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Simulation-Based Prediction of Available Safe Egress Time in Care Home Fires

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Abstract

Fire safety in care homes is critical due to the vulnerable condition of elderly residents and because smoke can spread rapidly across the building. The traditional fire safety measures are inadequate for the vulnerable population group, which calls for a specific assessment of fire dynamics and its relationship with evacuation feasibility. This study evaluates the Available Safe Egress Time (ASET) in an elderly care home facility using the Fire Dynamics Simulator (FDS). An IFC model of the building is used, and four fire scenarios – laundry room, kitchen, sauna, and occupant room – are defined using experimental heat release rate curves. Tenability is assessed using visibility and Fractional Effective Dose (FED) criteria. A parametric study based on occupant room fire scenario and a simplified corridor model examines the effect of the corridor length on time required by staff members to evacuate the occupants. A sensitivity analysis is conducted for the toxic species yield using the laundry room fire scenario.

The ASET/RSET analysis is based on both the full-scale, IFC-based simulations and a parametric study. The former shows that evacuation time exceeds ASET even when increasing staff members from one to two. The latter concludes that use of evacuation chair allows evacuation of up to five occupants before FED incapacitation, while evacuation mattress permits none. In both scenarios, visibility reaches its tenability limit before the staff can initiate evacuation. The results indicate insufficient time for evacuation to a safe zone in almost any fire scenario. Visibility deteriorates almost twice as early as FED, causing irritation, restricting the movement and reducing the available evacuation window. Untenable conditions arise between three and twelve minutes in corridors adjacent to fire source.

The study involves uncertainties due to assumptions such as self-closing doors remaining open even after the smoke detection, excluding role of sprinklers in suppression and ventilation limitations. The future studies should explore more efficient methods for BIM-FDS integration, conducting more detailed comparisons between true and surrogate toxic yields, and studying the effect of HVAC systems on the fire and smoke spread within the building.

Keywords Fire safety, care home fires, FDS, FED, ASET, RSET, visibility

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Preface and acknowledgements

This thesis was done as part of the “Kvantitatiivisen paloturvallisuus-arvioinnin kehittäminen monimuotoistuviin hoivalaitosympäristöihin” - project, funded by the Finnish Fire Protection Fund (Palosuojelurahasto). The coordinator of the project was South Karelia Rescue Department.

I would like to express my sincere gratitude towards Prof. Simo Hostikka, whose guidance and support turned this project into a well-structured body of work. I am also thankful to all the staff members at Ortamonpuisto Care Home in Lappeenranta for their time and input on the work during our visit. My thanks also go to Jarno Rautiainen for providing the BIM models, and all other team members from LAB and the South Karelia Rescue Department for their valuable comments and insights on the project during the monthly team meetings.

I am especially grateful to my parents, who supported me throughout the project and asked for regular updates! and my friends who helped me navigate through the minor issues here and there. Finally, I would like to express my gratitude to Allah for giving me the strength to complete this project.

Otaniemi, 24 March 2025
Abdul Moid

Abbreviations

PBD	Performance Based Design
FED	Fractional Effective Dose
SBI	Single Burning Item
SD	Smoke Detector
ASET	Available Safe Egress Time
RSET	Required Safe Egress Time
MPI	Message Passing Interface
HRR	Heat Release Rate

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1. Introduction

The core principle of fire safety engineering is to make sure that all the occupants have sufficient time to evacuate the building before the fire pose any threat to life. In fire engineering, this sufficient time is referred to as the Available Safe Egress Time (ASET) and it must exceed the Required Safe Egress Time (RSET) by an adequate safety margin (C. M. Fleischmann, 2009). There have been many fire events in Finland in the past few years which unfortunately resulted in the deaths of individuals in places like apartments, care homes etc., where most of the incidents involve elderly people (Terveyden ja hyvinvoinnin laitos, 2024). According to the Finnish national policy, all the elderly people have a right to live at home safely and should have access to the services that they require. As the elderly population is increasing so is the need of safe elderly care homes. Most of the occupants in care homes are highly dependent on the nurses for their day-to-day tasks, hence they are considered to be affected by fire events the most. The data in Figure 1 shows the distribution of Finnish population from the year 1900 to a predicted value in 2070. It is clear from the image that there is a huge increase in the population of people over 65 in the future (Kuntaliitto, 2020).

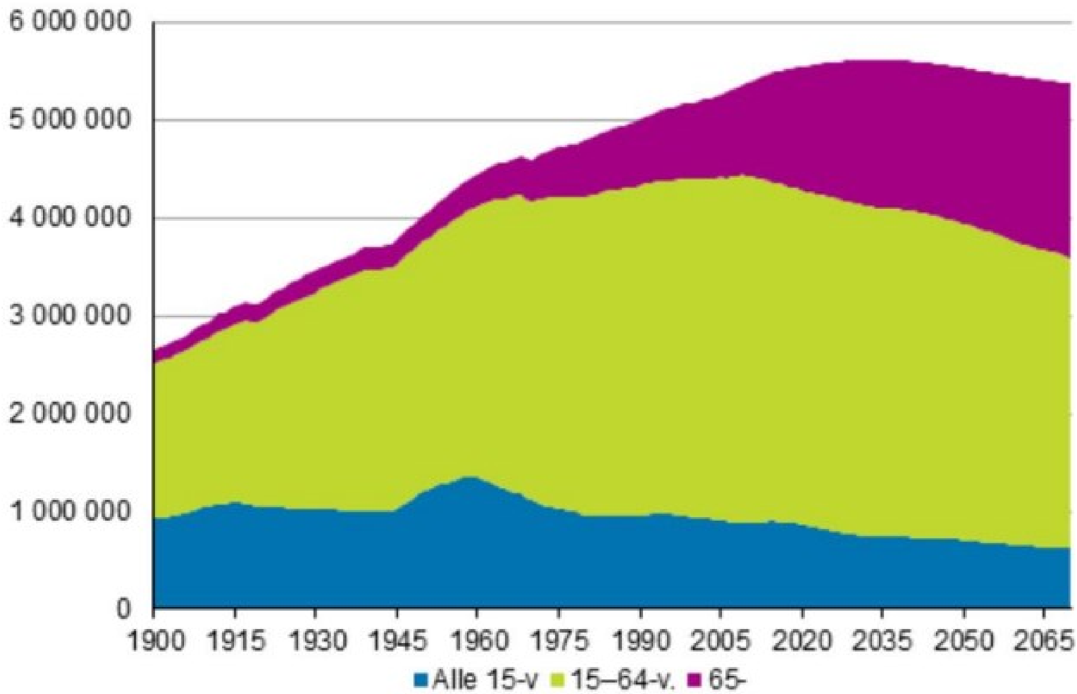

Figure 1: The share of different age groups in Finnish population in different years.

The safety level of the occupants is usually determined by comparing two timelines, i.e., the available safe egress time (ASET) and the required safe egress time (RSET). If the value of ASET is higher than RSET, occupants are considered to be safe; otherwise, they cannot evacuate to safe places before the untenable conditions develop and casualties occur (Kong et al., 2013). There is a freedom of design for the fire safety of a building during the design phase but if it has to be done for a completely constructed and inhabited building, it is suitable to collect the data of the people who use the building regularly. In the past, the ToPo (Functional Evacuation Safety in Care Services) project by LUT university did a study focused on data-based assessment for exit safety of elderly homes and it was identified that in order to describe the evacuation safety in a precise manner, the facility specific indicators are required i.e., characteristics of the residents, layout and purpose of building etc. (Koivuniemi et al., 2023). It also proposed the need for further assessment in this area by the future researchers. The issue is that there is no similar study made prior for this building and hence there is no accurate idea of how fast the conditions deteriorates during an event of fire, which called for a need of a thorough investigation. Because each building has its own requirements in terms of fire safety, results from other care home buildings could not be used for this one.

Hence, this thesis represents the one half of a two-part project that plans to determine the ASET and RSET of an elderly care home facility at Lappeenranta, South Karelia. The main focus of this part of the project is to determine the ASET at key locations in the building before the condition deteriorate to dangerous levels. To measure ASET, there are certain tenability conditions considered such as temperature, visibility, smoke layer height, FED etc. In this case, the tenability conditions taken as a measure of incapacitation are visibility and FED.

The experimental data used in this project was collected earlier by Antti Linna for his thesis work (Linna, 2024), where the tests were performed on different materials like sauna wood, kitchen stove, washing machine, and textiles. One purpose of the study is to make a comparison of the HRR obtained from the experimental data mentioned above with the simulated HRR, which later shows the effect of limited oxygen on HRR. The sensitivity analysis performed in the project indicates the precision of the results after changing some input parameters.

The thesis answers the following questions:

1. How does the input HRR curves developed from the experimental data compares to the HRR results obtained after the simulations for different fire scenarios and what are the factors causing any variations?

2. How do different fire scenarios i.e., sauna, kitchen, laundry room, and bedroom, affect the Available Safe Egress Time?
3. Is the ASET higher than the RSET based on the simulated fire scenarios and tenability conditions?

The section 5.2 shows the graphs that compare the trend of input HRR curves and the realized HRR obtained after different fire simulations. Each section of the fire scenario provides a reason for any possible deviation from the desired output. In the section 4.3.1, the experimental and the input HRR curves showing the relation between their trends and how the input HRR curves continue as t^2-fire.

The section 5.3 provides a comprehensive response to the effect of fire scenarios on the ASET by showing two different conditions i.e., early detection and delayed detection, with the help of graphs.

The third question is answered in the section 5.6 and 5.7, where the comparison of the ASET and RSET results obtained from the full-scale IFC model and parametric study are presented.

2. Literature review

The literature review consists of six different sub-sections where each section discusses specific parameters and its importance in the fire safety design. The section 2.1 explains the concept of ASET and RSET and their combined analysis using past studies. Section 2.2 defines the commonly used performance criteria in the fire simulations and their limits used in the design. The section 2.3 discusses the limitations and controversies involving the concept of ASET, while section 2.4 provides the detail of the commonly used tool in fire safety known as FDS. The section 2.5 provides an insight on the different FED methods used in the fire safety along with an alternative surrogate method also mentioned, while the last section 2.6 briefly mentions the importance of experimental data for the simulations performed in fire dynamics simulator.

2.1. Concept of ASET and RSET

Available Safe Egress Time (ASET) is defined as the amount of time available to people for escaping the fire affected area and reaching a safe zone. This time directly relates to the performance of the overall egress system (E. Tosolini et al., 2012). To estimate ASET, specific parameters are defined in the fire dynamics model by the user itself that include HRR, fire loads etc. (Kong et al., 2013). According to (Wu et al., 2023), ASET is the representation of time from the moment fire ignites until the conditions become dangerous for the people.

In the field of fire protection engineering, parameters like thermal radiation flux (kW/m^2 or W/cm^2), air temperature (˚C), concentration of CO or other toxic gases (%), smoke layer height (m), and visibility (m) are used as a measure to show tenability conditions in a certain place (Wu et al., 2023). The time taken to reach a specific tenability criterion is used to identify the safe egress time.

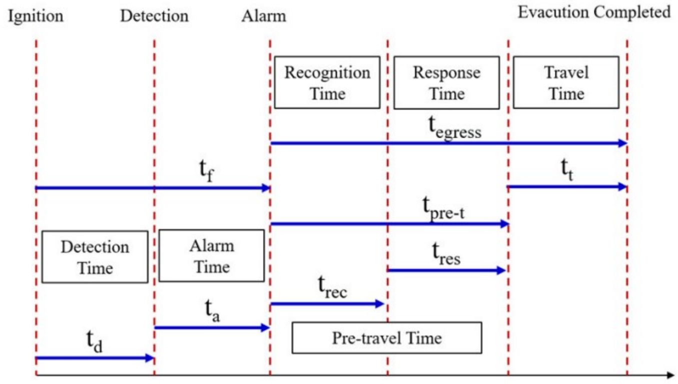

Figure 2: The timeline for the egress time (Wu et al., 2023).

The available time for the safe evacuation usually begins with the sounding of alarms, hence the timely detection of the smoke by the smoke detectors also plays a major role in extending the available time for the occupants. i.e., in Figure 2, the ASET starts from t_a (Wu et al., 2023). Whenever ASET is mentioned, the question to determine the RSET of that building also arises as both of them combines to give a comprehensive idea of the fire safety of the building.

As discussed, ASET is an important factor when dealing with fire safety; however, a complete fire safety design could not be completed without discussing the RSET, which gives the total time required by the occupants of a building to evacuate safely to the allocated safe zones. The difference between them is known as the safety margin (Schröder et al., 2020). For a person to safely evacuate from the vicinity of a fire event ASET has to be greater than RSET with a certain margin of safety defined here in the section. RSET mainly depends on several factors such as the detection time from the fire ignition, time of the day, occupants' health and age, travel time to the nearest safe zone etc. Initially, the concept was developed by Cooper in 1980 for a very simple two-zone model compared to the models these days, but it is now adopted and being used for the complex buildings. This is also the reason for the variations in the interpretation and definitions of the basic egress terms and has resulted in vast improvement across the fire safety field (Poon, 2014a). Figure 3 below shows the major factors on which the ASET and RSET depends, with the most important factors highlighted.

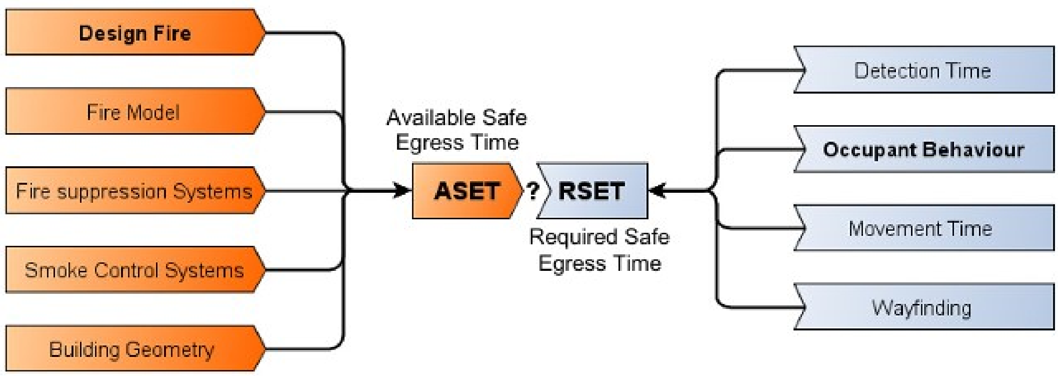

Figure 3: Factors affecting the ASET and RSET (Poon, 2014).

Straalen et al. explains the relation between ASET and RSET by assuming both in a normal distribution and such that their variation coefficients (V) also equate each other (van Straalen et, 2020). In a case, where the mean values of both ASET and RSET are equal, the probability of a person's safe evacuation is 0.5, which is not considered enough for the safe design of a building. The value of the probability depends on the variation coefficient if any other value of the safety factor is taken i.e., 1.5. Figure 4 depicts the change in the probability resulting in the change of variation coefficient. Variation coefficient shows how unpredictability is involved in the evacuation time and affects the chances of people evacuating safely in time.

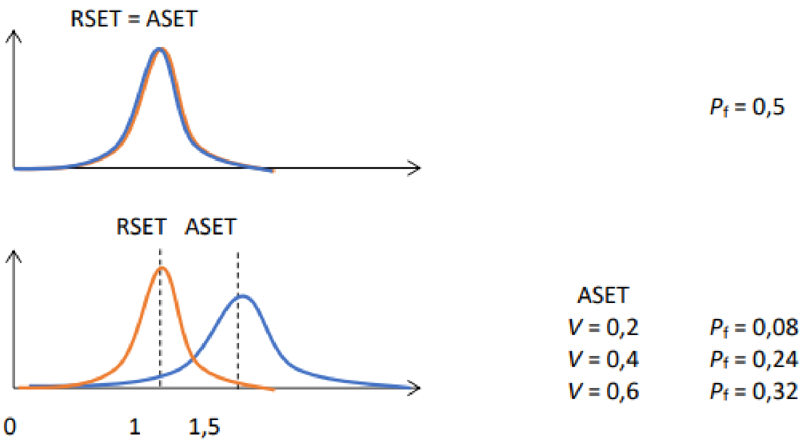

Figure 4: The graphical distribution of ASET and RSET (van Straalen et al., 2020).

2.2. Performance Criteria

When it comes to determining the ASET for a certain building, there are specific criteria on which the value is based on. These criteria are known as Performance Criteria which are mentioned already in the section 2.1. In this section, the explanation of criteria considered specifically in this project are explained in detail.

2.2.1. Fractional Effective Dose

Fractional Effective Dose (FED) is a measure of toxicity of the smoke and provides the indication of whether its dose is life-threatening to the people or not (Tuovinen et al., 2004). It is used to show the effect of asphyxiant gases on the human body in the form of comparison between the defined tenability limits and cumulative dose of those asphyxiant gases (Hostikka et al., 2021). It is a dimensionless quantity, and its value is usually measured in certain ranges as shown in table 1.

Table 1: The FED value ranges, and the respective percentage of the people incapacitated due to toxicity.

FED	Percentage of incapacitated population
0.0 – 0.3	0 – 11 %
0.3 – 1.0	11 – 50 %
1.0 – 3.0	50 – 89 %

The range of 0.0 – 0.3 shows the lowest safe limit used for almost all the age groups during the fire analysis, and it shows the maximum incapacitation of 11%. When the FED reaches 1.0, it can be observed that half of the population becomes incapacitated, while the value of 3.0 shows the incapacitation percentage of almost 90 for all age groups (ISO, 2007).

As mentioned earlier, the limit of 0.3 is used as the lowest safe limit but in projects involving sensitive groups such as elderly people who are extremely sensitive an even lower value is considered. In such cases, the tenability limit of 0.1 can also be considered, representing a very conservative assumption. However, even this limit could be high for highly sensitive people as about 4% of the population could get incapacitated at this dosage.

There are many gases causing the incapacitation during the fire events, which are cumulatively represented as FED; however, the combined effect of all gases is taken in terms of CO and HCN to avoid the complexity and make it simple for computational simulations unlike the Purser's method, which takes into consideration the effects of other gases separately.

Carbon Monoxide (CO)

It is present in all types of fire and is one of the toxic gases released during the burning of organic as well as synthetic polymers. When inhaled, it combines with haemoglobin present in human blood and form a compound called carboxyhaemoglobin (COHb). This slows the process of oxygen transport to the body and causes suffocation which may lead to unconsciousness or death. The concentration of COHb keeps increasing as long as the exposed person is inhaling Carbon Monoxide (F. Nystedt, 2003).

Hydrogen Cyanide (HCN)

Few decades back, the effect of HCN on humans was not taken into account as the half-life of cyanide in the blood is very low and the trace of its presence vanishes after few hours of a person's passing (Anderson et al., 1979). So, by the time blood samples were taken and tested, there were no traces of HCN, and it wasn't considered as a threat during the fire events or a cause of death. Now it is considered a major toxic component in fire incidents especially involving polyurethane, and textiles. It is 35 times more toxic than CO, and it damages the brain causing incapacitation and unconsciousness (Tuovinen et al., 2004).

2.2.2. Visibility

The formation of smoke during the fire event has a huge effect on the ability of a person to escape the fire zone. It not only obscures the light coming from any opening of the building but also affect the ability of people to follow any escape signs installed in the building (Purser et al., 2016). The staff of the buildings like care homes, hospitals etc., are responsible for the evacuation

of the occupants or patients and the smoke can create hinderance and lowers their performance levels, which makes it an even critical tenability criterion considered for the calculation of ASET, that ultimately affects the RSET. The property of smoke relies on the type of burnt material and it is a highly location-dependent quantity. A smoke with higher density can lead to a rapid decrease in the visibility as compared to a lower density smoke.
The limitations for the visibility during the event of fire are different for bigger and smaller buildings. Purser divides the buildings as large and small enclosures with small ones having the visibility limit of 5m, while the large ones with 10m (Purser et al., 2016).

2.2.3. Approach to measure the Performance Criteria

The performance criteria are measured in FDS by placing devices in the model at reasonable points. This section outlines the process of measuring those certain criteria.

Fractional Effective Dose

The FED device is added to the model for measuring the levels of toxicity and one out of three activity levels can be assigned to that device. The activity level, as clear from the term itself, tells if the person is at rest, doing light or heavy activity. In PyroSim, this can be selected by opening the device menu, while in FDS the rest, light, and heavy activity are chosen in terms of numbers on the property line as 1, 2 and 3 respectively. The default level is light activity. The FED levels are calculated against time and could be taken from the excel file created by the system.

Visibility

The visibility device can also be added similarly to the model at the required location, and the result can be checked in the same excel file as FED device results, and a graph can be plotted showing the variability in visibility with time.

2.3. Limitations in ASET Calculation

As with other aspects of fire safety analysis, there are also some controversies surrounding the methods used for calculation of ASET in buildings. Some believe that the concept has a lot of flaws and there is big room for consideration before one can confidentially accept the ASET values obtained. According to Babrauskas, the calculation of ASET after defining certain conditions is a two-part problem that first involves the careful definition of the tenability criteria and then comparing the results obtained from simulations to those defined criteria (Babrauskas et al., 2010). The study says that although the criteria are quite clear but the real-life experimentation to check their credibility is not possible because using human volunteers for the experiments could put their lives at stake. This affects the design process as the actual tenability criteria situations could end up being different from the simulated ones.

Junfeng write that ASET does not address the actual fire-related injuries to the occupants instead it deals with the spatial distribution of the hazardous condition (Junfeng et al., 2023). To elaborate, it means that the physical or psychological effects on the occupants exposed to fire-related accidents are not considered while defining ASET, which makes the understanding and prediction of potential risks posed to those occupants quite difficult or impossible. This becomes an even bigger issue if the targeted population belongs to sensitive groups like children, elderly, and sick people. The projects involving elderly people have limitations of toxicity based on the sensitive group requirements, but as mentioned in section 2.2.1 that there is a possibility those concentrations are still high for some of the occupants due to different health conditions.
Šplíchalová, A. et al. suggests a way to improve the ASET/RSET analysis by including a behavioural spectrum in the model, which takes into account the response of people with special needs in addition to the healthy people (Šplíchalová et al., 2021). Although this suggestion directly relates to the RSET of the process, but it also suggests that the final value for ASET be set in a way that it considers the ages and behaviour of all potential users of the building. In case, the fears or confusion of the occupants are not considered, it will delay the RSET, which will ultimately reduce the safety margin which separates RSET from ASET. Such cases could result in REST exceeding ASET and this represents a failed fire safety model.

Another interesting point is discussed by Schröder et al. (2020), which says that the specific points chosen for the measurement of ASET inside a building could not necessarily be the points where the conditions become life-threatening. As it is not possible to determine the ASET/RSET's defined limits at each point in the model, there is a possibility of having zero or negative difference in their values at points that are not considered. The engineers and designers are experienced personnel working on the projects, there is always a chance of overlooking a detail. It is also possible that the point, which is initially not considered vulnerable, ends up becoming somewhat a challenging point in the path of the occupants. However, it is a problem of a complex or large project. (Schröder et al., 2020)

This lack of spatial and temporal changes in the large spaces in ASET and RSET has been recognized by S. L. Poon in his work (Poon, 2014). He suggested the term Available Safe Utility Time (ASUT) and Required Safe Utility Time (RSUT) instead of regular ASET and RSET terms. The concept behind this is that he expressed the tenability conditions in terms of area of a certain room instead of considering the whole room, which is basically what is done in normal calculations. So, ASUT shows the available time to reach a defined tenability limit in a utility of an 'area' of a room instead of considering the whole room. However, the environmental conditions are changing when the tenability assessment of an 'area' is considered, so the simulations should be done until a steady state has been reached to get accurate results.

2.4. Fire Dynamics Simulator (FDS)

Fire Dynamics Simulator (FDS) is a Computational Fluid Dynamics (CFD) model which solves the Navier-Stokes equations that are appropriate for low-speed, and thermally driven flow on the transport of heat and smoke from fires (McGrattan et al., 2013). It is developed by the National Institute of Standards and Technology (NIST), which is available for free for the people to use. It has been used in the development and study of various fire-related projects in the industry and academia, both. The model has its applications in the Performance-Based fire safety design, smoke spread studies, sprinkler design etc. FDS takes the text-file as an input code to run the simulations and provides the results in both visual and numerical data. The visual representation of the model is done through SmokeView, which is a companion program of FDS. SmokeView reads the output file generated by FDS and presents an animation of the model mainly showing the path of smoke spread and HRR. A graphical interface of FDS is known as PyroSim developed by Thunderhead Engineering. This is a very convenient way of building a model and defining the properties as there is no longer the need to write each line of the code. The model can be made with the graphical features available in the interface of the software visualized in both 3D and 2D views; however, there is also the record view where one can see the actual FDS code being written side by side with the developing model. File formats like IFC is also supported by PyroSim and could be imported directly without any hassle. Figure 5 shows the interface of PyroSim with an imported IFC model of a building in 3D.

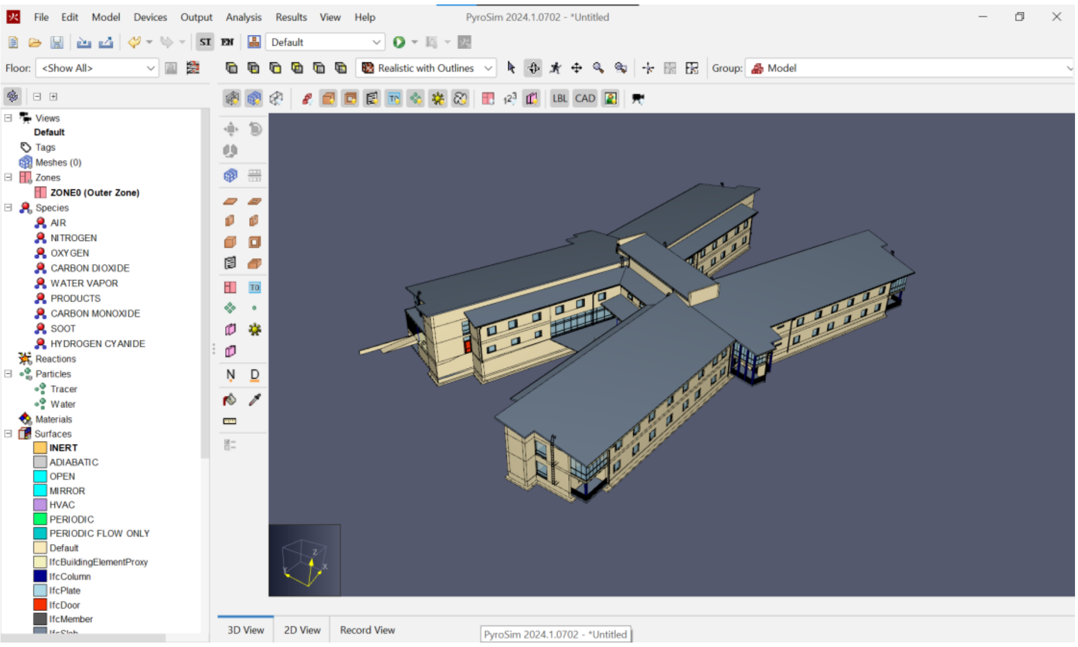

Figure 5: PyroSim version 2024.1.0702 interface.

The FDS code includes a defined mesh, desired simulation time, boundary conditions, fuel to be burned, HRR, yields of CO, soot and HCN (if any) etc. A complex model to have accurate results, relates to the size of the meshes. More detail on the mesh sizing is provided in section 4.1.2; however, a general idea is that a finer mesh leads to accuracy but beyond a certain point, the results stop changing significantly when the mesh is made any finer, this is known as convergence. Once reached, further mesh refinement is not recommended as it only increase computational cost without any meaningful accuracy gains. Message-Passing Interface (MPI) is a process which enables the use of multiple cores of a computer for running the FDS code, reducing the running time. The idea is to divide the FDS mesh to several parts in a way that each of the division satisfies the others surrounding it. Generally, each of the divided mesh is assigned an MPI 'process', which reduces the running time of large simulations. The MPI transfers the information between the meshes that helps in providing a unified result towards the end of the simulation instead of results for each of the divided meshes, separately (McGrattan et al., 2013).

2.5. FED Methods

As defined earlier in section 2.2.1, FED is a measure of toxicity which compares the cumulative dose of asphyxiant gases with the defined tenability limits. In this section, the two alternative methods of calculating FED are discussed: Purser's method and ISO 13571 standard method.

The Purser's method is a comprehensive one with more asphyxiant and irritant gases considered. The asphyxiant gases include HCN, CO, Nox, and the irritant gases include the HF, HBr, HCl, SO2, acrolein (C2H4o), and formaldehyde (CHOH). In this case, the FED equation becomes:

$$FED_I(t) = \int_0^t \left[\left(F_{I,CO} + F_{I,CN} + F_{I,NOx} + FLD\right)V_{CO2} + F_{O2}\right]dt \tag{1}$$

where 't' represents the time, and 'I' shows the point of incapacitation by the dose of that particular gas. Each of the factors involved has its own respective equations.

$$F_{I,CO} = \frac{3.317 \times 10^{-5} X_{CO}^{1.036} \times {}^{\cdot}V}{D} \tag{2}$$

$$F_{I,CN} = \left[\frac{1}{220} e^{\left(\frac{X_{CN}}{43}\right)} - 0.0045\right] \tag{3}$$

$$F_{I,NOx} = \frac{1}{1500}\left(X_{NO} + X_{NO_2}\right) \tag{4}$$

$$V_{CO_2} = \left[\frac{e^{\left(0.1903 \times X_{CO_2} + 2.0004\right)}}{7.1}\right] \tag{5}$$

$$F_{I,O_2} = \left[\frac{1}{e^{\left(8.13 - 0.54(20.9 - \% X_{O_2})\right)}}\right] \tag{6}$$

All the above equations have the factor 'X_i', which defines the volume fraction of the gas at a given time 't'. The unit of Oxygen is in percentage (%) while the rest of the gases are in ppm.

The above equations show the effect of asphyxiant gases, while the effect of irritant gases is represented a term called Fractional Lethal Dose (FLD) that is given by the following equation:

$$FLD(t) = \int_0^t \sum_{i=1}^{N} \frac{X_i(t)}{FLD_i} dt \tag{7}$$

ISO 13571 only considers the asphyxiant effect of HCN and CO as it assumes that these two gases are the major contributors towards achieving the untenable condition at a particular place.

$$FED_I(t) = \sum_0^t \frac{X_{CO}}{35000} \times v_{CO_2}\Delta t + \sum_0^t \frac{X_{HCN}^{2.63}}{1.2 \times 10^6} \times v_{CO_2}\Delta t \qquad (8)$$

where,

$$V_{CO_2} = e^{\left[\frac{X_{CO_2}}{5}\right]} \qquad (9)$$

The Δt in the ISO equation shows the increment of time between the measurement time instances (Hostikka et al., 2021).

2.5.1. Surrogate FED Method

As discussed above, the FED calculation by the Purser's method is a complex process as it considers asphyxiant as well as irritant gases in its calculation. The surrogate method is an alternative to Purser's FED formulation method which involves the simplification of the formula and considers CO and HCN as surrogates for other gases through the combination of close-to-linear gases included in the original equation to a single artificial gas (Hostikka et al., 2024).

In the study, surrogate equations are developed for CO and HCN that account for all other gases in the calculation of FED. The surrogate yield for CO is given as follows:

$$y_{CO,surr} = y_{CO} + \left(W_{CO} F_{ref,CO} \sum_{i \neq CO,CN} \frac{y_i}{W_i F_{ref,i}} \right)^{\frac{1}{1.036}} \qquad (10)$$

The surrogate yield for HCN is given by the following equation:

$$y_{HCN,surr} = y_{HCN} - W_{HCN} \left(\frac{y_{NO_2}}{W_{NO_2}} + \frac{y_{NO}}{W_{NO}} \right) \qquad (11)$$

The final FED equation after using the surrogates becomes:

$$FED_{in}(t) = \int_0^t \left[\left(\frac{X_{CO,surr}^{1.036}}{F_{ref,CO}} + \frac{1}{220} e^{\left(\frac{X_{HCN,surr} - X_{NO_x}}{43} \right)} - 0.0045 \right) V_{CO_2} + F_{I,O_2} \right] dt \quad (12)$$

2.6. Experimental Data for Fire Simulations in FDS

The fire safety in care homes create some challenges due to the sensitive and vulnerable group of occupants residing in the facilities. In order to create a workable fire safety plan, accurate and real-life input data is required that could be used as a reference for tools like FDS. (Linna, 2024) performed some experiments using different materials at the Eurofins Expert Service labs in Espoo. The data included the information regarding the HRR for different experiments, toxic yields, and the methods to utilize those toxic yields in a more simplified and efficient way, while keeping the overall effect similar. The data is collected for fires in sauna, washing machine, textile, stove, and hygiene mattresses. All the tests were performed according to standard EN13823 also known as the SBI test.

Multiple samples for each case were burned and the HRR for the tests have been recorded. The fitted curves were developed for each scenario to depict the growth trend of the measured results. These fitted curves are used as a reference for the input data used in the FDS simulations. The integration of the experimental data with different simulation approaches developed during the modelling process can result in a better understanding and development of fire safety system in the care home facilities that leads to more effective evacuation strategies.

3. Ortamonpuisto Care Home

The Ortamonpuisto care home building is located in Lappeenranta, South Karelia in eastern Finland, built in 2010. It is a place for the elderly people who are in need of 24 hours physical and mental assistance. The facility is owned and operated by the South Karelia welfare area (Etelä-Karjalan hyvinvointialue). It is a modern building with two floors, one basement and four wings as shown in Figure 6.

Figure 6: First Floor Plan of Ortamonpuisto Care Home.

There are 83 individual rooms for occupants with attached bathrooms in each of them. There are common spaces on both floors with TVs installed for the entertainment purposes, and offices for the staff members. There is one kitchen on the first floor, which is non-functional and two kitchens on the second floor in two different wings. The second-floor kitchens are only for the staff members and the occupants are not allowed to use them. One of the 83 occupants' rooms with bed and a nightstand along with the attached bathroom are shown in Figure 7.

Figure 7: The vacant occupant room and bathroom in the facility.

There is a small lawn area on the rear of the building for outdoor socializing in the summer. There is also one sauna on each floor. In the basement, there is a laundry room and some storage spaces shown in Figure 8.

Figure 8: Laundry Room

The hallways have glass doors that leads to the lobby area on both floors. Normally, these doors are open for the unrestricted movement of the occupants and staff member; however, in an unfortunate event of fire the

doors prevent the smoke spread in the neighbouring wings by closing automatically. There are smoke detectors and sprinklers installed in all occupant rooms, corridors and kitchen. Similar to other buildings, the use of elevators is also not allowed during the fire, instead, the occupants are supposed to be escorted out with the help of staff through the stairs.
There are different number of staff members in the building depending on the time of the day. There are nurses on-duty and are responsible for all kinds of tasks related to the occupants such as their food, regular walks, cleaning etc. According to the facility's management, there should always be at least one staff member present on each floor. The Figure 9 below shows the parking space leading to the main entrance of the care home.

Figure 9: The front parking space.

4. Methods

This chapter describes the geometry of the model used for this project, design of the fire scenarios using the experimental data, the tenability assessment discussing the points where the conditions become dangerous for the occupants and the sensitivity analysis in which a separate corridor model is made to measure the tenability conditions on either ends of the corridor. The experimental data for the design fires is taken from the experiments performed by Antti Linna during his project (Linna, 2024).

4.1. Simulation Geometry

PyroSim, the graphical interface of Fire Dynamics Simulator is used to edit the model geometry and define the necessary input parameter. The process of importing the model to PyroSim and the basic initial steps to perform before the design of fire scenarios are explained in this section.

4.1.1. Model Generation from IFC file

Industry Foundation Classes (IFC) is an open standard building information model, developed by the International Alliance for Interoperability (IAI) in 1995. IFC model is adopted as an international interoperability standard for the exchange of all building-related information between the Architecture, Engineering, Construction/Facilities Management (AEC/FM) community (Dimyadi et al., 2008). The model also contains information about any furniture and other additions in the model. The process of importing the model to PyroSim is straightforward and do not require the conversion to any other file type. This accelerates the fire modelling process as the tedious task of manual modelling is solved by the IFC file. The model of care home for this project was also obtained in the IFC format which was imported to PyroSim for simulations.

The use of IFC files is advantageous for the fire safety engineers as it makes the process very smooth and quick by importing the geometry of the structure. More time could be spent on determining the level of accuracy required from the results and hence defining the meshes accordingly instead of making the model from the scratch. Any minor modifications i.e., changing fire loads, adding devices etc., can be done easily and after defining all the parameters mentioned in section 2.2, the model could be run in a significantly lower amount of time.

Where IFC has its own advantages, it also has some disadvantages encountered during the process. The main downside of the model especially for fire simulations is the long run times of the simulations itself due to the number of cells in the meshes. If the buildings' plan is not a regular rectangular or square shaped unlike in this project, hundreds of thousands of cells or even more are wasted in the simulations as there is no building extension in that region. Even though the processors take their time and memory to simulate those 'wasted' cells (Figure 10), there is no useful output coming out of it, making it a waste of time and processing power. In one of the model cases, the wasted cells can be observed between the top and bottom right wings shown in Figure 10.

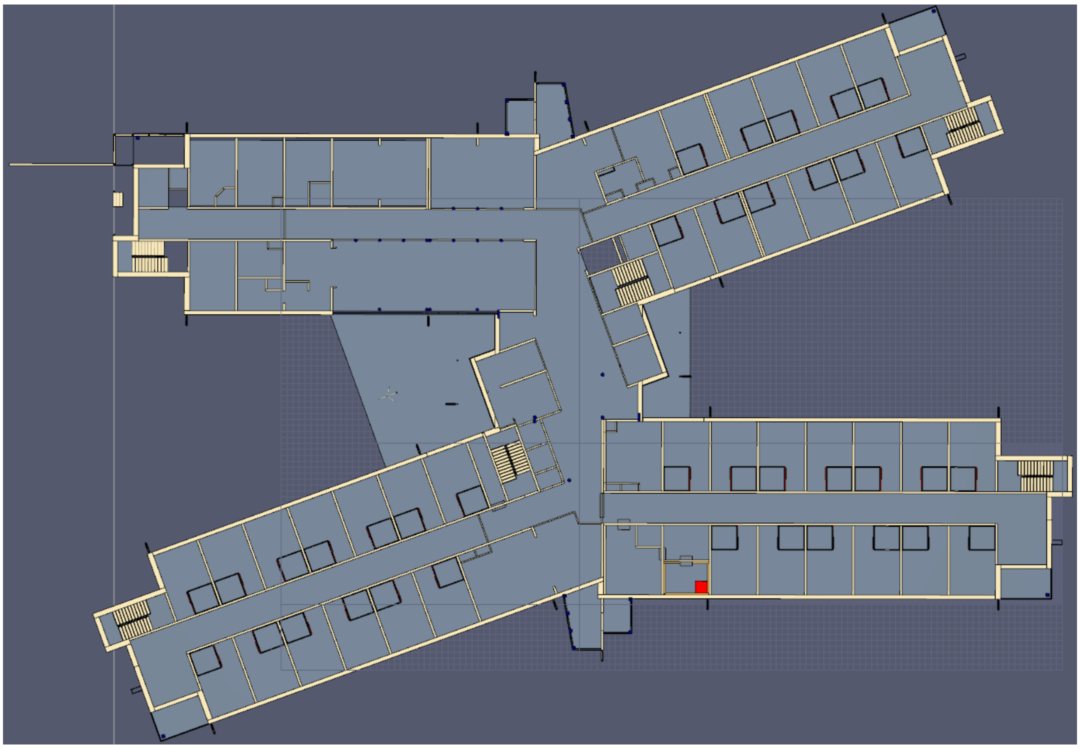

Figure 10: The care home model showing 'wasted' cells.

4.1.2. Defining Meshes

As mentioned in section 2.4, all FDS calculations should be performed within a domain made up of rectilinear volumes called meshes. Each mesh is divided into smaller cells, the number of which depends on the desired resolution of the flow dynamics. It has been discussed already that the decrease in size of each cell improves the accuracy of the results to a certain extent; however, slowing down the computation speed. In this project, each scenario has multiple meshes with multiple size mainly to limit the extra-long simulation time. For example, the Figure 11 shows the model in one of the fire scenarios having nine meshes. The mesh resolution is 0.5m except for the blue (highlighted) ones which has finer resolution of 0.16m because of the presence of fire source within its boundaries. This decision is made to achieve more accurate results with that particular mesh. Similarly, for other scenarios, the mesh sizes are different depending upon the location i.e., kitchen, laundry room etc., of the fire source.

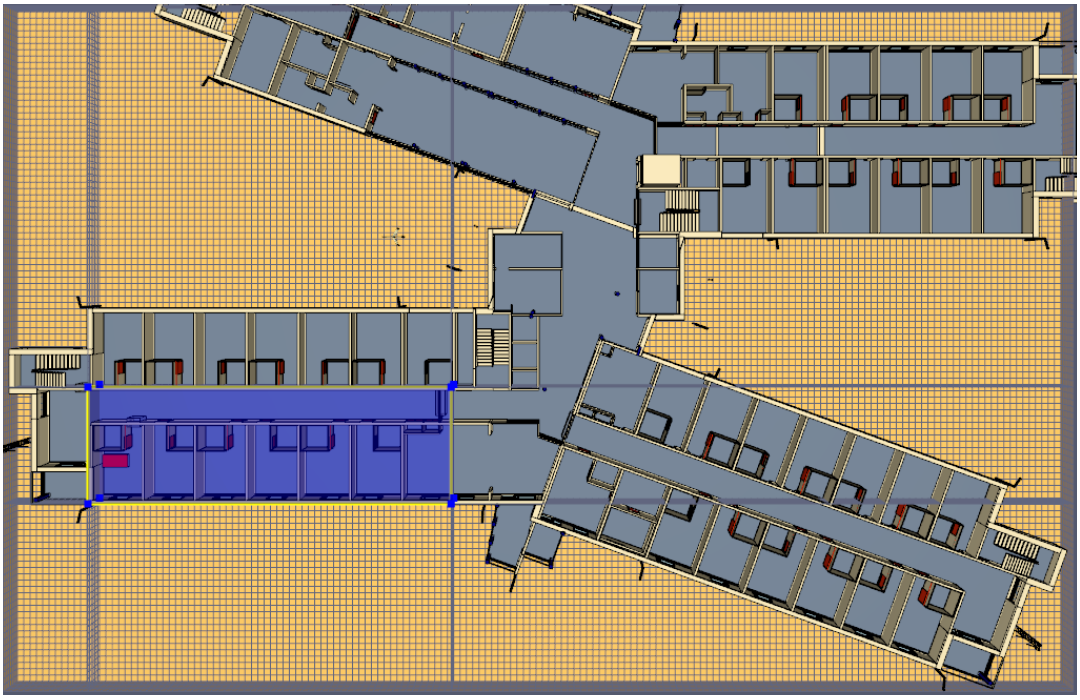

Figure 11: The model showing division of meshes.

4.2. Measurement of the Performance Criteria

The two mentioned performance criteria are measured at different locations in the model.

The FED is measured by taking into account the potential routes taken by the occupants to evacuate during an event of fire. FED devices are placed closed to the fire source, in corridors, stairs, lobbies etc., at a certain height from the floor level to measure the results.

In the model, the visibility during the fire event is also measured along the exit routes of the building that could be used by the staff and occupants. The measurements are taken at the same points as FED. Visibility directly relates with the smoke formation and the smoke correlates with the soot yield, whose value is inserted as an input in the model before the simulation (Węgrzyński & Vigne, 2017). Higher soot yield leads to a denser smoke.

4.3. Fire Scenarios

This section gives insights on all the input curves defined using the experimental data and the definitions of parameters used during the process. The building model is shown with the location of doors assumed to be open during the simulations. The values of toxic yields used in the model are also mentioned here.

4.3.1. Design Fires and HRR Curves

In all the graphs discussed in the coming sections, the experimental HRR curves are the fitted curves that were obtained from the test data measured in the lab.

Fire Parameters:

The time taken by the fire to reach 1050 kW of HRR is defined as growth time or growth rate (t_g).

When an ignition takes place, the fire develops a growth rate with which it spreads and an HRR which increases alongside its growth. The growth stage of the fire could be analytically calculated using the following equation:

$$Q_c = \alpha t^p \tag{13}$$

The exponent 'p' is equal to 2 for the fire spreading outward at a constant rate in a radial manner. This is because the area of the radial surface is growing with the square of the radius while the radius is expected to grow linearly with time (Ciani & Capobelli, 2018). So, the equation becomes:

$$Q_c = \alpha t^2 = 1000\left(\frac{t}{t_g}\right)^2 \tag{14}$$

Hence, such fires are called the t-square (t^2) fires. These could slow, medium, fast or ultra-fast depending on their growth rate.

The ignition time (t_{ig}) is the time period between the ignition of material through an external source and the beginning of combustion without external need. Table 2 shows the values measured from experimental data measured in Antti Linna's thesis project (Linna, 2024).

Table 2: The tg and t_o/t_{ig} values used in the project.

	t_{ig} (s)	t_g (s)	pHRR(kW) – Experimental	pHRR(kW) – Simulated
Sauna	30	1352	245	4450
Washing Machine	25	539	590	4450
Textile	10	247	430	700
Plastic on stove	10	1260	50	4450

Doors and Openings:

There are certain assumptions made in the project including the consideration of open fire doors for the worst-case scenario. Normally, fire doors are programmed to close after the alarm rings; however, in this case, the doors are assumed to remain open, allowing the smoke spread to multiple wings. Figure 12 illustrates all the openings, with highlighted rectangles, in the form of doors in one of the fire scenarios.

Figure 12: The doors assumed to be open during simulations.

Laundry Room:

The first scenario discussed here involves the fire in the washing machine located in the laundry room. It can be observed from the Figure 13 that the peak HRR for the experimental curve occurs at almost 600kW in over 6.5 minutes. The simulated curve follows the same trend and later continues as a fast-growing t^2-fire with peak HRR of 4450kW in 10 minutes. It can also be observed that there is a delay of about 5 minutes in the start of t^2 curve, which means that the fire takes this time to establish itself strong enough to transition to the defined t^2-growth phase.

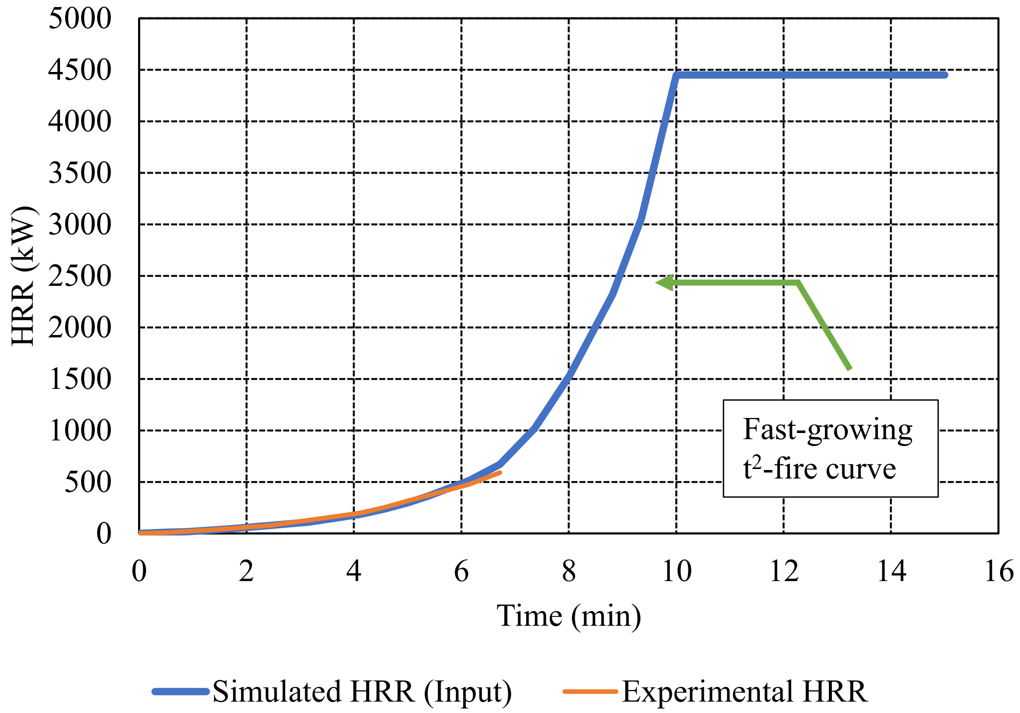

Figure 13: The simulated and experimental HRR of laundry room fire.

Kitchen:

The kitchen stove fire starts with the burning of polyethylene packages and is assumed to spread all over the stove. In this scenario, it can be observed from Figure 14 the maximum HRR of the experimental curve has quite low value and the fire also increases in a very slow manner, reaching 50 kW in about 4 minutes. This is mainly because it only involves the burning of small PE bags; however, the fire is defined as a fast-growing t^2-fire for the simulated case, which reaches the flashover with HRR of 4450 kW in 10 minutes and then stays the same for the rest of the simulation. The t^2 curve delay here is of about 4.5 minutes.

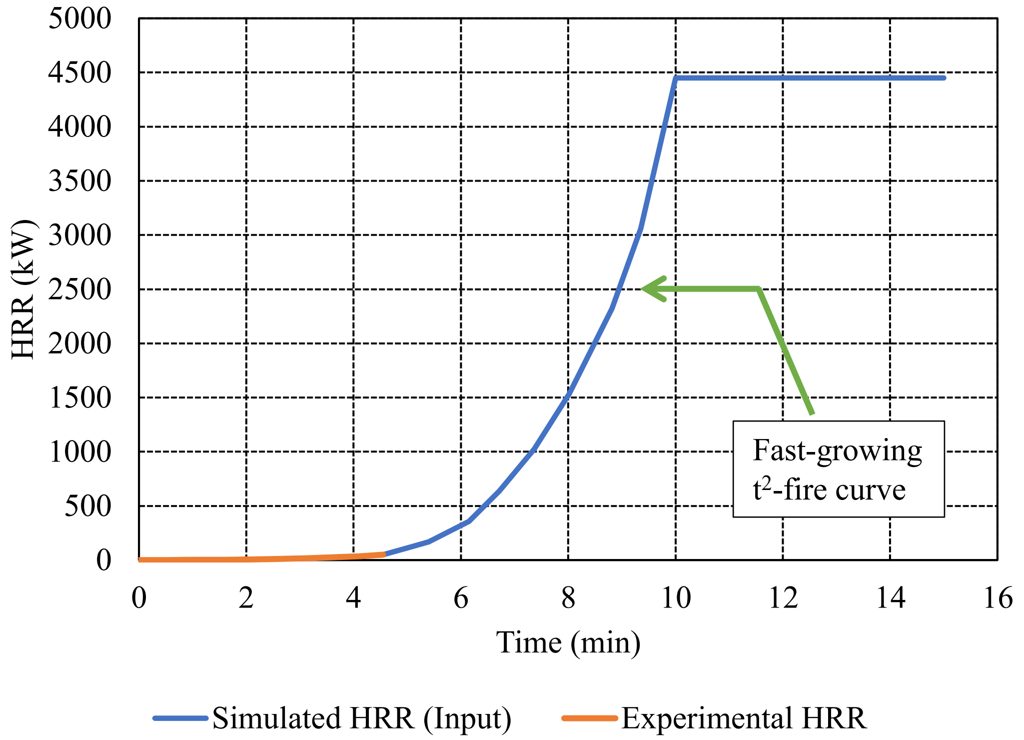

Figure 14: The simulated and experimental HRR of kitchen fire.

Sauna

In Figure 15 below, the HRR for experimental curve is over 240kW in just over 10 minutes, and the simulated HRR curve follows the same trend until 10 minutes after which it transforms to a fast-growing t^2-fire reaching the flashover at 4450kW in 13.5 minutes. The total simulation time is taken as 15 minutes, as this is the average time required by the Finnish fire department to reach the fire incidents. The delay in the t^2 curve for this fire scenario is of about 10 minutes.

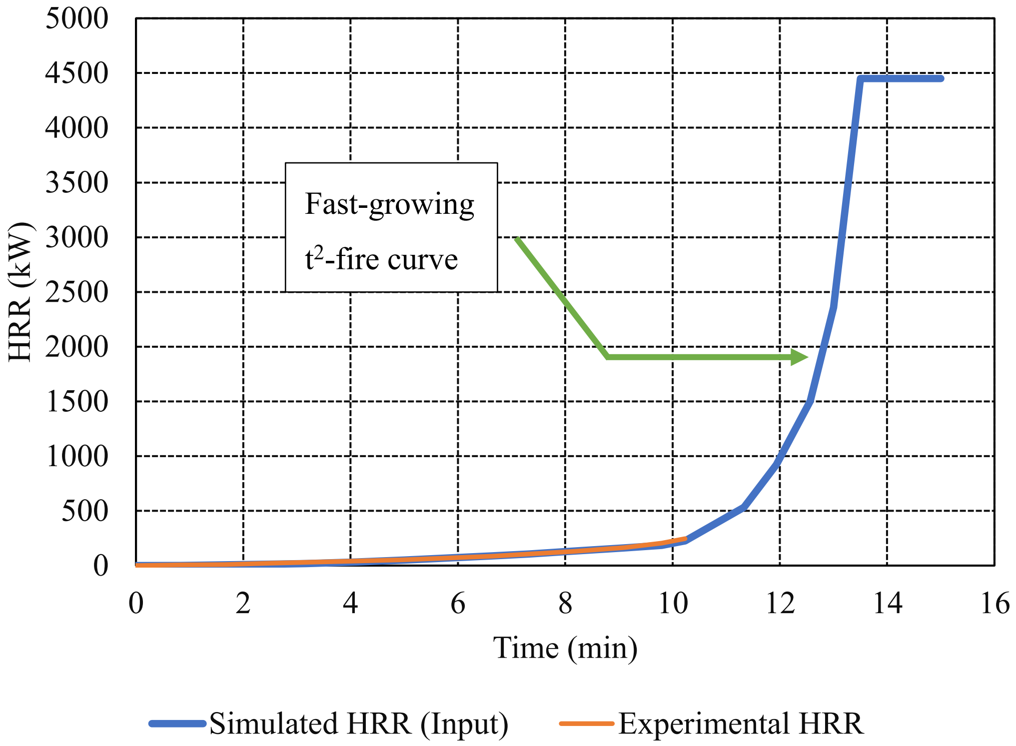

Figure 15: The simulated and experimental HRR of sauna fire.

Occupant room:

This last scenario is based on the textile fire inside one of occupants' rooms, and it involves the burning of sheets. In Figure 16, it can be observed that the time to reach pHRR is short as the experimental curve reaches its peak of 430 kW in 2.5 minutes, and then the simulated curve continues as a fast-growing t^2-curve until 700 kW in 3.4 minutes. There is no delay observed in the t^2 curve for this scenario.

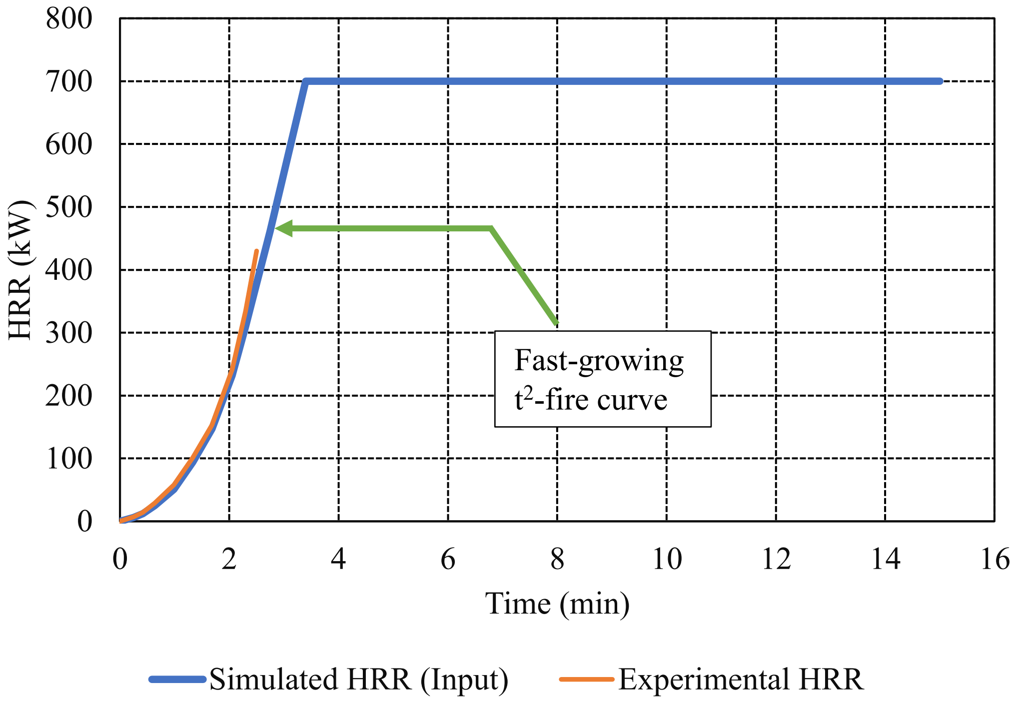

Figure 16: The simulated and experimental HRR of occupants' room fire.

4.3.2. Toxic Yields

FED surrogate method is used in this project and the toxic yields utilized as the input for the model is obtained from (Hostikka et al., 2024). The CO and HCN accounts for all the other asphyxiants present in the original FED equation. The FED values of both asphyxiants for all four scenarios are mentioned in table 3.

Table 3: The surrogate FED values of CO and HCN.

	Sauna	Washing Machine	Textile	Stove
COsurr	0.0898	0.2414	0.0220	0.0303
HCNsurr	0	0	1.212 x 10-5	0

The soot yield has a direct relation with the density of the smoke. The denser smoke also effects the visibility to a great extent, which ultimately effects the available time for achieving the untenable conditions. The soot yield 'Y_s' is taken as 0.05 in all scenarios.

4.4. Tenability Assessment

The tenability conditions represent the least acceptable values of certain parameters after which situation starts to become dangerous for the people present in that space. The two parameters that are chosen to perform the tenability assessment in the project are Visibility and FED that are explained in detail in Chapter 2.

Several visibility and FED devices are placed in the model to measure the respective values of these parameters. The smoke detectors follow two types of models: Heskestad model and Cleary model. The difference between both models is that the Heskestad model uses a single parameter i.e., “L”, while the Cleary model use four parameters i.e., α_e, β_e, α_c and β_c, and each of these parameters should be listed separately while using FDS, in the ‘PROP’ line. In this case, the Cleary model is used as it is the default model assigned to all SDs in PyroSim, and the smoke detector alarm is considered to be start buzzing once the threshold reaches 3.24%/m (McGrattan et al., 2013).

In addition to these devices, SDs are also used which detect the fire as soon as the smoke reaches in their periphery. On this basis, two conditions are considered: first one is named as early detection which suggests that the SD placed closest to the fire source room i.e., kitchen, bedroom, sauna etc., detects the smoke as soon as it reaches the detector, while the second condition is delayed detection and assumes that the closest detector fails and the smoke spreads to the second closest one that later detects it. The location of the SD in latter condition is in the adjacent corridor. The Figure 17 gives the idea of the typical locations for all the devices in one of the scenarios. The green dots in the figure represents the visibility and FED devices. The adjacent corridor in this case is the number "03" device highlighted with an orange box. The mesh is confined to certain areas of model to limit computation time.

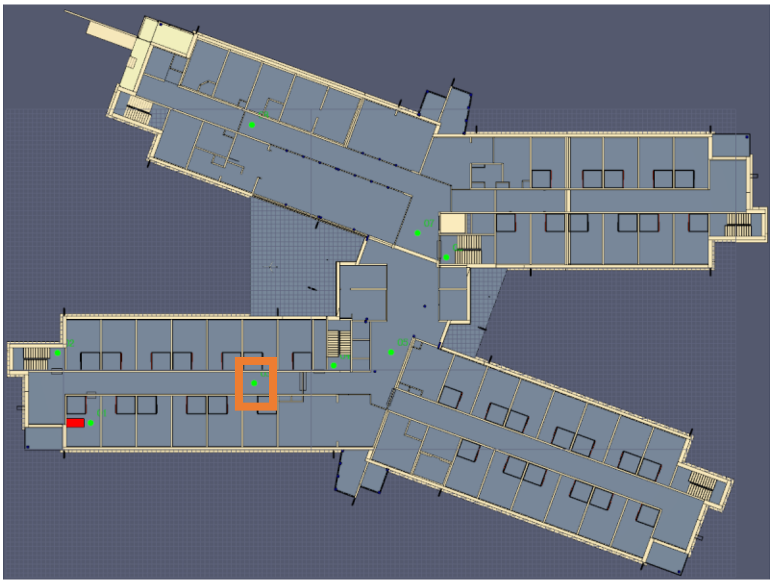

Figure 17: The model showing device locations.

These devices are used to measure the criteria mentioned in chapter 2 for both visibility and FED. In this project, the building is considered a domestic or small enclosure, so the visibility limit taken is 5m, while the FED limit is taken as 0.1. The reason for choosing a lower value for FED than a usual-low of 0.3 is because all the occupants in the rooms are elderly people who are highly sensitive to these asphyxiant gases even at such low levels.

4.5. Parametric Study:

In addition to the IFC model, a simpler model is made as part of the project to study the effect of length of the corridor on time required by a staff member to evacuate the occupants. The idea is to build a refined mesh resolution model having a corridor and rooms on one side to mimic one of the actual corridors from the IFC model with same dimensions. The length of the corridor is increased as a function of the number of rooms. The length of the room along x-axis is 3.82m, and along y axis is 5.76m, while the height is 3.5m. The width of the corridor is 2.5m. The main purpose of this model is to study the effect of increasing the corridor length on the tenability conditions in the corridor. Another purpose is to make a simple model with less details and a finer mesh to save the computational time wasted in running the complex IFC model.

The model has two variations in mesh resolution: one has cell size of 10cm and the other has 5cm. Each of the two variations has five models starting from corridor with two rooms to corridor with 10 rooms having an increment of two rooms in each model. Figure 18 shows the model with six rooms having fire source (red rectangle) in the first room, the point '01' and '02' show the visibility and FED devices on either ends of the corridor with smoke detector 'SD' inside the fire source room.

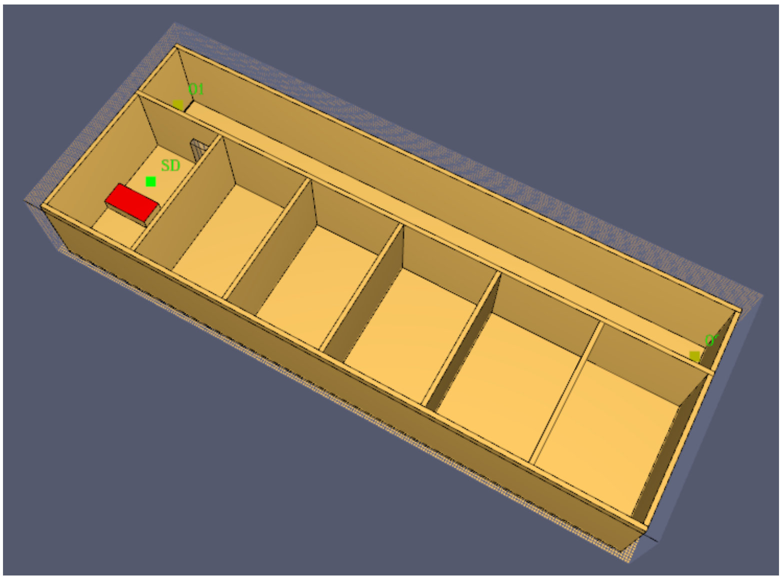

Figure 18: Corridor model with devices on either ends.

Additionally, both ends of the corridor has small openings of 5cm to account for any leakages to surroundings. The opening can be seen on the bottom left of the corridor as shown in Figure 19.

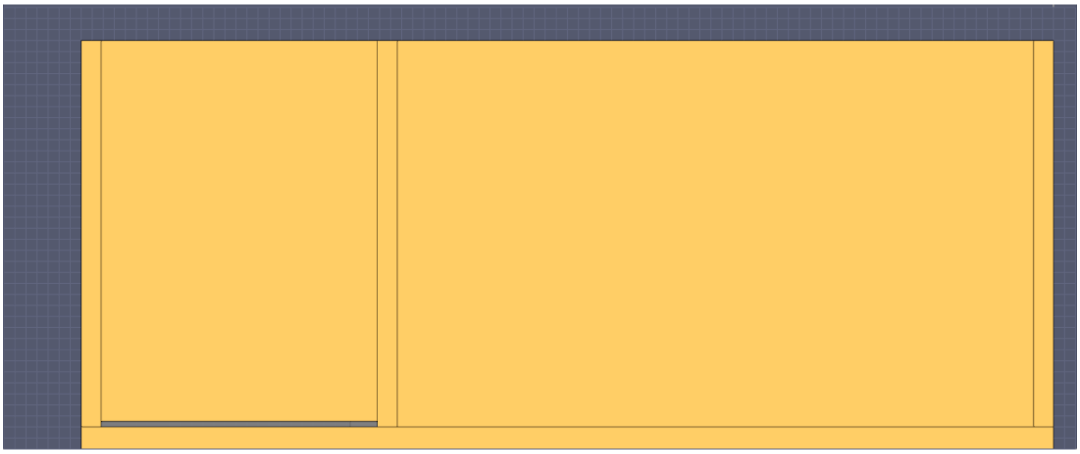

Figure 19: The openings made for leakage.

The models having 5cm mesh has comparatively a greater number of cells than the 10cm mesh, and that is why the MPI feature of FDS is used. The mesh is divided into smaller meshes and different processors of the system are assigned these meshes to process which ultimately saves computational time.

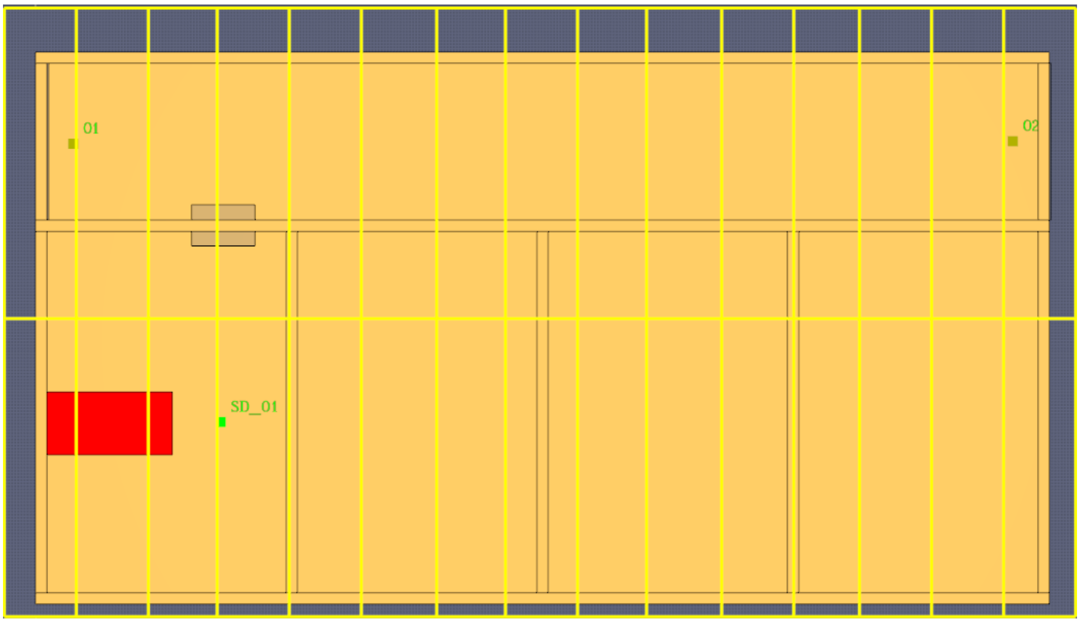

Figure 20: Corridor model with multiple meshes solved using MPI.

In Figure 20, it can be seen that the meshes are divided into 30 parts with the division shown in yellow vertical and horizontal lines. All the other characteristics of the model is same as the one with 10cm meshes.

4.6. Sensitivity Analysis:

In addition to the parametric study, a sensitivity analysis is also performed as part of the project. Figure 21 shows the plan of the model made by using dimensions from the original IFC model but using a simplified geometry. The length of the corridor is 44.4m and the width is 5.8m, while the room has a length of 4m and a width of 5.8m. The figure also shows the fire source as a white square in the room with a volume of 1m3. The entire model has a mesh resolution of 10cm. and the corridor mesh is divided into three parts for utilizing the MPI feature on FDS.

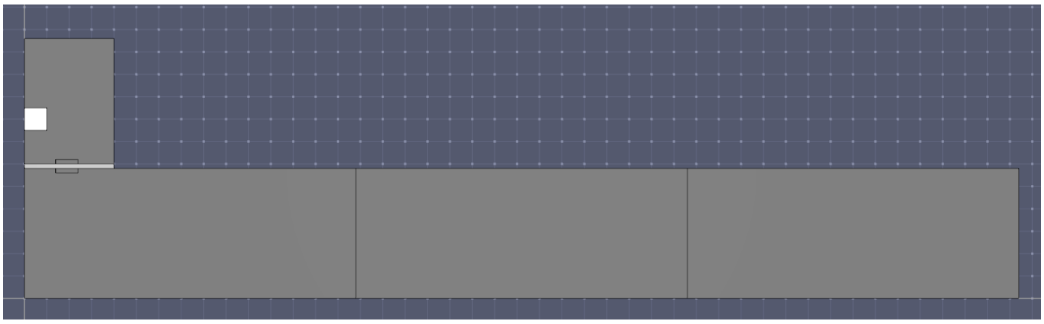

Figure 21: Simplified model for sensitivity analysis

Figure 22 shows the FED and visibility devices placed in the room and corridor labelled as '01' up to '04' at a height of 1.65m from the floor level. The smoke detector is mounted on the ceiling inside the fire source room referred as 'SD'. The door opening can also be seen between the room and the corridor with a width of 1m and a height of 2.1m.

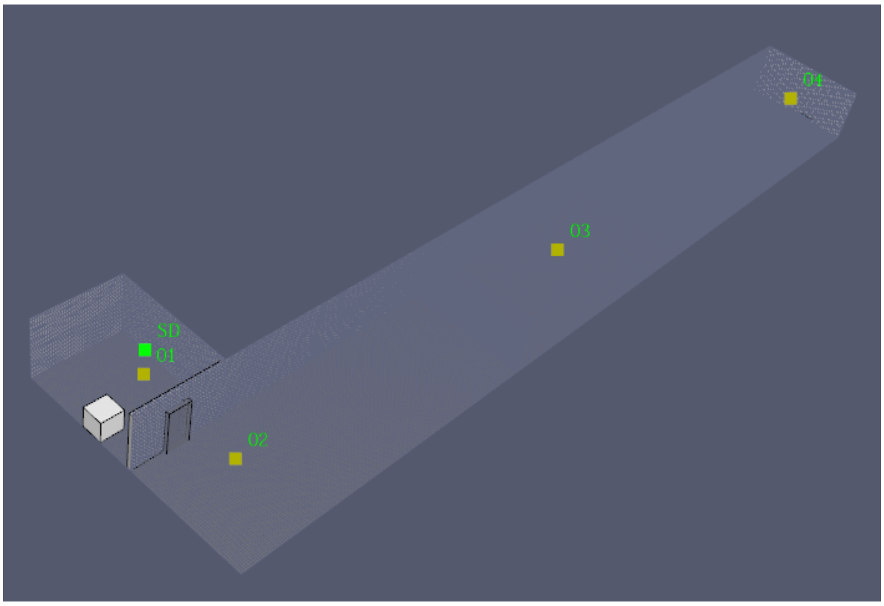

Figure 22: Model showing the location of devices, fire source and door.

Unlike the parametric study model, this model does not use the wall obstruction feature in PyroSim and that is the reason why meshes can be seen instead of walls and floor. The reason for using this simplified geometry is to save the computational time when using a comparatively finer mesh resolution than the one used in full-scale IFC model simulations.

5. Results

This section provides the results obtained from FDS simulations. The results of the ASET for the main model is presented in the graphs, and the parametric study results are also mentioned. The comparison of the ASET and RSET for both: full-scale IFC model and parametric study are also shown in this section.

5.1. Behaviour of Temperature, Visibility and FED

Before discussing and comparing the realized HRR with the simulated input HRR, the behaviour of temperature, visibility, and FED with respect to time is shown in this part of the section. The graphs shown later, depict how the three parameters mentioned change during the simulation. The measurements are from the laundry room fire scenario and the results are from the devices placed inside the fire source room. In Figure 23, the point '01' is where all the devices are located for each of the parameter.

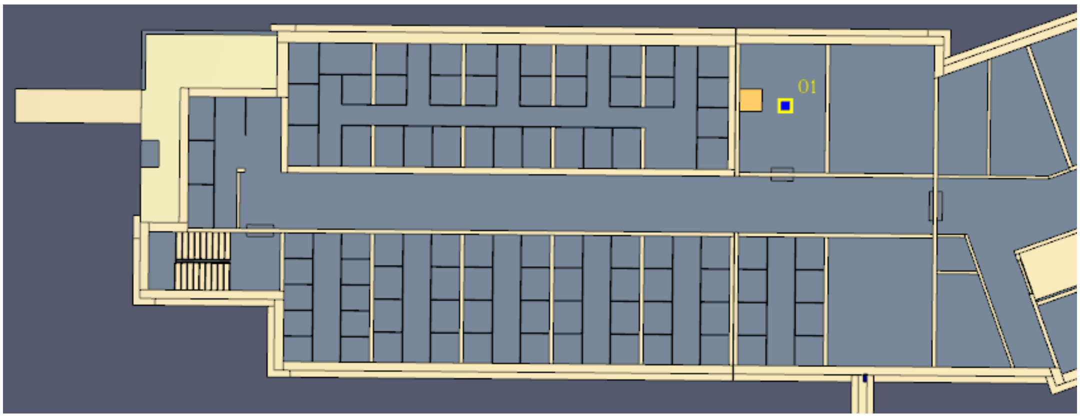

Figure 23: The laundry room with fire source and devices.

The curve shown in Figure 24, represents a temperature increase starting from 20°C, which is taken as the room temperature by PyroSim until about 10.3 minutes when it reaches 750°C. As soon as the HRR from that scenario gets constant, the temperature also shows fluctuation between 800°C and 500°C until the end of the simulation time.

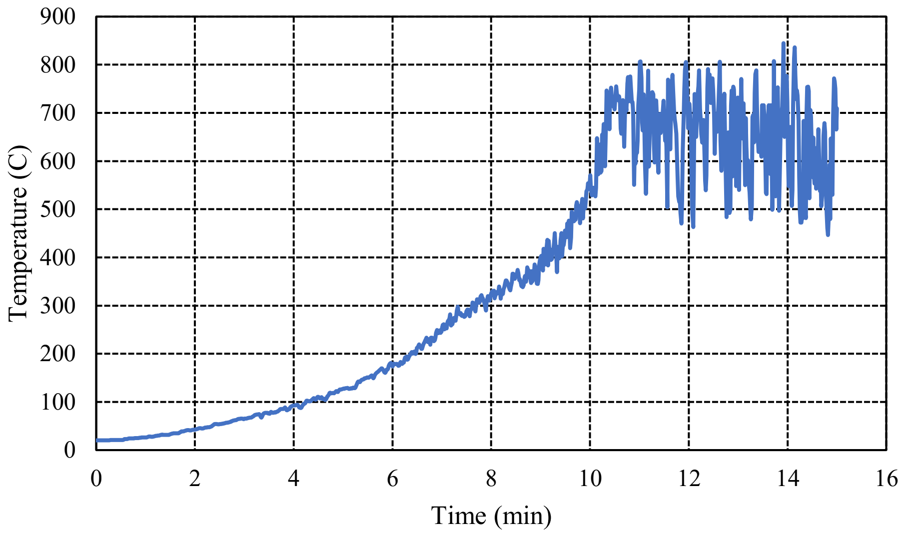

Figure 24: The trend of temperature with time.

The temperature increases with time, but the visibility shows the reverse trend. In Figure 25, the decreasing visibility curve can be observed which attributes to the spread of smoke inside the room. It starts at 30m, which indicates full visibility. This value is an indication of maximum visibility and doesn’t imply that one cannot see past this range. It starts to decrease just after 1 minute and drastically plummet to 5m is at 2.45 minutes, and reaches almost 0m, 10 minutes after the ignition.

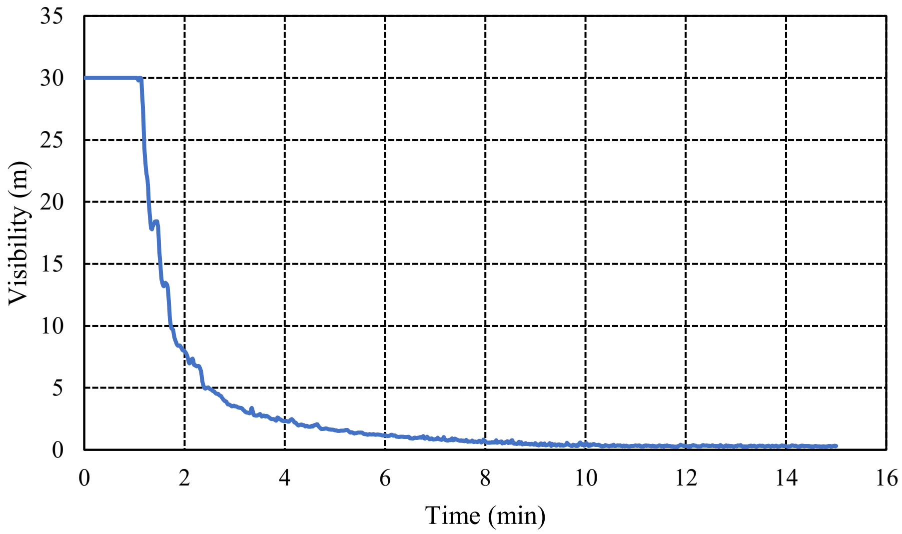

Figure 25: The decreasing trend of visibility with time.

Figure 26 apparently shows a slow increase in the FED value; however, the threshold value of 0.1 FED reaches at 5.22 minutes after the ignition. As this device is close to the fire source, the value reaches a high of over 70 which is catastrophic. The value shows a slow increase until 10.3 minutes after which a rather steep linear increase is observed. Compared to visibility, FED takes about twice as much time to reach the tenability limit in most cases.

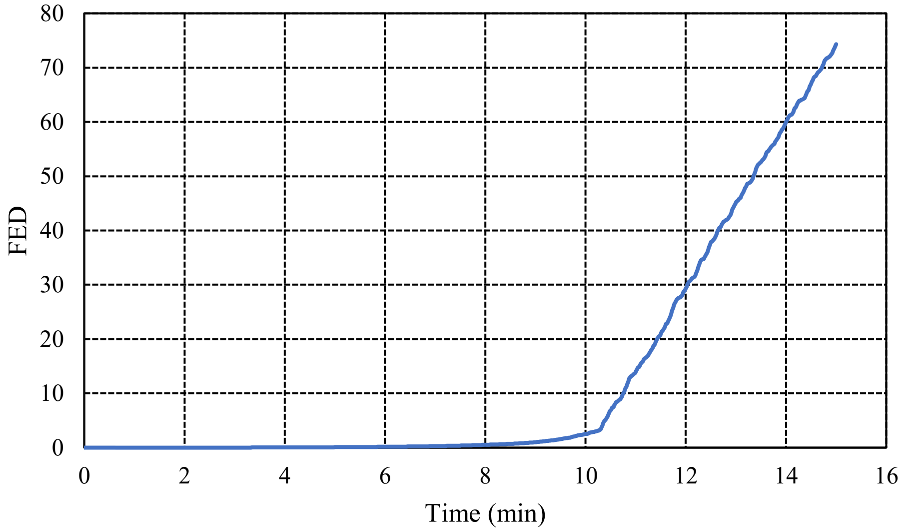

Figure 26: The increasing trend of FED with time.

5.2. Realized HRR

This section discusses and compares the output results obtained after running the FDS simulations with the input data that is explained earlier. These results take visibility and FED values as the measure of incapacitation for the occupants. So, these tenability conditions are measured at different locations for example, corridors, first floor lobby, and second floor lobby, respective of their fire source. First, the HRR curves obtained from the simulations are discussed and then the tenability conditions.

It is also very important to note how different some actual curves are from the desired curves used as input RAMP. One of the major factors for the difference could be the lack of oxygen for the burning of fuel as all the windows and doors opening outside of the building are closed.

5.2.1. Laundry Room:

The realized HRR curve of the washing machine fire is shown in Figure 27, and it follows the exact same pattern of the input HRR curve shown in chapter 4. The flashover happens at 4450kW, 10 minutes after the fire ignites. Afterwards, the HRR fluctuates around that value with no significant change in the trend. This steady trend indicates that sufficient oxygen is available for combustion of the fuel, while the fluctuations might refer to the variation in fuel consumption rate.

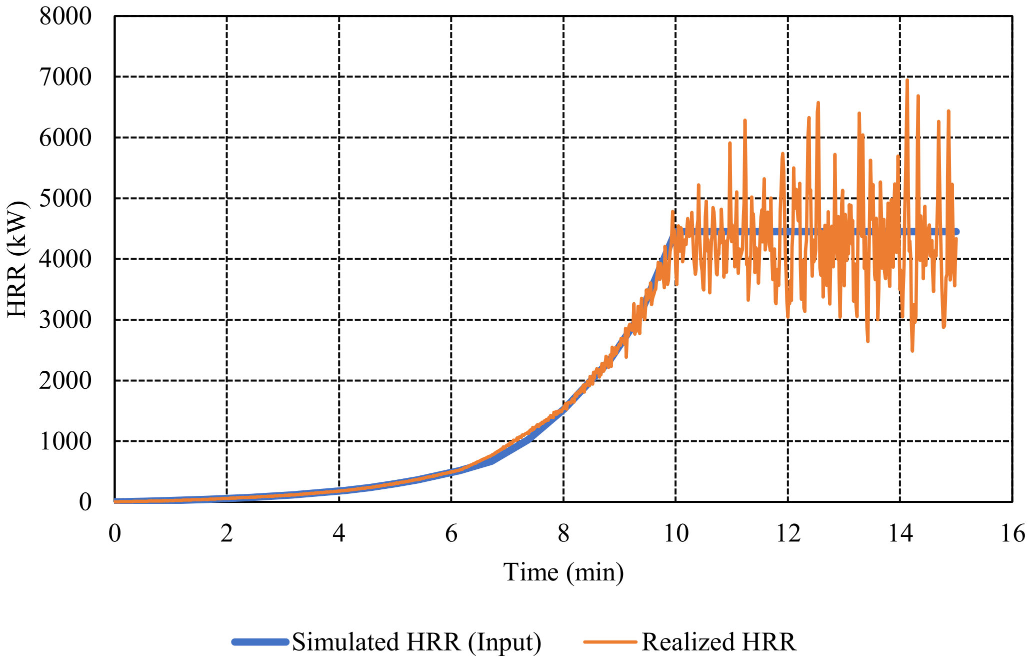

Figure 27: The simulated and realized HRR of laundry room fire.

5.2.2. Kitchen:

Figure 28 shows the realized HRR curve of the kitchen stove fire in comparison with the input HRR. The two follow a similar trend while realized HRR reaching slightly higher values at the same points compared to the input curve. It attains its highest HRR value of 5000kW after 10 minutes of ignition. After the flashover, unlike input HRR curve, the realized HRR starts to decrease as there are probably reduced levels of oxygen available to burn the fuel. Towards the end of the simulation, around 13.5 minutes, it can be observed that the HRR value fluctuates which attributes to the possible interaction of fire to its surrounding materials.

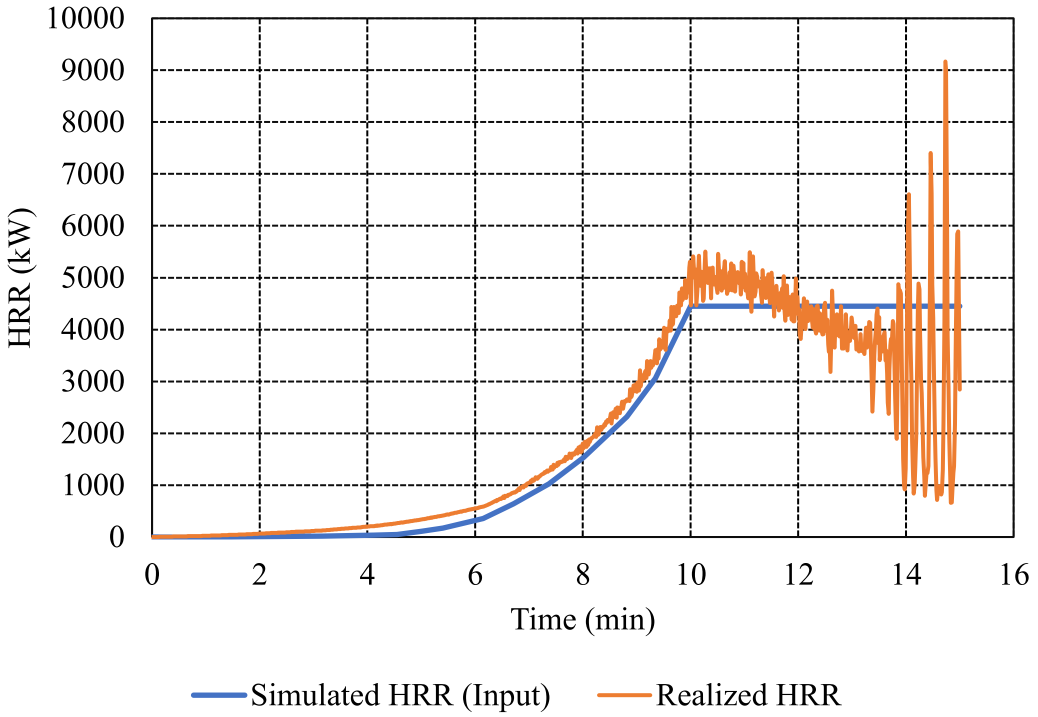

Figure 28: The simulated and realized HRR of kitchen fire.

5.2.3. Sauna:

The result obtained from the sauna simulation are shown in Figure 29 below. The realized HRR curve follows the same trend as the input curve until 10 minutes, when it reaches HRR of 200kW; however, after wards it behaves in a completely different way as its peak value of about 1100kW is attained just before 15 minutes. This difference is attributed to the extremely under-ventilated room where there is not enough availability of oxygen. The reason is that sauna does not directly open to the corridor, instead two rooms must be passed through to access the sauna room which lowers the oxygen levels considerably.

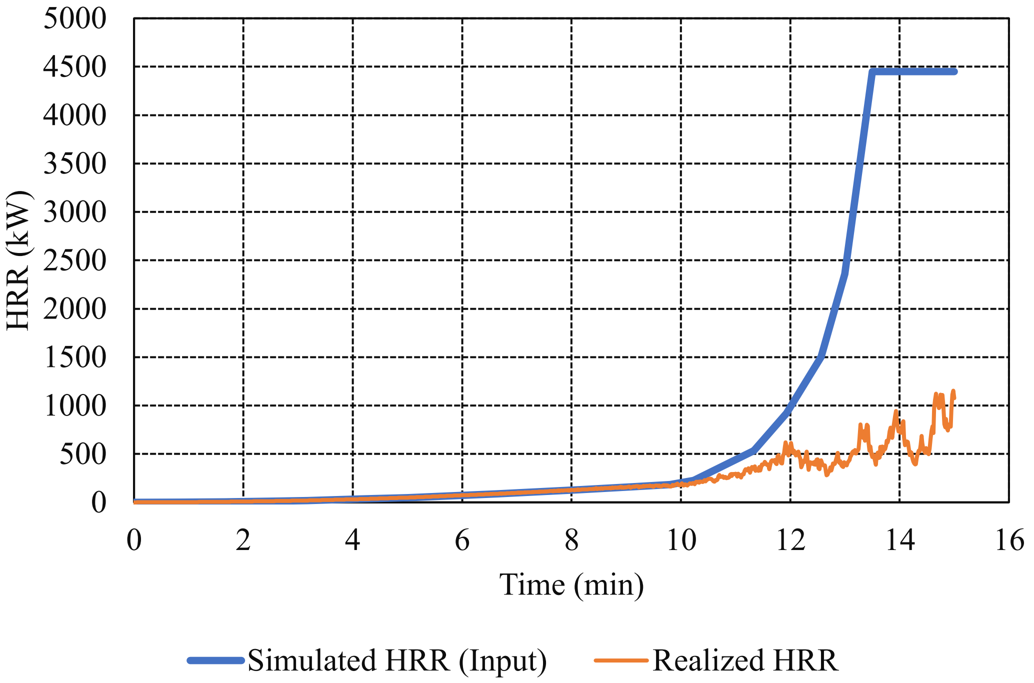

Figure 29: The simulated and realized HRR of sauna fire.

5.2.4. Occupant room:

The relation between the simulated and realized HRR curves can be seen in Figure 30 shown below. Both curves follow exactly the same trend and overlap each other throughout the simulation time. The t^2 trend curve starts right away after the ignition and pHRR of 700 kW is reached in 3.5 minutes, which is the same time as the input HRR curve. The realized HRR remains almost the same for the rest of the simulation period, unlike the other results discussed earlier where there were a lot of fluctuations. This constant HRR even after the peak value has reached could be due to low pHRR value when compared to other scenarios. As the fire load is less, there is abundance of oxygen for combustion.

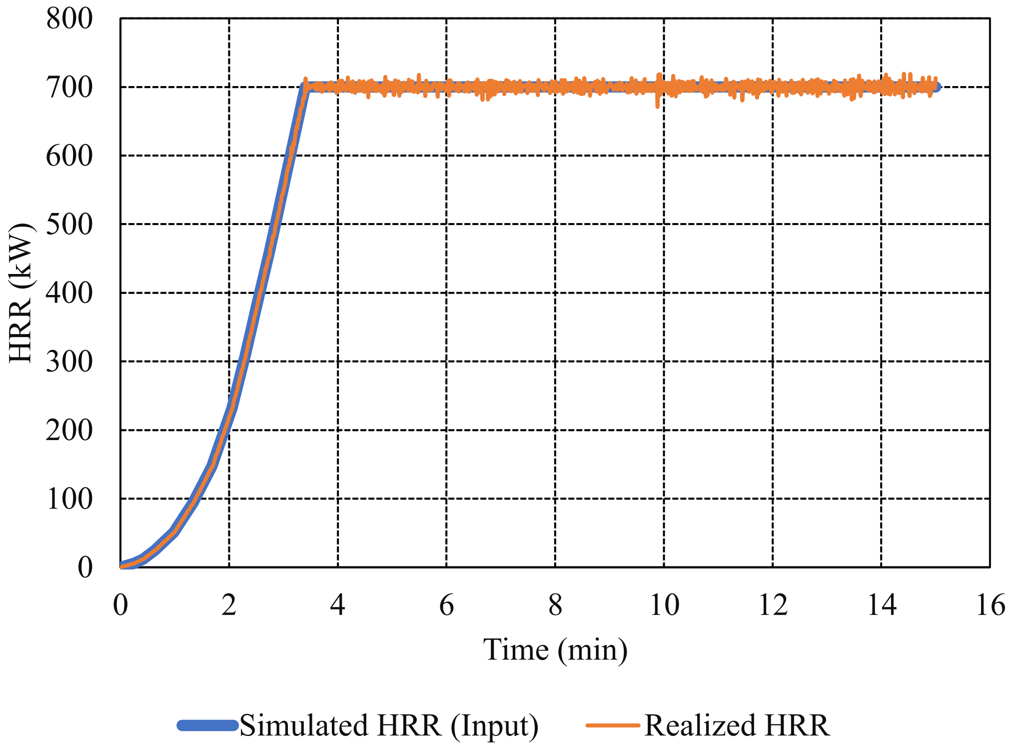

Figure 30: The simulated and realized HRR of occupants' room scenario.

The behavior of fire in different scenarios over time is discussed in this section. It is observed that in two cases i.e., laundry room and kitchen, the realized HRR values followed the similar growth curves and reached pHRR values of 4450kW as the input curves, with some fluctuations post-flashover time. However, the sauna fire gives a completely different curve due to very low oxygen levels available for combustion. The realized pHRR value and curve in occupants' room scenario follows precisely the same trend as input HRR curve, mainly attributed to its lower fire load compared to earlier cases and high oxygen availability. It highlights the importance of ventilation in the combustion process in different locations of a building.

5.3. ASET

The ASET for the early detection and the delayed detection cases explained earlier are shown in this section.

5.3.1. Early Detection Case

This section explains when the smoke detector closest to the fire source detects the smoke, starting from the moment the fire ignites until the specified conditions are met. The measurements are taken at three different locations, with the first one being in the adjacent corridors to the respective fire sources i.e., Kitchen – Floor 1 shows the time for the tenability conditions to reach in the corridor right next to that kitchen. The column chart in Figure 31 shows the time from fire ignition until the smoke detection. The detection times range from as low as 13 seconds in occupants' room fire scenario to almost 3 minutes in the sauna fire. All the rooms except sauna, have smoke detectors installed in them, making the smoke detection quicker resulting in lower recorded times. For sauna, the smoke must pass through two adjacent rooms in order to reach the closest SD, hence the longer detection times.

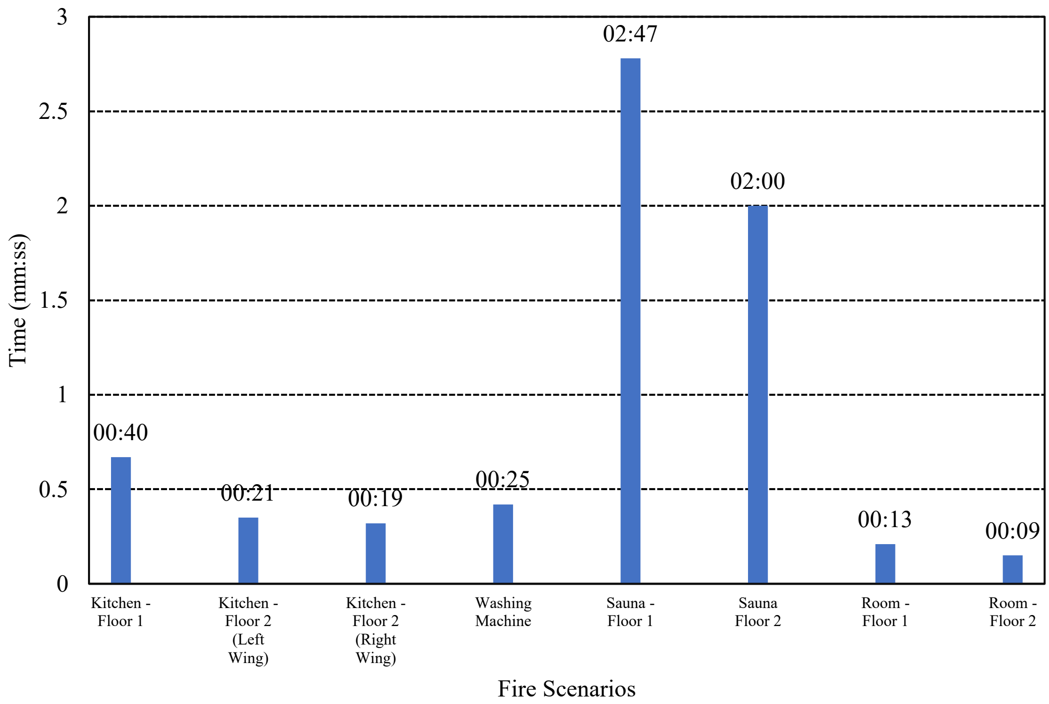

Figure 31: The time taken to detect smoke in early detection case.

Figure 32 shows one example of the adjacent corridor to one of the second-floor kitchens, where the detector is considered in this case.

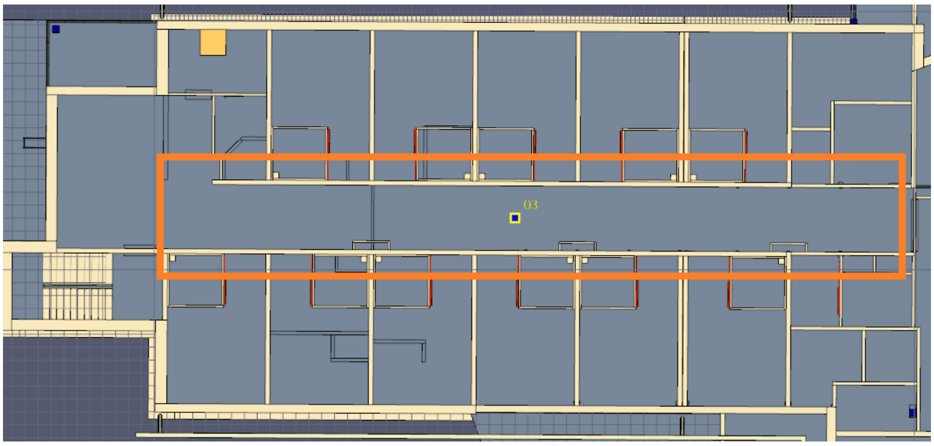

Figure 32: The adjacent corridor to the second-floor left-wing kitchen.

The times presented in the graphs below are measured from the moment SD detects the smoke until the respective tenability limits for visibility and FED are reached. In some cases, it can be observed that certain scenarios show zero value, which indicates that the limit never reached for that particular case. In Figure 33, the column graph shows the time taken by the visibility to reach 5m at the corridor adjacent to the fire source in respective scenarios. The longer time for visibility deterioration in sauna fire scenario is because of the same reason explained earlier that sauna doesn't have direct access to the corridor, causing a delay in the smoke to reach that area.

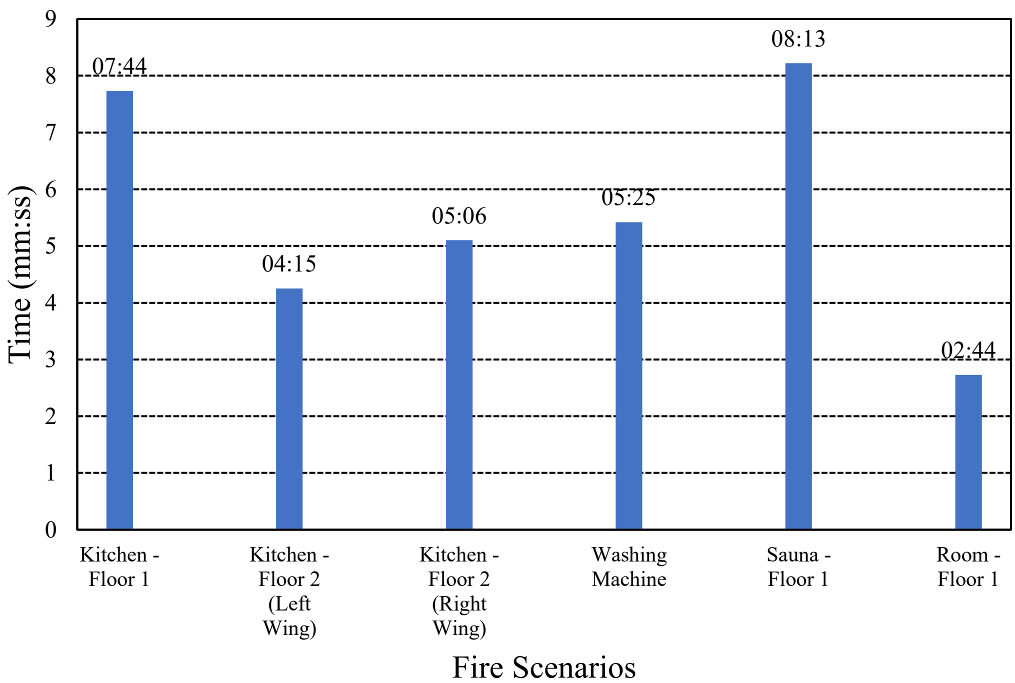

Figure 33: Time taken to reach 5m visibility at adjacent corridors in early detection case.

The time taken for the FED value to reach 0.1 at the corridor adjacent to the room of fire source in all discussed fire scenarios are shown in Figure 34. It can be noted that these times are higher than the ones mentioned in Figure 33, although they are measured at the same points. It suggests that even though the visibility is lost, and some irritation starts to occur, there is still time left before incapacitation starts.

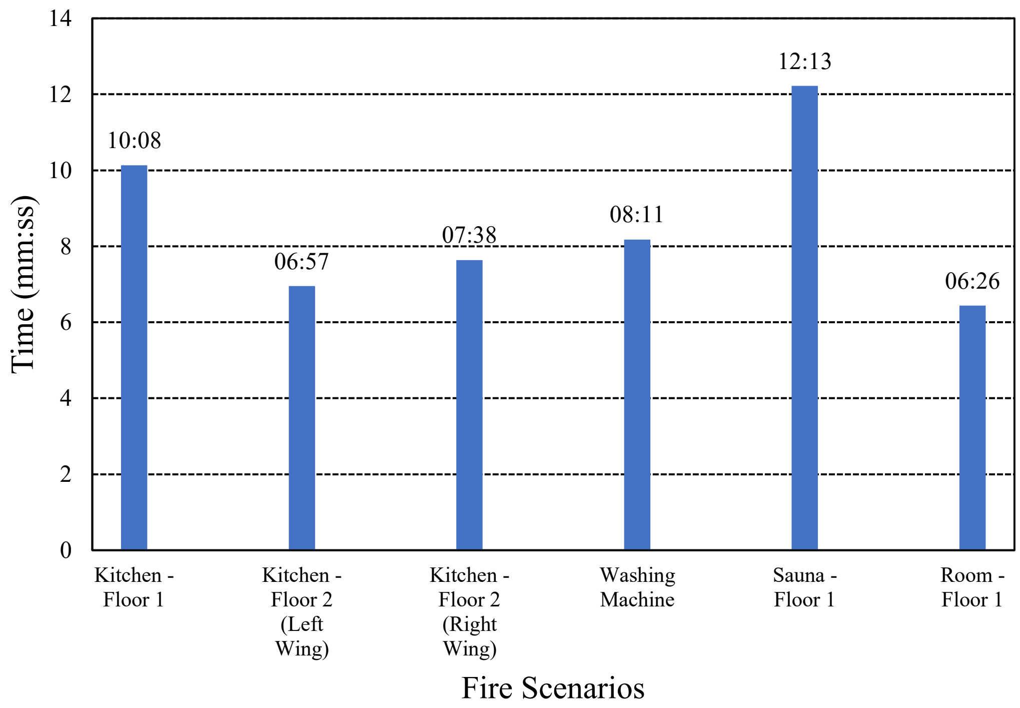

Figure 34: Time taken by FED to reach 0.1 at adjacent corridor in early detection case.

The highlighted box in Figure 35 shows the location of the visibility and FED devices placed in the lobby of first floor of the building. As first and second floors have almost identical distances from respective rooms to the lobby so the same figure can be considered for the second-floor lobby also.

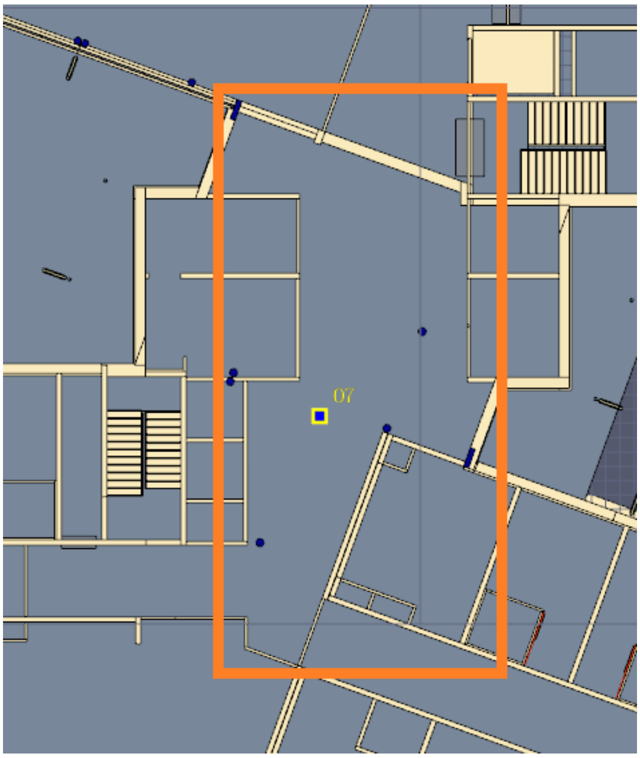

Figure 35: Visibility and FED devices location at the lobby.

The column graph in Figure 36 represents the time taken to reach the tenability condition for visibility at this lobby. As the laundry room is only in the basement, it is not considered in this case. It takes a longer time for the smoke to reach the lobby, with the sauna fire taking the longest at over 12 minutes.

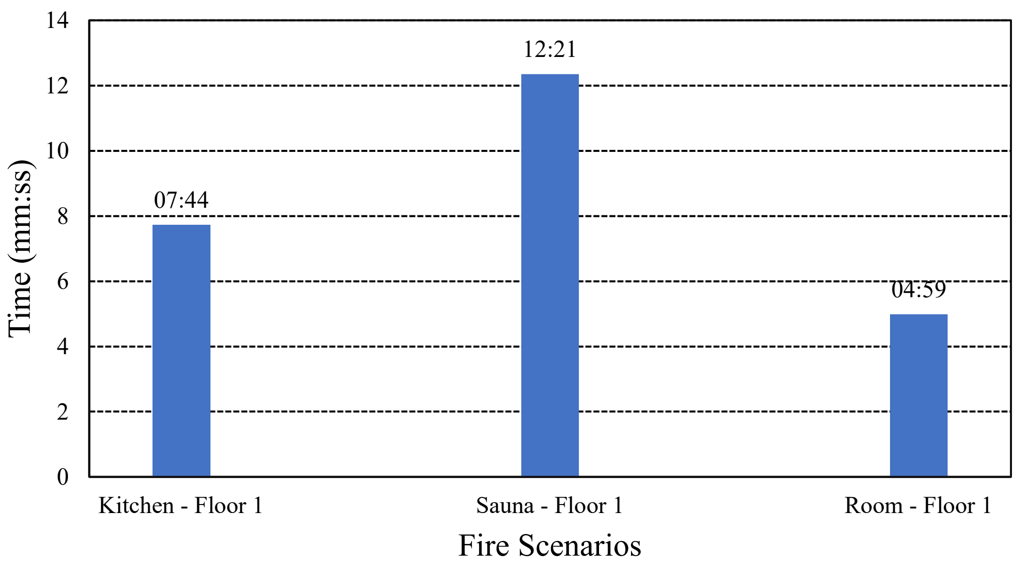

Figure 36: Tenability condition for visibility in 1st floor lobby in early detection case.

Similarly, the Figure 37 shows the time taken by FED to reach 0.1 at the first-floor lobby. The zero value for the sauna indicate that FED never reaches the limit in this scenario.

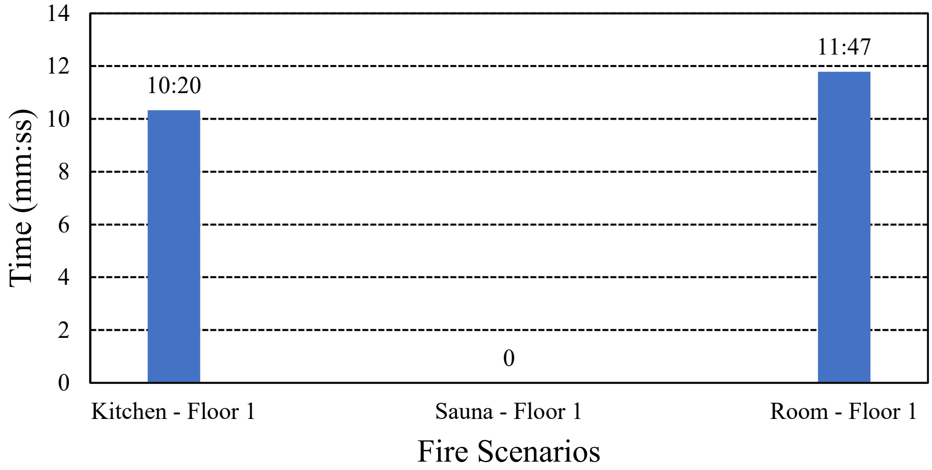

Figure 37: Tenability condition for FED in 1st floor lobby in early detection case.

In Figure 38, the time taken for the defined visibility limit to reach on the second-floor lobby is shown. The times for both kitchen scenarios are shorter compared to first-floor lobby mainly due the smaller areas of these kitchens. The smaller area allows the smoke to fill and leave the room of origin comparatively quicker leading to the deterioration of visibility in the vicinity.

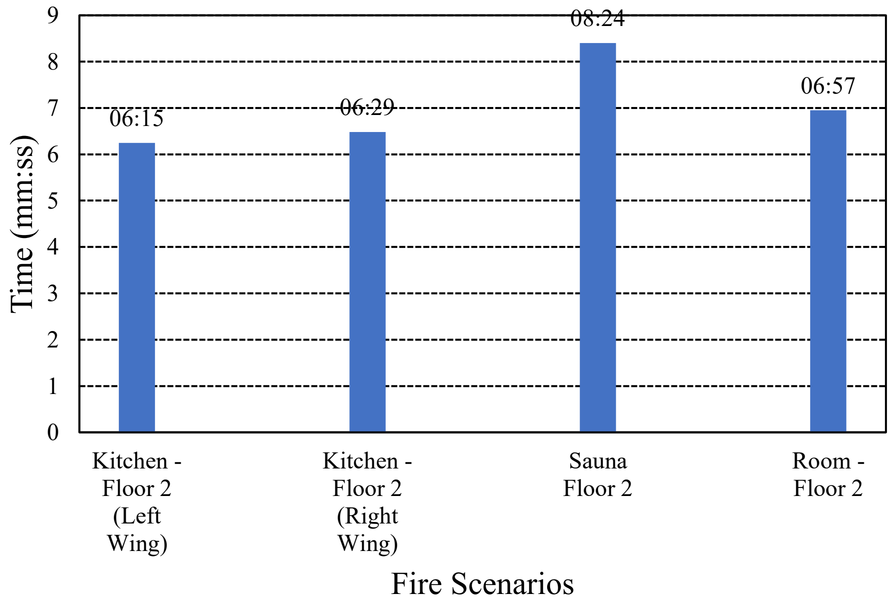

Figure 38: Tenability condition for visibility in 2nd floor lobby in early detection case.

Likewise, the Figure 39 represents the time for FED limit to reach at the second-floor lobby. As in the previous case, the absence of values for sauna and room scenarios shows the failure to reach the defined limits in those cases.

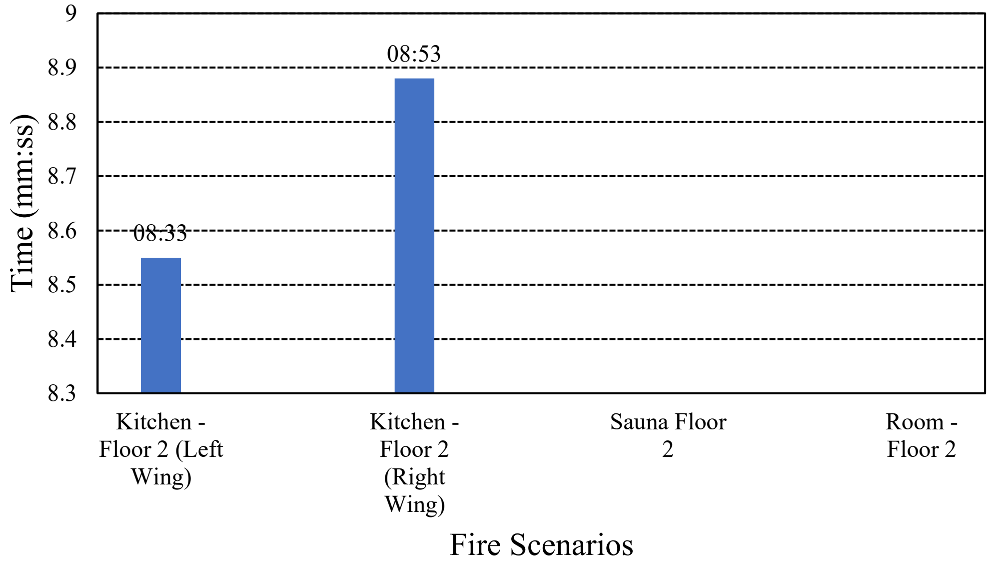

Figure 39: Tenability condition for FED in 2nd floor lobby in early detection case.

5.3.2. Delayed Detection Case

If due to some technical error, the closest SD doesn't work then the time bracket from detection to reaching the tenability conditions becomes confined as it will take some more time for smoke to reach the next closest detector, and hence less time from detection to incapacitation.

In Figure 40, the column graph shows the times it takes for the second closest detector to detect the smoke. It can be observed that these time values are higher than the early detection case by a large margin, and similar to the sauna fire has the longest and the occupants' room fire has the shortest detection time.

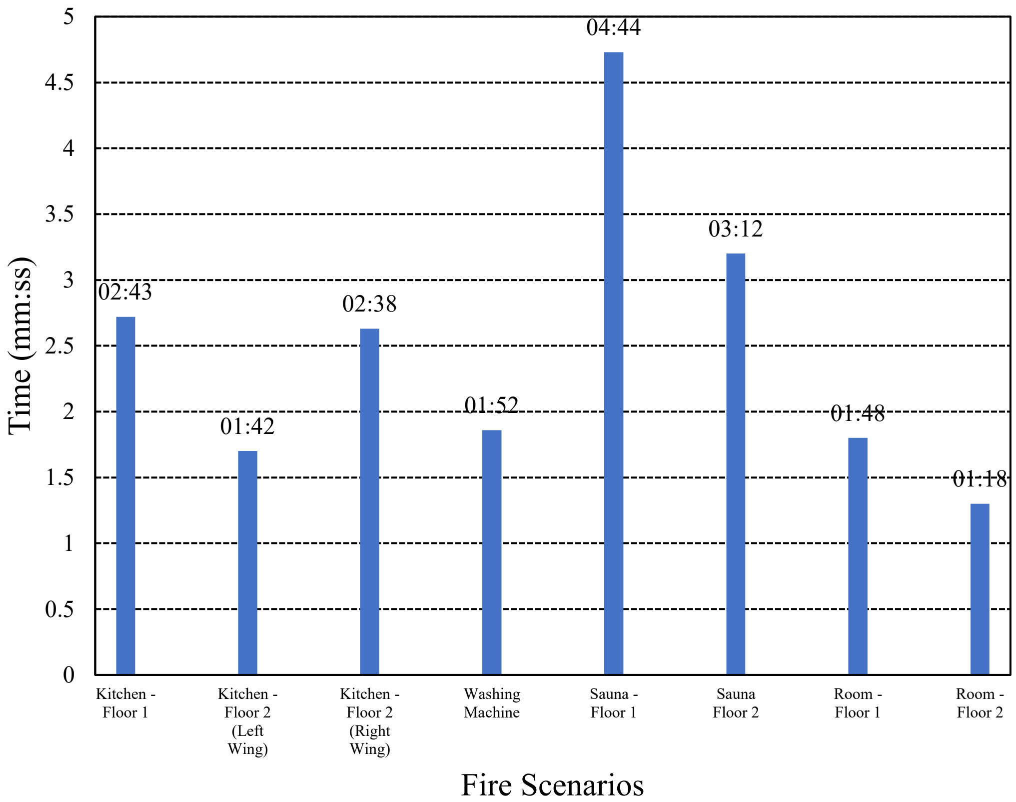

Figure 40: The time taken to detect the smoke in delayed detection case.

Similarly, the following times are shown in the way as described in Section 5.3.1 and are measured from the time the second closest detector detects the smoke until visibility limit of 5m and FED of 0.1 are reached. Just like before, both of these parameters are measured at three different locations i.e., adjacent corridors, first-floor and second-floor lobbies, respective of the fire source. Figure 41 shows the time taken to reach visibility limit at the corridors adjacent to the fire source in each of the mentioned scenario.

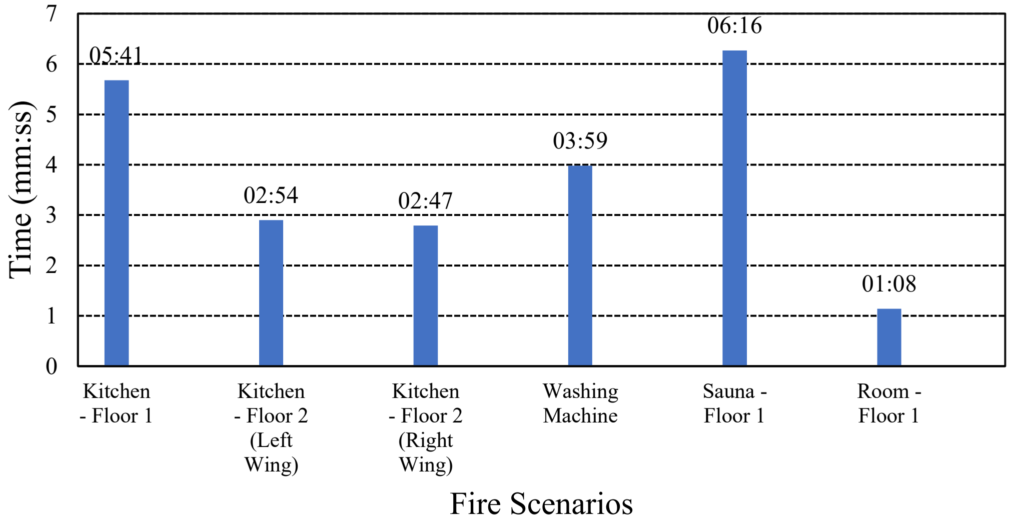

Figure 41: Time taken to reach visibility of 5m in delayed detection case.

The FED limit of 0.1 at the adjacent corridors, due to the respective fire sources, is reached at the times indicated in Figure 42. The largest gap between the visibility and FED times is in the sauna fire of about 4 minutes. In all the other scenarios except the occupants' room fire, the FED limit takes about 2.5 more minutes to reach than visibility limit.

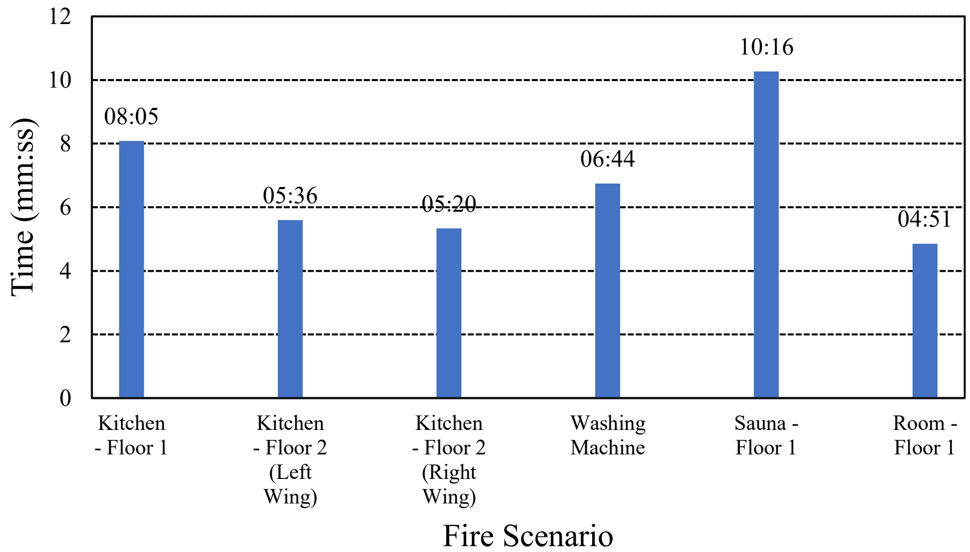

Figure 42: Time taken by FED to reach 0.1 in delayed detection case.

The column graph in Figure 43 represents the time taken to reach the tenability condition for visibility at the first-floor lobby. As expected, the times here are shorter than the first-floor lobby times in early detection case.

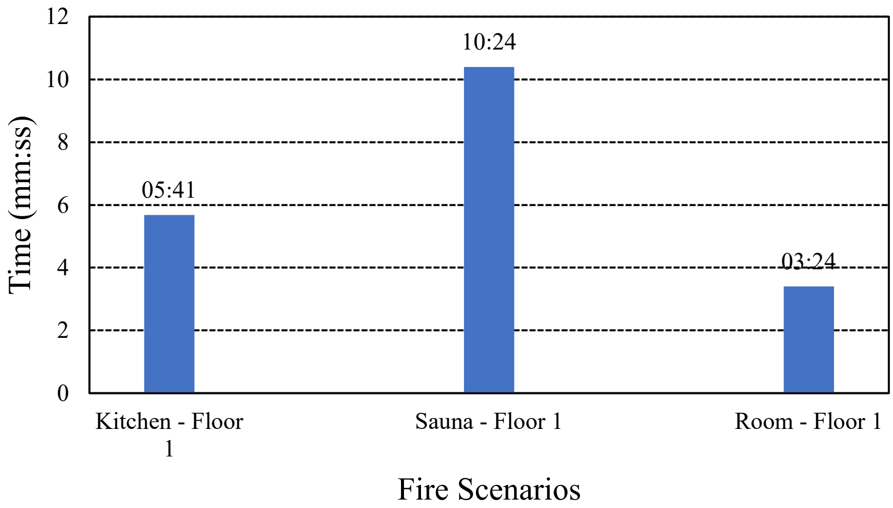

Figure 43: Tenability condition for visibility in first-floor lobby in delayed detection case.

The Figure 44 depicts the time taken to reach the tenability condition for FED at the first-floor lobby. The tenability conditions still can't be reached in sauna fire in this scenario.

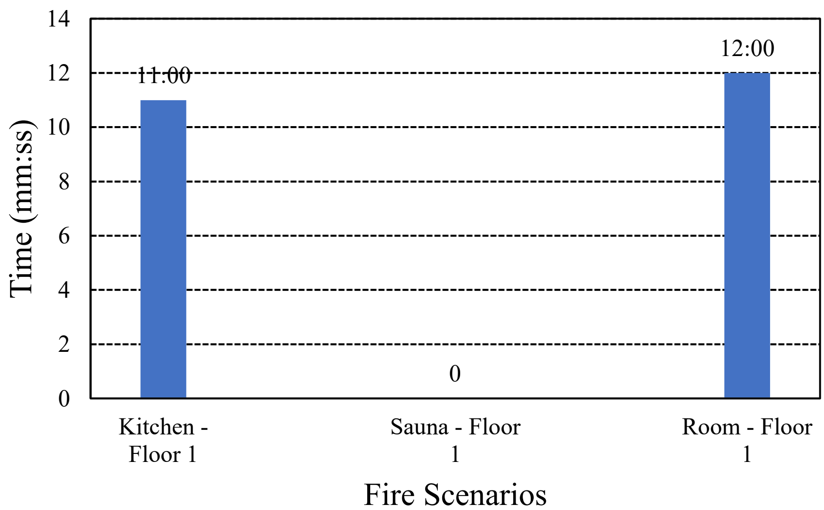

Figure 44: Tenability condition for FED in first-floor lobby in delayed detection case.

Similarly, the following graph in Figure 45 shows time for losing the visibility to the defined threshold of 5m at the second-floor lobby.

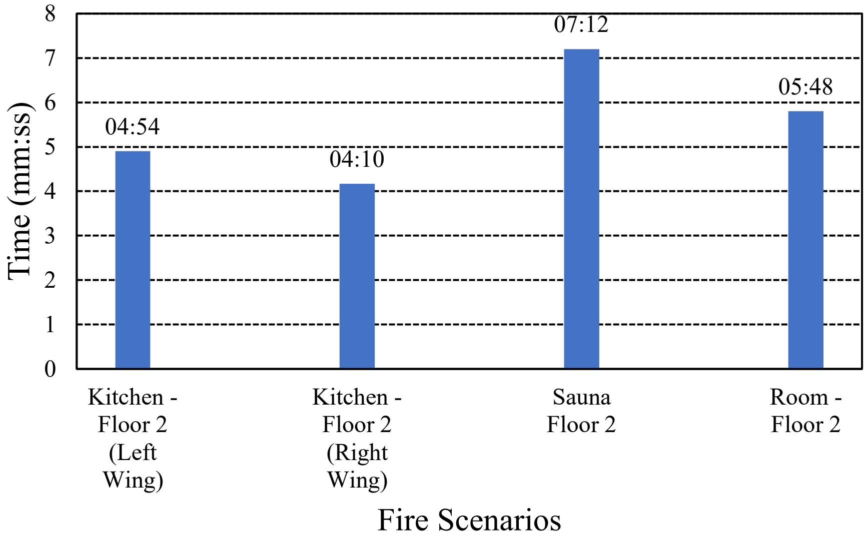

Figure 45: Tenability condition for visibility in second-floor lobby in delayed detection case.

Figure 46 shows time for FED to the defined limit of 0.1 at the second-floor lobby. Similar to the earlier cases, the time to reach the tenability condition has shrink, and the two scenarios with no value also remains the same.

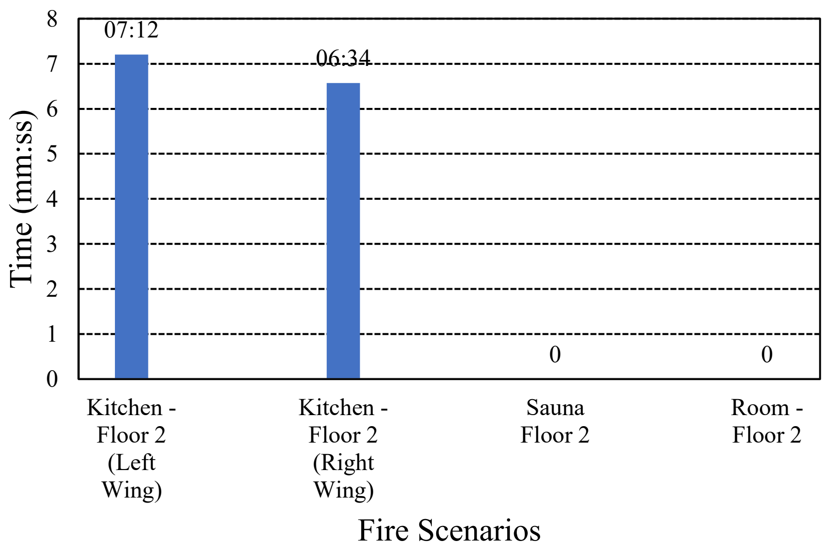

Figure 46: Tenability condition for FED in second-floor lobby in delayed detection case.

This section analyzed the smoke detection times and the tenability condition of different scenarios. The detection times vary among the scenarios, with the occupants' room detecting smoke earliest while the sauna detects it the latest.

In the case of tenability conditions, it is observed that the visibility deteriorates quicker than the FED. Even though the FED limit is not reached, the loss of visibility causes irritation and difficulty in the mobility, especially to the concerned population of elderly; however, this delay of time between both limits still gives a brief window before incapacitation. In the delayed detection case, the available time decreases with the increase in detection time. Additionally, the FED limit fails to reach in sauna and occupants' room scenarios, which highlights the variation in the smoke movement and toxicity.

5.4. Parametric Study

As mentioned in section 4.5, there are two variations of the corridor model based on the mesh size each having further 5 cases with different length of the corridor. The results after running the simulations are obtained from the visibility and FED devices placed in the corridor, while the SD is placed in the fire-source room. The results are compiled in the form of smooth lines for both cases and the times mentioned in the graphs are taken from the moment SD detects the smoke and alert the occupants until those certain tenable conditions reach.

Model with 10cm mesh

Figure 47 shows the model with 8 rooms and mesh resolution of 10cm. The visibility and FED devices are placed at left and right ends shown as green squares and labelled as pt. 01 and 02 respectively at a height of 1.65m, while the SD is placed inside the room.

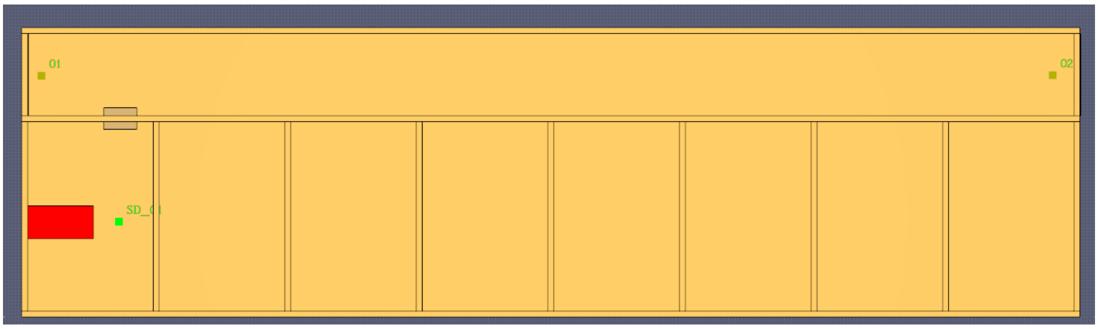

Figure 47: The corridor model with 10cm mesh resolution.

Figure 48 shows the time measured from the moment fire ignites until the smoke detector detects the smoke at 3.24%/m threshold. The reason for using this value has explained in section 4.4.

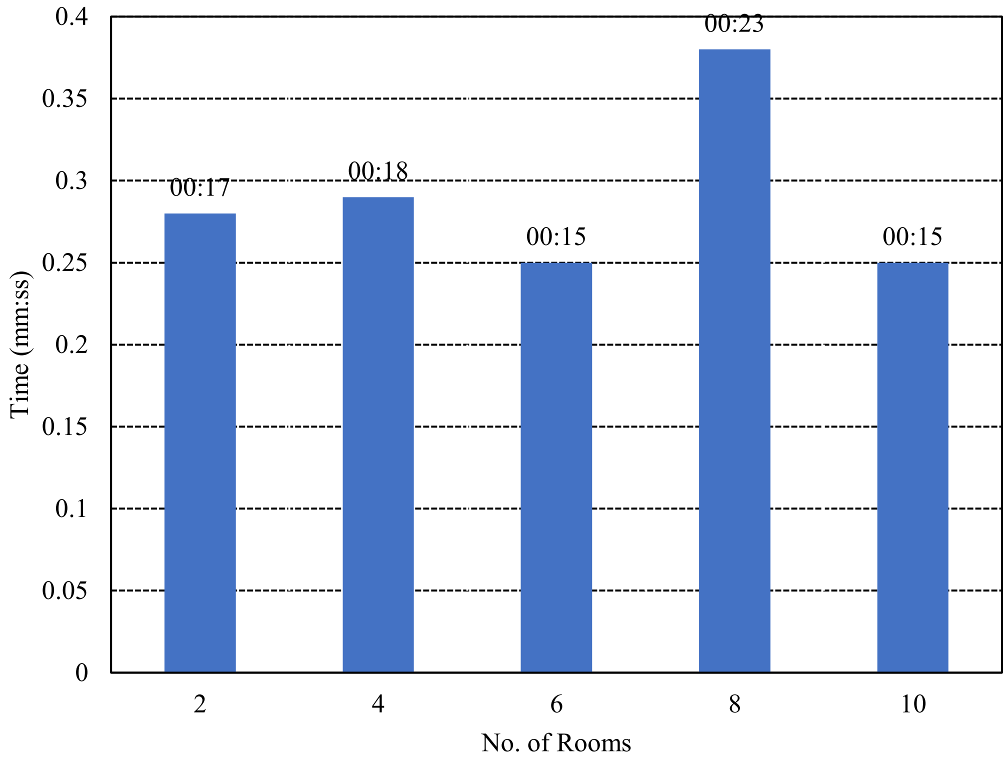

Figure 48: The time taken to detect smoke by SDs in parametric study with 10cm mesh resolution.

Model with 5cm mesh

The corridor model with 5cm mesh divided into 32 parts for MPI process is shown in Figure 49. The 'SD_01' represents the smoke detector installed close to the fire source, while pt. '01' and '02' represents the FED and visibility devices on left and right ends, respectively.

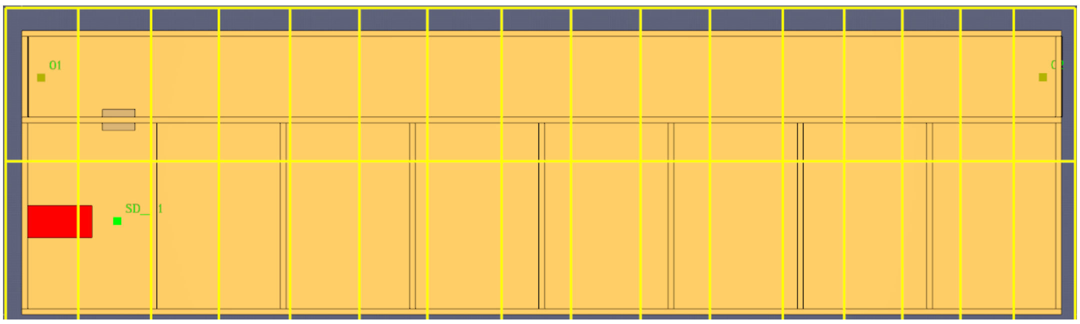

Figure 49: The corridor model simulated using MPI.

The same model of smoke detector is used in these simulations as mentioned earlier in this section, and the detection times are shown in Figure 50.

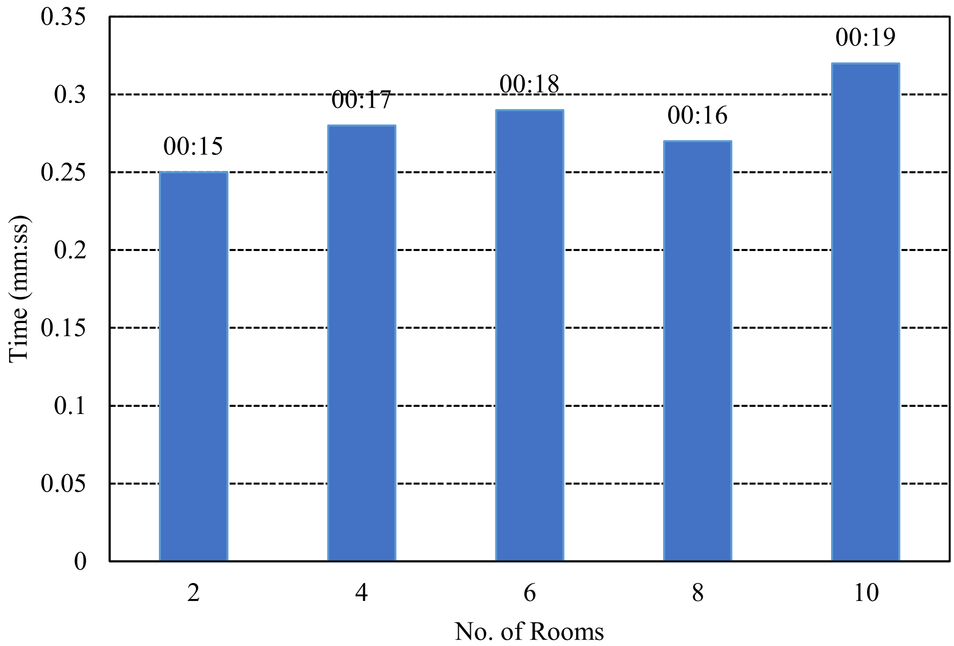

Figure 50: The time taken by the SDs to detect smoke in parametric study with 5cm mesh resolution.

Figure 51 shows comparison of the results obtained from the visibility devices placed in the corridor models for both cases mentioned in this section. It can be observed that refining the mesh resolution from 10cm to 5cm does not have any major effect on the result, on the other hand, the computational time increased considerably. It can also be observed that the time for the visibility to reach tenable condition is faster than FED. So, even though the vision levels get very low shortly after the fire, the incapacitation factor takes more time to reach dangerous levels and hence the occupants have more time to leave the building.

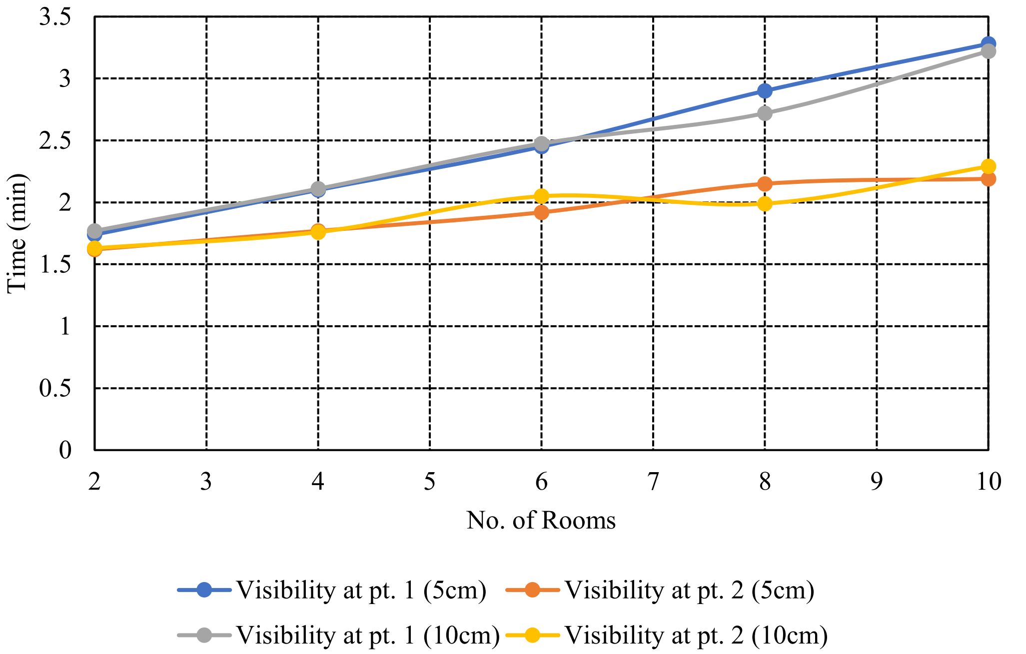

Figure 51: Comparison of visibility devices in a model with different mesh resolutions.

Figure 52 shows the results of FED devices placed on both ends of the corridor model in both cases. Like visibility, FED devices also show almost similar results even after making the resolution finer.

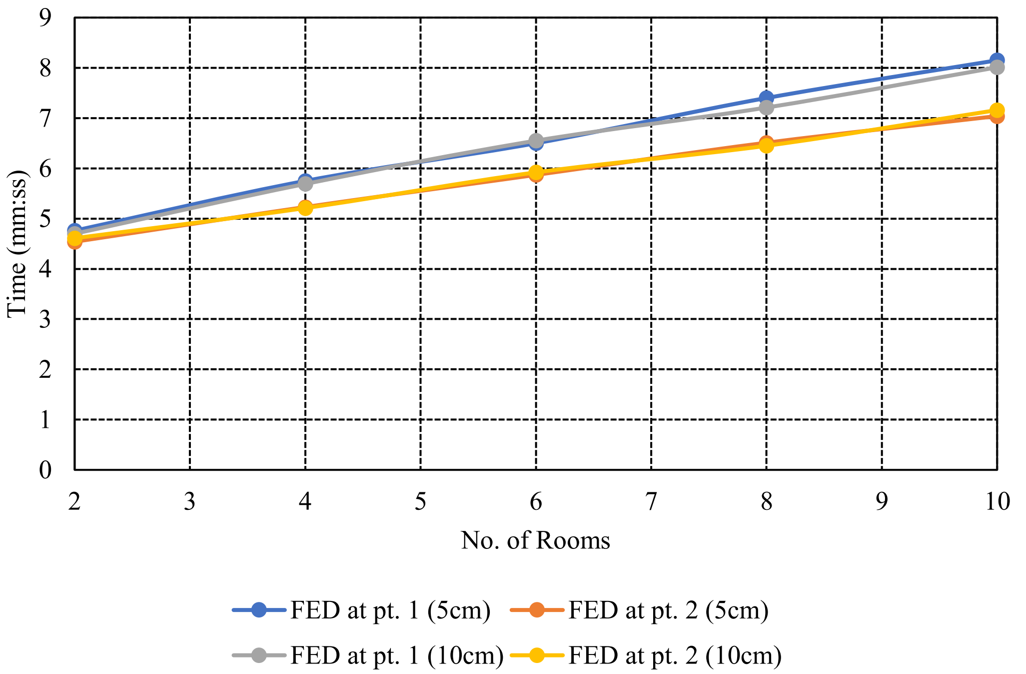

Figure 52: Comparison of FED devices in a model with different mesh resolutions.

The parametric study of this corridor model with fire source in one of the rooms displayed the detection times quite close to the one shown in early detection case earlier in this chapter. Although the visibility results from two cases showed minor differences, the overall trend suggests that refining the mesh from 10cm to 5cm does not affect the results for both tenability conditions significantly but increases the computational time. As discussed earlier, the visibility deteriorates before FED in this case too.

5.5. Sensitivity Analysis

The sensitivity analysis aims to study the impact of varying toxic yields on the simulation output. One of the fire scenarios i.e., laundry room, is considered and a simpler model is used for the simulations. As mentioned earlier, this project primarily uses the surrogate CO and HCN yields; however, this analysis compared the outputs from true CO, true CO and HCN, and the surrogate yields. Unlike surrogate yields, true CO and HCN doesn't account for any other asphyxiant and similar is the case with true CO. The results of the three simulations are presented in Figure 53 taken from device '03' shown in Figure 22.

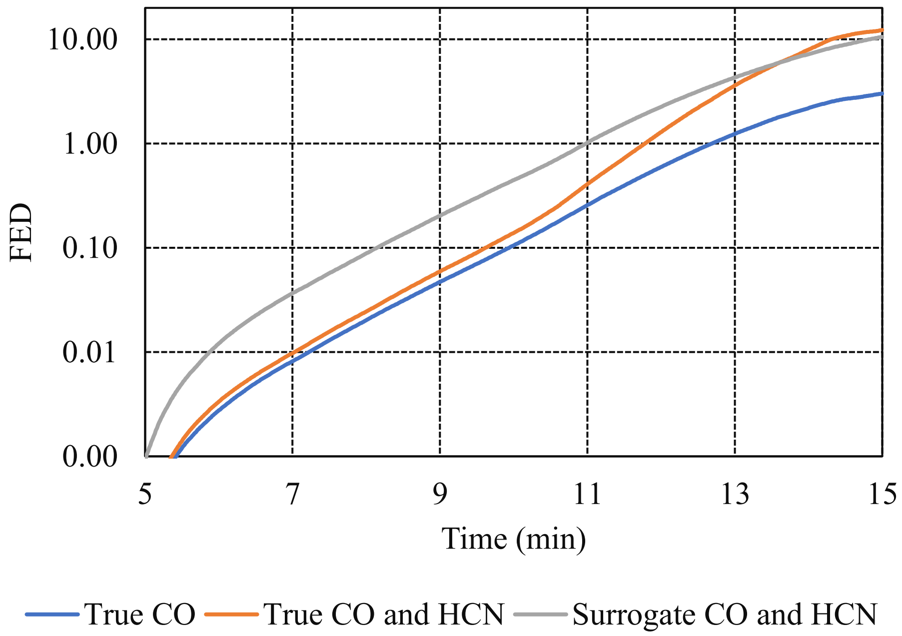

Figure 53: Toxicity in sensitivity analysis.

The results indicate that the FED value for surrogate yield begins to increase after 5 minutes of ignition, while the others show a slight delay. Throughout most of the simulation, the trend suggests that the surrogate yields exhibit higher toxicity, as expected, due to the inclusion of the effects of other asphyxiant gases. The incapacitation threshold is reached after 8 minutes for surrogate yield, while 9.6 and 9.8 minutes for true CO and HCN, and true CO yields respectively. The true CO and HCN yield shows a noticeable increase at 10.5 minutes, when its FED value increases and matches that of the surrogate yield. Ideally, the curve for true CO and HCN yield should not have crossed the surrogate yield; however, this is due to the influence of NO and NO_2 compensation that ultimately reduced the HCN surrogate yield.

5.6. ASET – RSET Comparison using full-scale IFC model

This section compares the results obtained from fire and evacuation simulations using the full-scale IFC model. For evacuation, one of the four wings of the care home building is considered, where there are 13 total rooms. The RSET is compared with the ASET from the most conservative condition of all the fire scenarios i.e., textile fire. Figure 54 depicts the case of horizontal evacuation, where all the occupants are evacuating to the neighboring wing or compartment. There are two variations based on the number of assistants as seen in this graph. In case of one assistant, about 26 minutes are required for the complete evacuation; however, the ASET for visibility reaches 5m in 2.73 minutes with early detection and in 1.14 minutes with delayed detection, while ASET for FED reaches 0.1 in 6.43 minutes with early detection and 4.85 minutes with delayed detection. In the case of two assistants, the RSET is 14.3 minutes, while the ASET for visibility and FED are the same mentioned earlier.

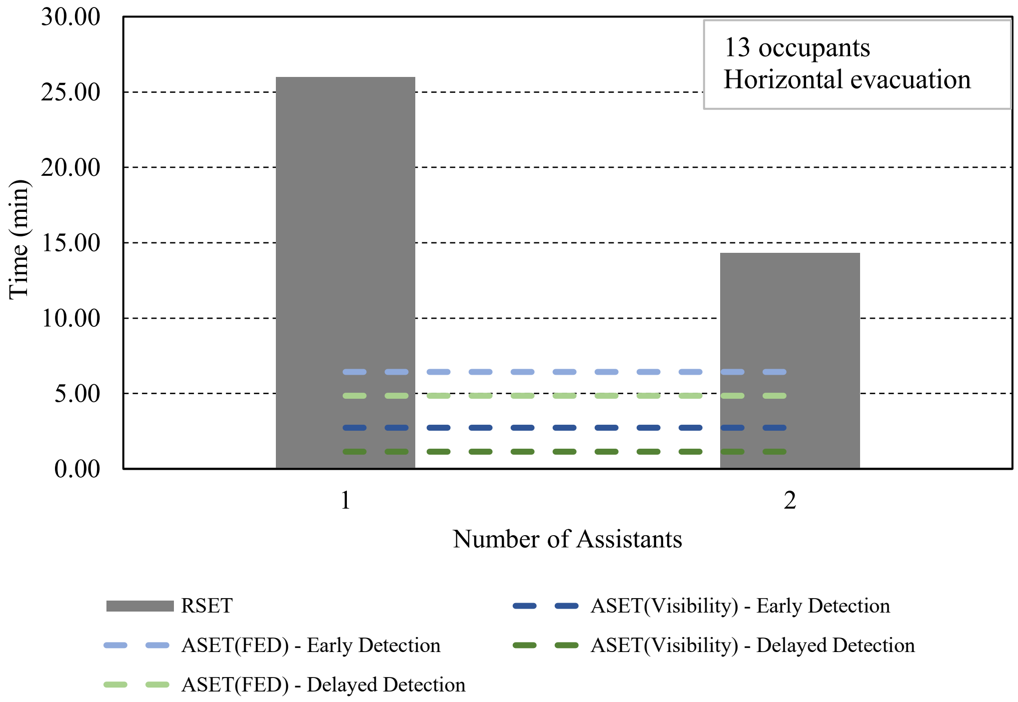

Figure 54: The ASET/RSET relation for horizontal evacuation.

In Figure 55, the vertical evacuation is considered, which means all the occupants have been evacuated downstairs instead of moving them to the neighboring wing. Compared to the first case, this takes longer as it takes more time for assistance to evacuate the occupants from the second to first floor. The RSET in the case of one assistant is 31.76 minutes, and for two assistants it is 17.45 minutes, while for both cases the ASET for visibility and FED is the same as the earlier case.

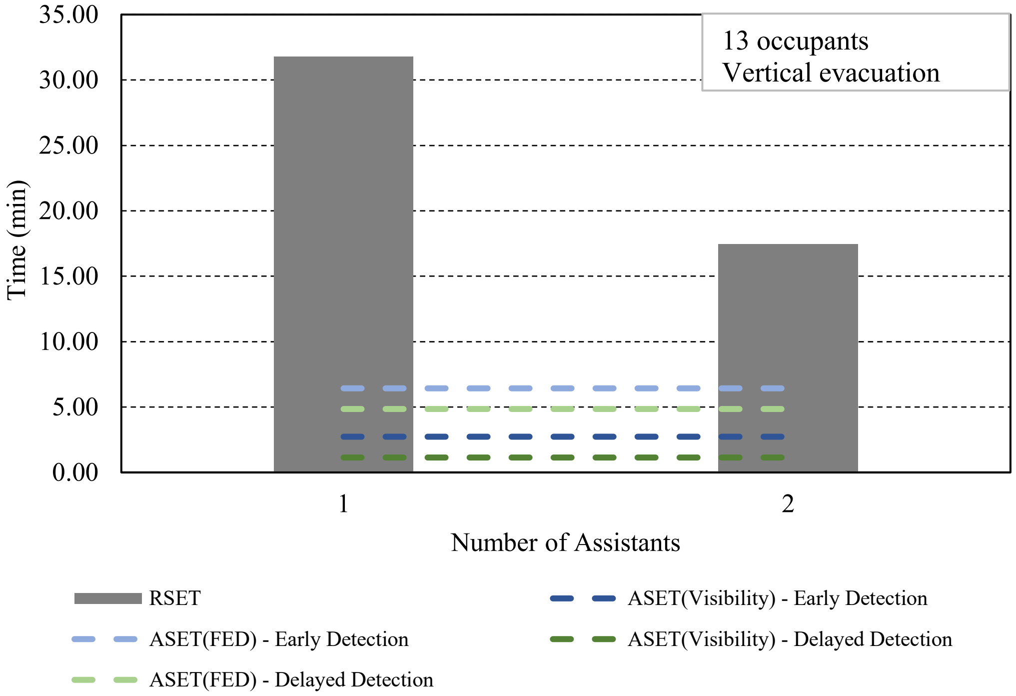

Figure 55: The ASET/RSET relation for the vertical evacuation.

The results clearly indicate that the RSET exceeds ASET by a huge margin, implying that the 13 occupants in the wing do not have enough time to safely evacuate the compartment before the conditions become untenable in terms of both visibility and FED. While doubling the assistants reduces the RSET by half, further increase in their number may not necessarily lead to a proportional decrease in the RSET value.

5.7. ASET – RSET Comparison in Parametric Studies

Another comparison of the ASET and RSET is conducted through parametric study, with details mentioned in section 5.4. For the evacuation analysis, a similar model is developed, and the simulations are performed by two methods: evacuation chairs and evacuation mattresses. While the results of fire simulations have already been discussed in section 5.4, this section focuses on their comparison with the evacuation results. The ASET for visibility and FED are measured at ‘pt. 02’, which is shown in Figure 46 for reference. The data in Figure 56 shows the comparison between the evacuation chair scenario and the fire simulation results across varying room numbers. It indicates that the safe evacuation in terms of FED is possible for up to 5 minutes; however, visibility conditions deteriorate before the evacuation starts, making the RSET insufficient for safe evacuation. It can be observed that occupants from only five rooms can be rescued before incapacitation. However, the irritation caused by the visibility can already affect the occupants and the staff assisting in evacuation. For perspective, the entire corridor could develop incapacitating conditions in seven minutes while the evacuation would continue for about twenty-three minutes.

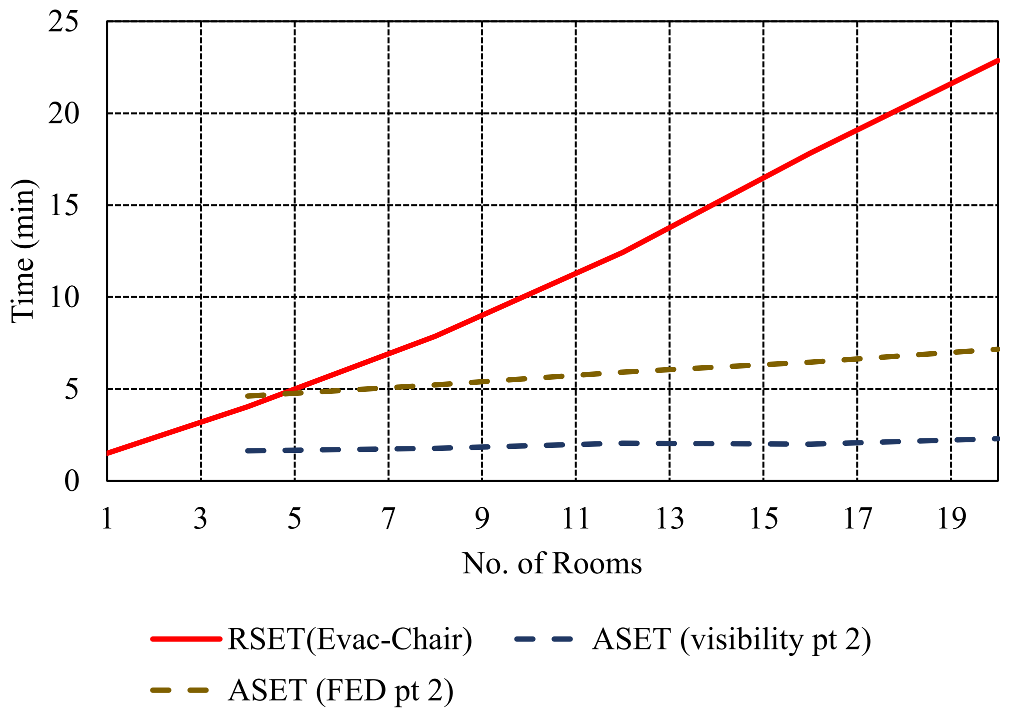

Figure 56: The comparison of ASET for visibility and FED with the RSET obtained by evacuation chair.

Figure 57 shows the comparison of ASET with RSET using the evacuation mattress. This is the method that the facility is currently planning to practice in case of a fire event. It can be observed from the graph that RSET exceeds ASET and there is insufficient time for the safe evacuation of the occupants before the untenable conditions develop in the compartment. Both criteria reach their respective limits before the evacuation could even start developing lethal conditions for the occupants.

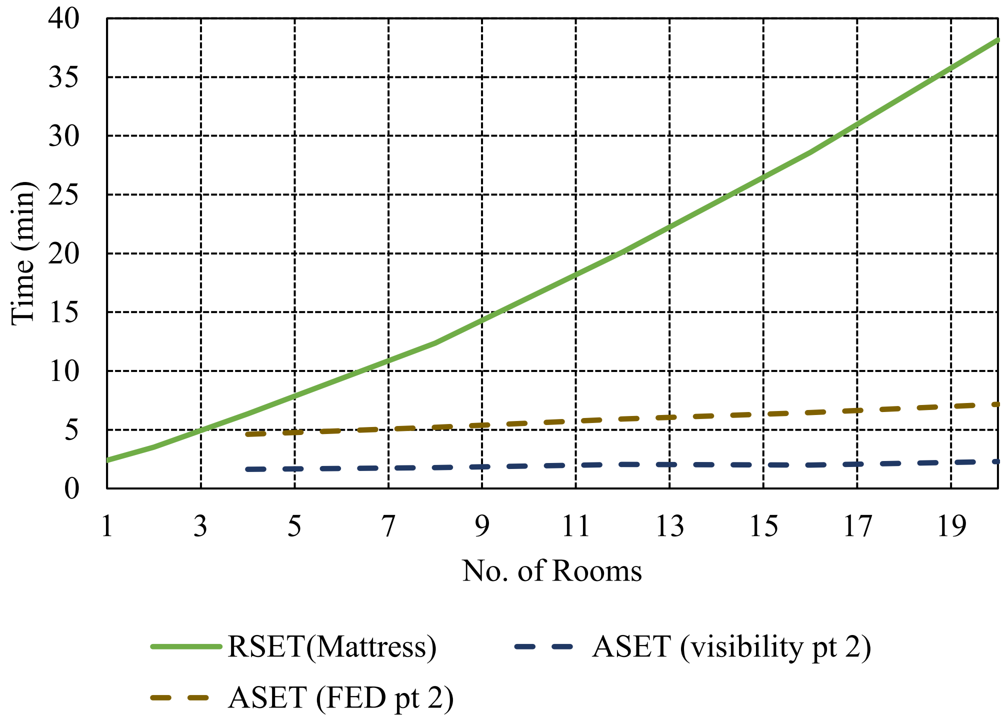

Figure 57: The comparison of ASET for visibility and FED with the RSET obtained by evacuation mattress.

The comparison between ASET and RSET shows that safe evacuation of the occupants is only achievable within 5 minutes using an evacuation chair, by which time the visibility has already deteriorated by then. Even though the evacuation mattress is being planned to be used, its slow speed results in the RSET exceeding ASET and making timely evacuation impossible.

6. Discussion

This study highlights the critical role of simulation-based tools like FDS/PyroSim in defining the fire safety of buildings. The use of IFC model in such projects was advantageous as it streamlined the process by eliminating the need to create a model from the scratch. However, a challenge arises from thousands of unused cells which consume the processing capacity of the system and prolong the computation time but give no meaningful output, ultimately resulting in the waste of computation power and time. Each defined scenario simulated one floor at a time and hence the adjacent floors were not considered due to extended computation times. One possible solution is to avoid the waste cells which is not possible in this case as the building has four wings and an irregular geometry. Alternatively, processors with higher computation power can be utilized, though this solution is expensive. If implemented, these improvements could allow to perform full-building simulations and provide a better understanding of fire and smoke behaviour on multiple floors simultaneously.

In this project, the worst-case scenarios are considered, which means that most of the fire doors are assumed to remain open even after the alarm activates and alerts the staff. This assumption is acceptable for one or two doors, but it is unlikely for all doors to stay open simultaneously. For example, fire doors are installed between each wing and the lobby which automatically close once the fire alarm rings to avoid the smoke spread to other areas of the building; however, it was ignored intentionally to analyse the untenable conditions in both lobbies. The reason for such an assumption is to identify the worst outcome possible from the fire events. These results indicate that even though the overall output might not fully reflect the real-life conditions, the output of wing containing the fire source provides the accurate and valuable insights. Additionally, there was disparity between the input and realized HRR curves in some cases especially in sauna fire scenario, attributing to under-ventilation. This draws the attention towards the importance of an efficient HVAC system. If considered in this project, the results could have been totally different; however, the compliance with worst-case scenario led to this decision of excluding it from the simulations.

The parametric analysis in the project was conducted using a separate corridor model so finer mesh could be used efficiently and computational time could be minimized by eliminating extra cells. The two mesh variations of 10cm and 5cm used in the model, did not show any considerable change in outputs of both cases when the length of the corridor was being changed. Hence, the analysis delivered reliable results for the ASET with first mesh variation, demonstrating that further refining the mesh was not essential for getting better and accurate results.

The sensitivity analysis using the laundry room fire scenario was performed to compare the toxicity yields of surrogate CO and HCN with the true CO and HCN, and true CO. This method is also utilized for working with a finer mesh instead of the original, complex geometry, and save time by using a simpler model. The trend for the surrogate yield aligns with expectations as it showed the highest toxicity among the three considered; however, towards the end, the true CO and HCN toxicity value nearly surpass the surrogate which indicates some chemical changes later in the combustion reaction. It can be inferred that the surrogate method is a useful approach for future simulations provided that the effect of all asphyxiants is incorporated. It provides a more efficient way of accounting for all toxic gases and simplify fire modelling. It also suggests that the simplified geometry could be applied to other scenarios to balance the accuracy and efficiency.

The comparison of ASET and RSET indicates significantly lower ASET than RSET, contrary to the desired outcome. In all cases, the visibility deteriorates before FED resulting in irritation and further delaying the evacuation process. The RSET from the evacuation techniques such as evacuation mattress indicate that no occupant is able to evacuate before the untenable conditions develop in the compartment because they reach very quickly. This is alarming as it is the same procedure that the care home staff are planning to practice in an event of fire, and if not done efficiently could pose critical risk to the lives of occupants. The site visit to the facility proved beneficial as it gave insight into their own practices and sparked a constructive discussion about their decision-making in different emergency situations. It also highlighted the possible challenges that could arise during the actual event of fire such as resistance from occupants, difficulty in safely evacuating people using stairs etc. The results from this project have been shared with the facility and the South Karelia rescue department, who are already incorporating it into their practice.

7. Conclusion

This project analyzed the fire safety of the elderly care home by defining different fire scenarios using the Fire Dynamics Simulator (FDS) to determine the Available Safe Egress Time. The IFC model is utilized, which eliminated the need of designing a model from scratch and saved time; however, due to irregular geometry of the building, it created millions of unused cells during simulations, increasing the computation time. Four different fire scenarios were designed using experimental data obtained from an earlier project. The input HRR curves were developed based on that experimental data. Visibility and Fractional Effective Dose (FED) were taken as the tenability criteria across all scenarios. Additionally, a parametric study with a simplified model and refined mesh was conducted to evaluate the effect of defined tenable conditions and draw a comparison between ASET and RSET for that case. A sensitivity analysis was performed using the laundry room fire scenario to compare the toxicity of surrogate yields against the true yields from the experimental data. Finally, the ASET results from both tenability criteria were compared with RSET from two different evacuation techniques.

The results indicate that the conditions deteriorate quickly, which impacts occupant safety and require revised evacuation strategies and safety measures. The simulation output gives the total Available Safe Egress Time that is required by the occupants for evacuation to safe zone. These results are the combination of the assumptions made for the simulations and the real-life practices in-use by the care home staff. Visibility deteriorates almost twice as quickly as FED, but restricts the movement of the occupants considerably, providing a small window for evacuation before incapacitation caused by FED. The shortest time to reach the untenable conditions is just under three minutes while the longest is about twelve minutes, both in the corridors next to the fire source room. The longest tenability times are measured in the sauna fire as the smoke must travel through two rooms before reaching the detectors and the corridor. In parametric study, the two variations in the mesh resolution i.e., 10cm and 5cm have no significant effect on the ASET results but finer resolution increased the computational time considerably. The sensitivity analysis suggests that the surrogate yields for CO and HCN can be used instead of true yields as they are easier to define and produce similar results.

A detailed analysis of ASET/RSET in this project was conducted in two ways. First, the ASET obtained from full-scale IFC model simulations was compared with the RSET from horizontal and vertical evacuation scenarios. Both scenarios suggested that even with an increased number of assistants, the evacuation times far exceeded the available time. The second comparison was made using ASET values from parametric study against RSET from two different evacuation techniques i.e., evacuation chairs and evacuation mattresses. The results conclude that the occupants from almost 5 rooms can be evacuated using the evacuation chair before incapacitation caused by FED begins, while no timely evacuation is possible with evacuation mattresses. Even in the first case, the visibility deteriorates beyond its defined limit, ultimately affecting the performance of the staff evacuating the occupants. These findings highlight the urgent need for improved fire safety measures and evacuation protocols.

Despite the insights made during this study, there are uncertainties caused by the assumptions such as the failure of the nearest smoke detector, ignoring the role of sprinklers in suppression, keeping the automated fire doors open during the fire event – allowing the smoke to spread throughout the building – and the limited ventilation problems especially in sauna fire cases. The reliability of the results could be improved by avoiding opening the fire doors and modelling them according to their actual functions to prevent unnecessary smoke spread, acknowledging the role of sprinklers in the fire suppression and performing the multi-floor simulations at once for a comprehensive analysis. These ideas can be included in future studies along with the development of more efficient methods for integrating BIM models with FDS, conducting more detailed comparisons between true and surrogate toxic yields, and studying the effect of HVAC systems on the spread of fire and smoke within the building.

References

A. Linna. (2024). Hoivalaitosten palosimulaatioiden lähtötietojen muodostaminen polttokokeista.

Anderson, R. A., Thomson, I., & Harland, W. A. (1979). The importance of cyanide and organic nitriles in fire fatalities. Fire and Materials, 3(2), 91–99. https://doi.org/10.1002/fam.810030207

Babrauskas, V., Fleming, J. M., & Don Russell, B. (2010). RSET/ASET, a flawed concept for fire safety assessment. Fire and Materials, 34(7), 341–355. https://doi.org/10.1002/fam.1025

C. M. Fleischmann. (2009). Prescribing the Input for the ASET versus RSET Analysis: Is This the Way Forward for Performance Based Design?

Ciani, F., & Capobelli, M. (2018). Fire Growth Rate Strategies in FDS. Journal of Physics: Conference Series, 1107, 042007. https://doi.org/10.1088/1742-6596/1107/4/042007

D. A. Purser, & J. L. McAllister. (2016). Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In SFPE Handbook of Fire Protection Engineering.

Dimyadi, J., Spearpoint, M., & Amor, R. (2008). Sharing Building Information using the IFC Data Models for FDS Fire Simulation.

E. Tosolini, S. Grimaz, L. C. Pecile, & E. Salzano. (2012). People Evacuation: Simplified Evaluation of Available Safe Egress Time (ASET) in Enclosures .

F. Nystedt. (2003). Deaths in Residential Fires: An Analysis of Appropriate Fire Safety Measures.

Tuovinen, H., Blomqvist, P., & Saric, F. (2004). Modelling of hydrogen cyanide formation in room fires. Fire Safety Journal, 39(8), 737–755. https://doi.org/10.1016/j.firesaf.2004.07.003

Hostikka, S., & Linna, A. (2024). Using CO and HCN as surrogates for multiple gases in fire toxicity calculations. Journal of Physics: Conference Series, 2885(1), 012091. https://doi.org/10.1088/1742-6596/2885/1/012091

Hostikka, S., Veikkanen, E., Hakkarainen, T., & Kajolinna, T. (2021). Experimental investigation of human tenability and sprinkler protection in hospital room fires. Fire and Materials, 45(6), 823–832. https://doi.org/10.1002/fam.2893

Hostikka, S., Veikkanen, E., Hakkarainen, T., Kajolinna, T., & Kling, T. (2021). Effect of sprinklers on the patient's survival probability in hospital room fires. Fire Safety Journal, 120, 103092. https://doi.org/10.1016/j.firesaf.2020.103092

ISO, I. (2007). 13571: Life-threatening components of fire - Guidelines for the estimation of time to compromised tenability in fires.

Junfeng, C., Maohua, Z., Peiyun, Q., Zeng, L., & Jiacheng, C. (2023). Mapping the fire risk in buildings: A hybrid method of ASET-RSET concept and FED concept. Reliability Engineering & System Safety, 240, 109571. https://doi.org/10.1016/j.ress.2023.109571

Koivuniemi, J., Huuskonen, H., Kanerva, J., Carlson, J., Kapulainen, K., Kuukka, A., Lampila, J., Lehtoviita, T., Rautiainen, J., & Seppälä, C. (2023). Poistumisturvallisuuden tietoperusteisen arviointimenettelyn kehittäminen ikääntyneiden asumispalveluyksiköissä .

Kong, D., Johansson, N., van Hees, P., Lu, S., & Lo, S. (2013). A Monte Carlo analysis of the effect of heat release rate uncertainty on available safe egress time. Journal of Fire Protection Engineering, 23(1), 5–29. https://doi.org/10.1177/1042391512452676

Kuntaliitto, S. (2020). Laatusuositus hyvän ikääntymisen turvaamiseksi ja palvelujen parantamiseksi 2020–2023: Tavoitteena ikäystävällinen Suomi.

L. Wu, R. Pan, S. Wang, C. Su, & W. Wu. (2023). Characteristic Analysis of Four Major Nighttime Fire Cases on Fire Safety of Long-Term Care Institutions Using Fire Protection Defense-In-Depth Strategy. Fire, 6(3), 118. https://doi.org/10.3390/fire6030118

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., & Overholt, K. (2013). Fire dynamics simulator user's guide. NIST special publication.

Poon, S. L. (2014a). A Dynamic Approach to ASET/RSET Assessment in Performance based Design. Procedia Engineering, 71, 173–181. https://doi.org/10.1016/j.proeng.2014.04.025

Poon, S. L. (2014b). A Dynamic Approach to ASET/RSET Assessment in Performance based Design. Procedia Engineering, 71, 173–181. https://doi.org/10.1016/j.proeng.2014.04.025

Schröder, B., Arnold, L., & Seyfried, A. (2020). A map representation of the ASET-RSET concept. Fire Safety Journal, 115, 103154. https://doi.org/10.1016/j.firesaf.2020.103154

Šplíchalová, A., Karásek, T., & Apeltauer, T. (2021). Classification of the Socio-Psychological Aspects of Protecting Soft Targets: a Case Study for Evacuation of the Railway Terminals. Communications - Scientific Letters of the University of Zilina, 23(3), F71–F82. https://doi.org/10.26552/com.C.2021.3.F71-F82

Terveyden ja hyvinvoinnin laitos. (2024). Palokuolemat.

van Straalen, I. J., & de Vries, R. (2020). Alternative Approach for Performing ASET-RSET Analyses in Practice.

Węgrzyński, W., & Vigne, G. (2017). Experimental and numerical evaluation of the influence of the soot yield on the visibility in smoke in CFD analysis. Fire Safety Journal, 91, 389–398. https://doi.org/10.1016/j.firesaf.2017.03.053

Appendix: FDS Input File

The appendix shows the FDS input file code from one of the parametric study cases involving a corridor with six rooms. This model uses a mesh resolution of 5cm, split into 30 smaller meshes to utilize the MPI function of FDS.

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