.

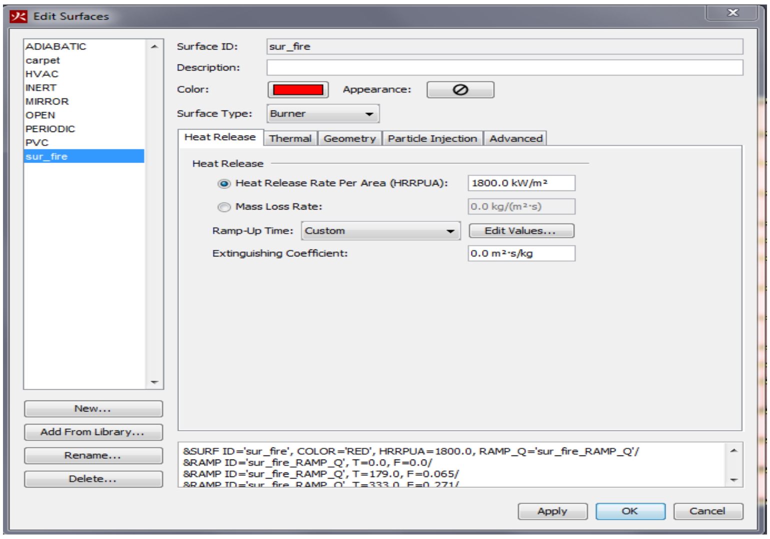

Figure 115 Surface properties used in the research

➢ The use of slices

Slices allow the user to evaluate various quantities throughout a XY plane at a specific height set by the user, for the entire surface area of the experiment.

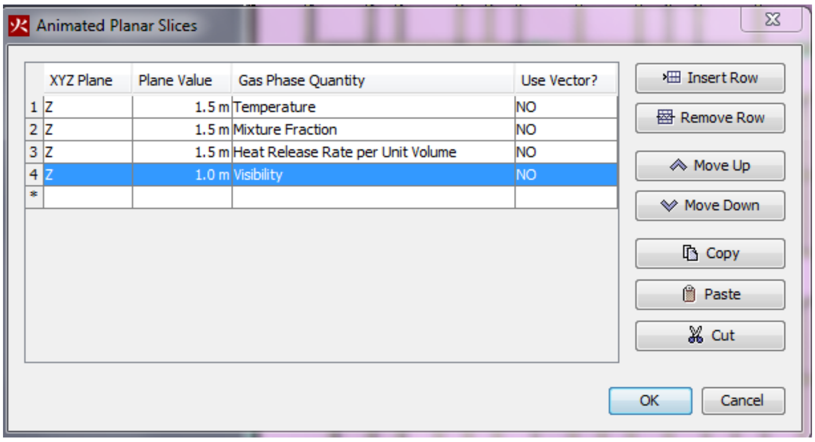

Figure 116 Slices used in the research

➢ Results Exported

Results are exported from the Pyrosim simulation as Excel files, giving details for the quantities requested during design for every second as shown in the pictures following.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	s	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kg/s	kg/s
2	Time	HRR	Q_RADI	Q_CONV	Q_COND	Q_DIFF	Q_PRES	Q_PART	Q_GEOM	Q_ENTH	Q_TOTAL	MLR_FUEL	MLR_TOTAL
3	0.00E+00	0.00E+00	-2.12E-03	2.22E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-2.11E-03	0.00E+00	0.00E+00
4	8.13E-01	0.00E+00	-2.63E-05	-4.50E-07	-2.07E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-2.31E-04	-2.70E-05	0.00E+00	0.00E+00
5	1.63E+00	4.00E-03	-4.99E-04	5.99E-05	-2.98E-06	-7.32E-07	0.00E+00	0.00E+00	0.00E+00	2.04E-03	3.55E-03	3.24E-07	3.24E-07
6	2.44E+00	3.54E-02	-9.75E-03	4.37E-04	-7.12E-05	-4.42E-06	0.00E+00	0.00E+00	0.00E+00	1.81E-02	2.60E-02	1.99E-06	1.99E-06
7	3.25E+00	1.34E-01	-2.63E-02	1.83E-03	-5.71E-04	-1.30E-05	0.00E+00	0.00E+00	0.00E+00	8.57E-02	1.09E-01	5.90E-06	5.90E-06
8	4.07E+00	3.24E-01	-4.90E-02	4.64E-03	-2.49E-03	-2.90E-05	0.00E+00	0.00E+00	0.00E+00	2.39E-01	2.77E-01	1.30E-05	1.30E-05
9	4.88E+00	5.45E-01	-7.96E-02	7.84E-03	-5.94E-03	-5.57E-05	0.00E+00	0.00E+00	0.00E+00	4.28E-01	4.67E-01	2.43E-05	2.43E-05
10	5.69E+00	8.31E-01	-1.24E-01	1.19E-02	-9.80E-03	-9.28E-05	0.00E+00	0.00E+00	0.00E+00	6.50E-01	7.09E-01	4.02E-05	4.02E-05
11	6.51E+00	1.26E+00	-1.66E-01	1.84E-02	-1.50E-02	-1.42E-04	0.00E+00	0.00E+00	0.00E+00	1.01E+00	1.09E+00	6.16E-05	6.16E-05
12	7.32E+00	1.74E+00	-2.03E-01	2.58E-02	-2.31E-02	-1.96E-04	0.00E+00	0.00E+00	0.00E+00	1.45E+00	1.54E+00	8.50E-05	8.50E-05
13	8.09E+00	2.27E+00	-2.50E-01	3.38E-02	-3.46E-02	-2.52E-04	0.00E+00	0.00E+00	0.00E+00	1.92E+00	2.02E+00	1.09E-04	1.09E-04
14	8.91E+00	2.79E+00	-2.89E-01	4.17E-02	-4.82E-02	-3.06E-04	0.00E+00	0.00E+00	0.00E+00	2.41E+00	2.49E+00	1.32E-04	1.32E-04
15	9.70E+00	3.30E+00	-3.31E-01	4.94E-02	-6.65E-02	-3.62E-04	0.00E+00	0.00E+00	0.00E+00	2.90E+00	2.95E+00	1.57E-04	1.57E-04
16	1.05E+01	3.76E+00	-3.82E-01	5.58E-02	-9.52E-02	-4.16E-04	0.00E+00	0.00E+00	0.00E+00	3.28E+00	3.34E+00	1.80E-04	1.80E-04
17	1.12E+01	4.25E+00	-4.27E-01	6.28E-02	-1.32E-01	-4.69E-04	0.00E+00	0.00E+00	0.00E+00	3.70E+00	3.76E+00	2.03E-04	2.03E-04
18	1.21E+01	4.77E+00	-4.68E-01	6.98E-02	-1.76E-01	-5.26E-04	0.00E+00	0.00E+00	0.00E+00	4.14E+00	4.20E+00	2.27E-04	2.27E-04
19	1.28E+01	5.30E+00	-5.00E-01	7.68E-02	-2.27E-01	-5.82E-04	0.00E+00	0.00E+00	0.00E+00	4.59E+00	4.64E+00	2.51E-04	2.51E-04
20	1.36E+01	5.90E+00	-5.50E-01	8.54E-02	-2.99E-01	-6.35E-04	0.00E+00	0.00E+00	0.00E+00	5.08E+00	5.13E+00	2.74E-04	2.74E-04
21	1.45E+01	6.32E+00	-5.83E-01	9.05E-02	-3.96E-01	-6.92E-04	0.00E+00	0.00E+00	0.00E+00	5.39E+00	5.43E+00	2.99E-04	2.99E-04
22	1.52E+01	6.85E+00	-6.57E-01	9.70E-02	-4.79E-01	-7.48E-04	0.00E+00	0.00E+00	0.00E+00	5.76E+00	5.81E+00	3.24E-04	3.24E-04
23	1.60E+01	7.37E+00	-7.10E-01	1.03E-01	-5.45E-01	-8.02E-04	0.00E+00	0.00E+00	0.00E+00	6.16E+00	6.21E+00	3.47E-04	3.47E-04
24	1.69E+01	7.90E+00	-7.62E-01	1.08E-01	-6.24E-01	-8.60E-04	0.00E+00	0.00E+00	0.00E+00	6.57E+00	6.62E+00	3.72E-04	3.72E-04

Figure 117 Characteristics of Fire used in Extreme Scenarios

	A	B	C	D	E	F	G	H	I	J	K	L
1	s	%/m										
2	Time	SD	FED	FED01	FED02	FED03	FED04	FED05	FED06	FED07	FED08	
3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
4	8.13E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
5	1.63E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
6	2.44E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
7	3.25E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
8	4.07E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
9	4.88E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
10	5.69E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
11	6.51E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
12	7.32E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
13	8.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
14	8.91E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
15	9.70E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
16	1.05E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
17	1.12E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
18	1.21E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
19	1.28E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
20	1.36E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
21	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	

Figure 118 Values of Detector used in Extreme Fire Scenarios

Appendix B

Pathfinder Software

A brief presentation on the use of Pathfider is indicated in the figures used below.

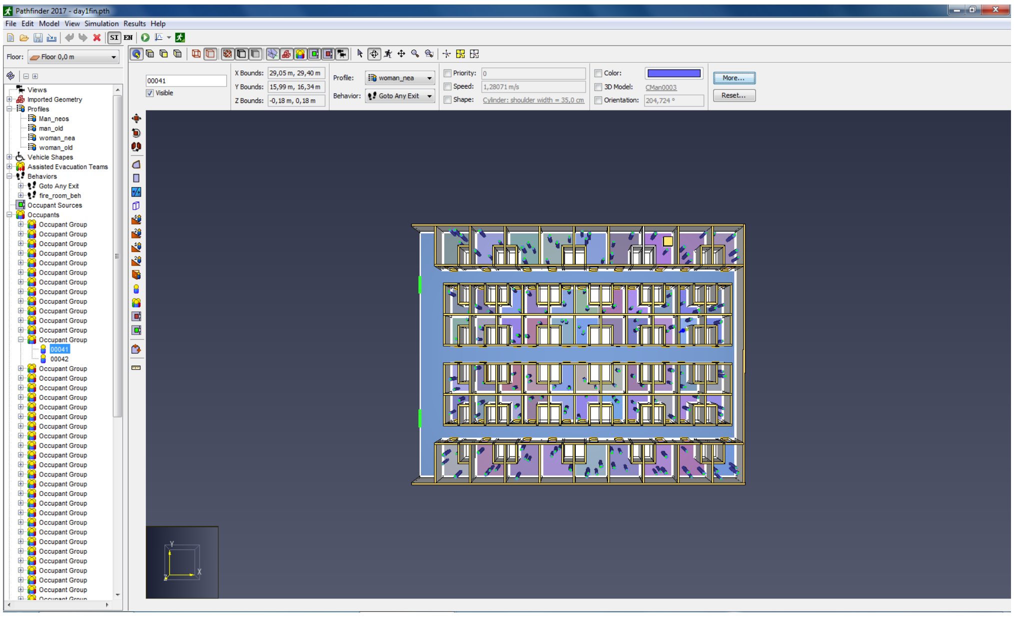

Figure 119 Interface used at the research

Pathfider offers a variety of options for the user such as the ability to use population with different profiles and behaviors, as well as the use assistance evacuation teams.

➢ Characteristics of the Population

A plethora of characteristics can be assigned on population, such as the speed and acceleration of their movement, the dimensions of their body, and which exit to choose.

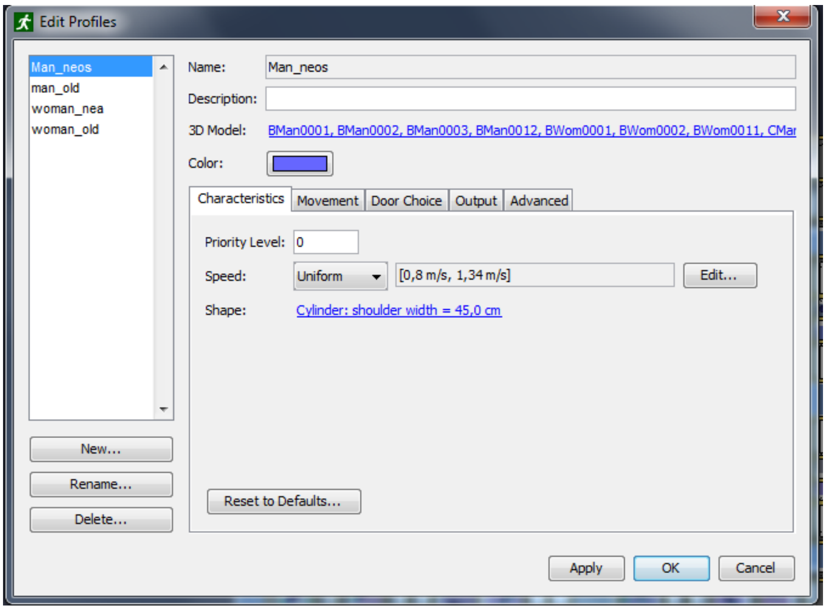

Figure 120 Characteristics of Population used in the research

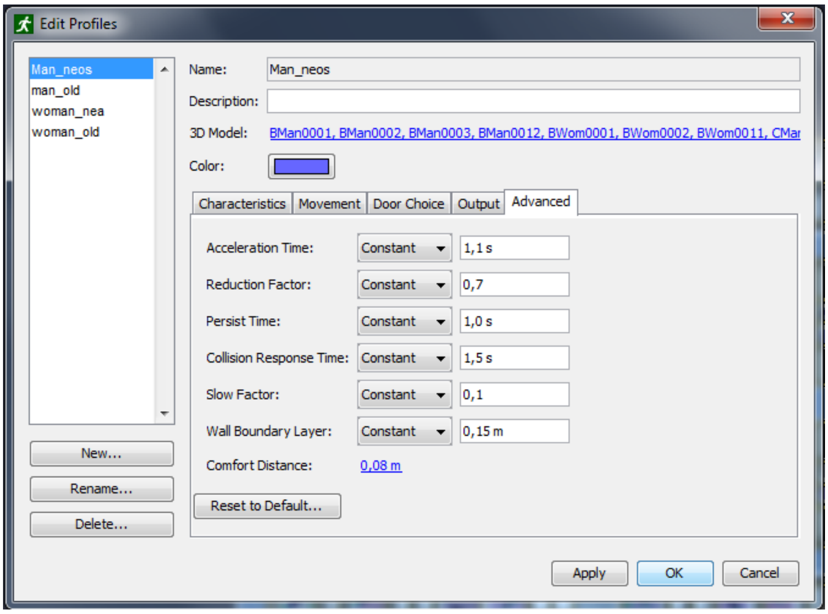

Figure 121 Characteristics of Population used in the research

➢ Results Exported

After a Pathfinder simulation, results are exported into Excel files, giving details for each passenger respectively, and for each second of the simulation about the quantities requested during design as well as the position of the passenger.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	t	id	name	active	x	y	z	v	distance	location	last_goal_sta	CARBON DIO	CARBON MO	OXYGEN VOL	HRRPUV	TEMPERATU	*FED_TOTAL*	
2	s				m	m	m	m/s	m			mol/mol	mol/mol	mol/mol	kW/m3	C		
3	0	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0	0	0	0	0	0	
4	1	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.00012	0.000005	
5	2	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.00012	0.00001	
6	3	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.00012	0.000016	
7	4	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.00012	0.000021	
8	5	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.00012	0.000026	
9	6	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.001311	0.000031	
10	7	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.001018	0.000037	
11	8	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.000725	0.000042	
12	9	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.000432	0.000047	
13	10	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.000139	0.000052	
14	11	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000397	0	0.207808	0	20.142675	0.000058	
15	12	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000394	0	0.207812	0	20.108137	0.000063	
16	13	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000392	0	0.207815	0	20.073598	0.000068	
17	14	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000389	0	0.207819	0	20.039059	0.000074	
18	15	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000387	0	0.207823	0	20.004521	0.000079	
19	16	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.00039	0	0.207818	0	20.055186	0.000084	
20	17	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.000392	0	0.207815	0	20.084366	0.000089	

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	t	id	name	active	x	y	z	v	distance	location	last_goal_sta	CARBON DIO	CARBON MO	OXYGEN VOL	HRRPUV	TEMPERATU	*FED_TOTAL*	
217	214	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.008555	0.000213	0.195663	0.000001	95.943832	0.013938	
218	215	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.008465	0.000211	0.195797	0	95.940907	0.014093	
219	216	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009641	0.000242	0.194046	0.001246	106.178495	0.014275	
220	217	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009461	0.000237	0.194313	0.00094	103.657397	0.014454	
221	218	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009282	0.000232	0.19458	0.000635	101.136298	0.014628	
222	219	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009103	0.000228	0.194848	0.000329	98.6152	0.014798	
223	220	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.008923	0.000223	0.195115	0.000023	96.094102	0.014965	
224	221	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009236	0.000231	0.194649	0.000294	103.100485	0.015134	
225	222	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009379	0.000235	0.194435	0.000603	104.469112	0.015307	
226	223	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009523	0.000239	0.194222	0.000912	105.83774	0.015484	
227	224	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009666	0.000242	0.194009	0.001221	107.206368	0.015663	
228	225	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009809	0.000246	0.193796	0.00153	108.574996	0.015846	
229	226	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.010195	0.000256	0.193222	0.000001	106.825001	0.016043	
230	227	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009923	0.000249	0.193625	0.000001	105.581409	0.016233	
231	228	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009652	0.000242	0.194029	0.000001	104.337817	0.016417	
232	229	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.009381	0.000235	0.194432	0.000001	103.094225	0.016595	
233	230	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.00911	0.000228	0.194836	0.000001	101.850633	0.016767	
234	231	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.010749	0.000271	0.192397	0.000003	110.143493	0.016973	
235	232	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.010676	0.000269	0.192505	0.000003	109.618003	0.017179	
236	233	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.010603	0.000267	0.192614	0.000002	109.092512	0.017383	
237	234	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.01053	0.000265	0.192722	0.000001	108.567022	0.017586	
238	235	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.010457	0.000263	0.19283	0.000001	108.041532	0.017787	
239	236	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.011489	0.00029	0.191295	0.000108	128.784491	0.018012	
240	237	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.011323	0.000286	0.191543	0.000082	124.279169	0.018235	
241	238	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.011156	0.000281	0.19179	0.000056	119.773846	0.018454	
242	239	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.01099	0.000277	0.192038	0.00003	115.268524	0.018669	
243	240	5	6	0	27.648118	24.894501	0	0	0	Room07	0	0.010823	0.000273	0.192286	0.000004	110.763202	0.018879	
244	241	5	6	1	27.790115	24.595123	0	0.58325	0.33684	Room07	1	0.011875	0.0003	0.190721	0.000007	122.81561	0.019109	
245	242	5	6	1	27.630598	24.036567	0	0.515588	0.928634	Room07	1	0.012022	0.000304	0.190501	0	124.421129	0.01935	

Figure 122 Quantities Measured for Each Occupant of the Research

Other useful results such as jam time for each passenger, the total distance covered and the time needed to cover the distance are also exported in excel files.

id	name	exit time(s)	active time(s)	jam time total(s)	jam time max continuous(s)	start time(s)	finish time(s)	distance (m)	last_goal_started time(s)
0	1	335.7	35.675	0.65	0.25	0	335.7	29.414	300.025
1	2	338.325	38.3	1.1	0.275	0	338.325	29.051	300.025
2	3	338.9	38.875	1.8	0.5	0	338.9	26.201	300.025
3	4	331.45	31.425	0.35	0.275	0	331.45	25.693	300.025
4	5	270.95	30.925	0.3	0.3	0	270.95	28.719	240.025
5	7	278.3	38.275	0.35	0.35	0	278.3	30.487	240.025
6	9	333.875	33.85	0.7	0.325	0	333.875	26.081	300.025
7	10	330.025	30	0.4	0.275	0	330.025	22.313	300.025
8	11	328.35	28.325	0.25	0.25	0	328.35	23.711	300.025
9	12	333.675	33.65	0.75	0.3	0	333.675	24.969	300.025
10	13	318.1	18.075	0.375	0.225	0	318.1	16.688	300.025
11	14	324.85	24.825	0.525	0.275	0	324.85	20.38	300.025
12	15	336.125	36.1	1.925	0.4	0	336.125	22.297	300.025
13	16	320.725	20.7	0.375	0.25	0	320.725	19.622	300.025
14	17	347.575	47.55	0.525	0.35	0	347.575	34.693	300.025
15	18	340.65	40.625	0.325	0.325	0	340.65	31.682	300.025
16	19	342.75	42.725	1.05	0.275	0	342.75	34.959	300.025
17	20	342.475	42.45	0.575	0.275	0	342.475	34.868	300.025
18	21	322.1	22.075	1.35	0.725	0	322.1	15.635	300.025
19	22	327.075	27.05	0.875	0.325	0	327.075	16.863	300.025
20	23	317.175	17.15	0.3	0.275	0	317.175	13.861	300.025
21	24	322.05	22.025	2.2	1.075	0	322.05	15.284	300.025
22	25	318.525	18.5	1.05	0.225	0	318.525	13.749	300.025
23	26	310.325	10.3	0.275	0.275	0	310.325	9.407	300.025
24	27	315.375	15.35	0.45	0.35	0	315.375	10.475	300.025
25	28	317.7	17.675	0.425	0.275	0	317.7	13.533	300.025
26	29	307.3	7.275	0.25	0.25	0	307.3	7.004	300.025

Figure 123 Movement Data for Each Occupant of the Researh