Evaluation of Strategies for the Integration of Building Information Modelling (BIM) with Simulation of Fires in Enclosures

Silvia Milena Parra Diettes

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Abstract
Computational Fluid Dynamics (CFD) is the study of fluid flows for the analysis of phenomena by scenarios simulated in a computer-based environment. One of the most well-known CFD simulation packages in the fire safety field is Fire Dynamic Simulator (FDS). The tasks of setting up an FDS input file can be time-consuming especially for complex building geometries. Building Information Modelling (BIM) allows the creation of three-dimensional representations of buildings with realistic graphics and with a high level of detail. Additionally, thermal properties of the materials can be found in a BIM model which can be used for performing fire simulations. Thus, BIM can help to avoid manually re-inserting data for setting an FDS input file.

This thesis evaluates the strategies for using the relevant information contained in a BIM model for the simulation of fires using FDS, which required the analysis of Industry Foundation Classes (IFC) as a data-exchange format. It was identified that IFC files contain data regarding the thermal properties of materials in BIM models, though Pyrosim (pre-processor for FDS) does not read this information during the import process. A scripting tool was written in the Python programming language for enhancing the FDS input file obtained from Pyrosim with thermal data from the IFC file. Fire simulations were performed in three different building models to check the overall implementation of strategies. It was confirmed that once the Python script enhances the FDS input file, this can be read by FDS and used for the calculation of heat transfer through the boundaries.

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EVALUATION OF STRATEGIES FOR THE INTEGRATION OF BUILDING INFORMATION MODELLING (BIM) WITH SIMULATION OF FIRES IN ENCLOSURES

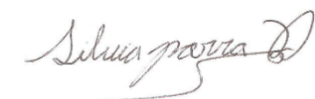Silvia Milena Parra Diettes

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DISCLAIMER

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April 30th, 2019

Abstract

Computational Fluid Dynamics (CFD) is the study of fluid flows for the analysis of phenomena by scenarios simulated in a computer-based environment. One of the most well-known CFD simulation packages in the fire safety field is Fire Dynamic Simulator (FDS). The tasks of setting up an FDS input file can be time-consuming especially for complex building geometries. Pyrosim is a pre-processor for FDS which facilitates the job of creating geometries and selecting the correct parameters and measurements required for a fire simulation.

Building Information Modelling (BIM) allows the creation of three-dimensional representations of buildings with realistic graphics and with a high level of detail. Additionally, properties of the materials and other data should be contained in a BIM model. This information is required for performing fire simulations, so BIM can help to avoid manually re-inserting data for setting an FDS input file.

This thesis evaluates the strategies for using the relevant information contained in a BIM model for the simulation of fires using FDS, which requires the analysis of Industry Foundation Classes (IFC) as a data-exchange format. It was identified that IFC files contain data regarding the thermal properties of materials in BIM models, though Pyrosim does not read this information from the IFC file during the import process. A scripting tool was written in the Python programming language for enhancing the FDS input file obtained from Pyrosim with thermal data from the IFC file. Fire simulations were performed in three different building models, starting from a basic building to analyse parametric data exchange. Finally, a more complex model was used to check the overall implementation of strategies. It was confirmed that once the Python script enhances the FDS input file, this can be read accordingly by FDS and used for the calculation of heat transfer through boundaries.

Resumen

Computational Fluid Dynamics (CFD) (dinámica de fluidos computacional) es el estudio de fluidos para el análisis de sus fenómenos mediante escenarios simulados en un entorno informático. Uno de los paquetes de simulación de CFD más conocidos en el campo de seguridad contra incendios es el Fire Dynamics Simulator (FDS). Las tareas de configuración de un archivo de entrada FDS pueden llevar mucho tiempo, especialmente para geometrías de edificios complejos. Pyrosim es un preprocesador para FDS que facilita el trabajo de crear geometrías y seleccionar los parámetros y las mediciones correctas requeridas para una simulación de incendio.

Building Information Modelling (BIM) permite la creación de representaciones tridimensionales de edificios con gráficos realistas y con un alto nivel de detalle. Adicionalmente, las propiedades de los materiales y otros datos deberían estar contenidos en un modelo BIM. Esta información es necesaria para realizar simulaciones de incendios, por lo que BIM puede ayudar a evitar la reinserción manual de datos para configurar un archivo de entrada de FDS.

Esta tesis evalúa las estrategias para usar la información relevante contenida en un modelo BIM para la simulación de un incendio utilizando FDS, lo cual requiere el análisis de Industry Foundation Classes (IFC) como un formato de intercambio de datos. Se identificó que el archivo IFC contiene datos sobre las propiedades térmicas de los materiales en el modelo BIM, aunque Pyrosim no lee esta información del archivo IFC durante el proceso de importación. Se escribió una herramienta de scripting en el lenguaje de programación Python para mejorar el archivo de entrada FDS obtenido de Pyrosim con datos térmicos del archivo IFC. Las simulaciones de incendios se realizaron en tres modelos de edificios diferentes, partiendo de un edificio básico para analizar el intercambio de datos paramétricos. Finalmente, un modelo más complejo fue usado para verificar la implementación general de las estrategias. Se confirmó que una vez que el script de Python mejora el archivo de entrada de FDS, FDS puede leerlo y usarlo para calcular transferencia de calor en las fronteras.

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List of abbreviations

AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
CAD	Computer-aided design
CFD	Computational Fluid Dynamics
DTV	Design Transfer View
FDS	Fire Dynamics Simulator
HRRPUA	Heat Release Rate Per Unit Area
IFC	Industry Foundation Classes
ISO	International Organisation for Standardization
MVD	Model View Definition
R-Value	Thermal Resistance
U-Value	Heat Transfer Coefficient
XML	Extensible Mark-up Language

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1   Introduction

For assessing the development of a fire in a building, there are several deterministic models available to be used. One of them is called Two-Zone Model which rely on the assumption that the hot and cold gases in a compartment create two well-defined zones with uniform temperatures. Although this simplification is suitable for a wide range of experimental results, it still includes a significant amount of approximations and uncertainty. In the other hand, the most advanced tool nowadays is Computational Fluid Dynamics (CFD) which divides the volume in study into several small volumes and calculates the fundamental laws of conservation of mass, conservation of momentum and conservation of energy. The solution applied by CFD is focused on the so-called Navier-Stokes equations.

One of the most known CFD software used in the Fire Safety field is Fire Dynamics Simulator (FDS) which numerically solves a form of the Navier-Stokes equations for fire driven flows. This software developed by the National Institute of Standards and Technology (NIST) does not have a graphical user interface. It is needed to write down the lines of input required for the simulation. Inputs such as de building geometry, fire size, materials properties are written line by line. Similarly, the desired output is introduced by selecting the location of measurement devices or temperature contours. However, these tasks are time-consuming and make it impossible to think in creating complex geometries by writing down one by one the location and shape of every element in the building. Pyrosim is a pre-processor of FDS which makes it easier the job of creating the geometry and selecting the correct parameters and measurements required for the simulation.

Building Information Modelling (BIM) is being used in the Architecture, Engineering and Construction (AEC) field for the design, construction and maintenance of buildings. It allows creating three-dimensional representations of buildings with realistic graphics and with a high level of detail. Besides the geometry, it incorporates information such as material characteristics, physical properties, element function, quantities, costs, etcetera. Among this information, it is possible to include the thermal properties of the materials that are part of every element in the building.

Since the geometry, thermal properties of the materials and other information might be contained in the BIM model of a building, it results relevant to use this digital information for performing a fire simulation to avoid re-entering data manually in the FDS input file. This results in a more efficient way of transferring information for example from Architects to Fire Safety Engineers.

This thesis evaluates strategies for using the relevant information contained in a BIM model in the simulation of a fire using FDS. This process requires the analysis of a data-exchange format, Industry Foundation Classes, to allow this export and import process. It was identified

the relevant information contained in the BIM model and the data losses that occur when bringing this information into FDS using Pyrosim.

Authors such as Dimyadi et al. (Dimyadi, Solihin, & Amor, 2018) have done research using information from BIM models to support the simulation of fires in enclosures by using BIMRL as a query engine to provide the required BIM data from an IFC file for mapping the FDS input file. It was also consider the use of Blender FDS, an interface within Blender modelling environment, to guide users in manually inserting the required FDS input data. However, that research has not analysed the capabilities of commercial software such as Pyrosim in getting data from an IFC file.

It was identified that the IFC file contains the building geometry data and information regarding the thermal properties of materials in the BIM model. Pyrosim interprets the geometry in the model but does not read information about material properties. This restrains the possibility of taking into account heat loses through the boundaries. In order to enhance this transfer of data, a scripting tool was written in the Python programming language for extracting relevant information from the IFC format and inserting it into the FDS input file from Pyrosim. Finally, for evaluating the functionality of the FDS file obtained, fire simulations were performed in three different BIM models.

1.1 Objectives

- To determine methodologies of coupling Building Information Modelling (BIM) and the simulation of fires in enclosures in Computational Fluid Dynamics (CFD) through a suitable data-exchange.

- To identify the required data in the Building Information Model in order to get the necessary input for performing a simulation of a fire in Computational Fluid Dynamics (CFD).

- To evaluate the feasibility of performing a Computational Fluid Dynamic (CFD) simulation of a fire event in a case study building by the use of information obtained from a Building Information Model (BIM).

- To create and evaluate a prototype tool to address shortcomings in the model data transport from Building Information Modelling (BIM) to Computational Fluid Dynamics (CFD) software packages.

- To analyse limitations and challenges during the implementation of different methods for integrating Building Information Modelling (BIM) with the simulation of fires in enclosures in Computational Fluid Dynamics (CFD) and communicate these outcomes to developers and researchers.

1.2 Methodology

A literature review was carried out to collect information about essential concepts in the Building Information Modelling and the Fire Safety Engineering areas. This required to search for articles, thesis or studies that were done in applying BIM for creating building models and the use of CFD for the assessment of fire scenarios. The first step was to find accepted definitions of BIM and to identify where it is used, what it is used for, which fields and countries are working with it, and how it has been used in the Fire Safety Engineering field.

Later, it was investigated the data-exchange options available to migrate the information from a BIM software to CFD, including concepts such as Open BIM and Closed BIM for the understanding of the different approaches and workflows for sharing BIM data. Industry Foundation Classes (IFC) was explored in more detail, to understand the different Model View Definitions offered in the IFC format, its data structure and versions.

In order to understand and evaluate the data export and import from the BIM software to the CFD software, a basic building was modelled in the BIM software. Some variations in the parametric definitions of the model were introduced, analysed and compared. In order to inspect the geometry and data in the IFC file, BIM Viewer was used, which is a freeware IFC model viewer which allows working with files in format IFC 4 (Datacomp Sp. z o.o., 2019). For reading the text in the IFC file, it was used Notepad ++ (Ho, 2019) a free source code editor that supports several programming languages.

Later, the IFC file was imported into the FDS pre-processor program, Pyrosim. The variations in the input file from the BIM model were analysed against the information received and presented in Pyrosim in order to identify data losses and appropriate configurations to be selected while performing export and import activities. A digital datasheet was created to control the different version of the BIM model, the IFC files exported and the Pyrosim projects created. In this datasheet it was registered the findings during the process, the specific definitions analysed and a graphical record of the appearances of the models in Revit, BIM Viewer and Pyrosim.

A second building was also used to analyse the transfer of information from BIM to IFC and Pyrosim. This BIM model, called the Two-room model, contained additional elements than the Basic building model, such as windows, doors and openings, and helped to understand the development of a fire in a building with multiple rooms.

During this process, shortcomings in the transfer of data were identified in the IFC Export tool of Revit. A tool was created in the Python programming language to read thermal properties from the IFC file in order to enhance an FDS input file obtained from Pyrosim. In PyroSim is

was set most of the fire scenario conditions, including mesh size, fire location, fire size, type of fuel, simulation time, temperature and visibility measurements.

The scripting tool was evaluated in a more complex model, a Health Center provided by Autodesk Inc. While performing the implementation of the case study, it was analysed the different strategies and how to address them. Finally, simulation results were obtained in the form of temperature and visibility contours as well as wall temperature in the boundaries, and these were analysed against performance criteria. There were identified limitations, and challenges for during the implementation process which were communicated via email to developers and researchers interested in this topic.

1.3 Scope

As many programs are available for BIM and CFD, it will not be possible to address all of them. Just the most widely used software in the field was analysed. Since the author already had some established proficiency with Autodesk Revit, FDS and Pyrosim, and considering the time constraint for the development of the present research, this group of software was prioritised during the review of the implementation strategies regardless of other software that might bring similar or better results.

The significant amount of information and the detailed geometrical model from BIM requires long calculation times or advanced hardware requirements if precise results are wanted. However, this study was focused on the workflow from setting up the BIM model until getting results from FDS. A detailed mesh sensitivity analysis was not performed. The size of the grid-cells was limited to perform simulations with fewer computation demands. Therefore, the results from the CFD model might not be precise.

The building models analysed in this study were simulated for fire conditions that might not be representative or critical. It was not assessed the probability or the level of hazard of the fire conditions set in those scenarios. The fire size, type of fuel, locations of the fire, and ventilation conditions were used for testing the workflow of using a BIM model until getting results from FDS but might not be representative of the contents and conditions in those buildings. The performance criteria evaluated in this study should be understood as an example that these simulations from FDS can be interpreted in a life safety context, but not as conclusive fire performance results.

The Python script proposed in this study is based on the current output of IFC files from the Revit IFC Export tool and the FDS output from Pyrosim. If updates are made in the output data in those software packages that modify the information read by the scripting tool, it might be required to verify that the tool continues working as intended.

2 Literature study

2.1 Building Information Modelling (BIM)

Building Information Modelling (BIM) in general terms is a digital construction of the three-dimensional geometry of a building including detailed information of its components which allows a better interpretation of their function, material properties, location and construction process. It facilitates a multi-disciplinary collaboration between architects, engineers and contractors who can find relevant data for activities of design, construction, maintenance and management of the building during its whole life cycle. BIM offers useful capabilities for professionals in the AEC industry since it facilitates activities such as detailed three-dimensional drawing and rendering, development of quantity take-offs and cost estimates, clash-detection, monitoring of construction schedule, among others (Parra Diettes & Vecino Barbosa, 2014).

There is no consensus on a definition of BIM. Its meaning is frequently adapted to the context or discipline in which BIM is applied. Some current definitions are given by documents such as *EN ISO 19650-1:2018* which modified the widely used definition from *EN ISO 29481-1:2017*. This recent standard defines BIM as *"use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions"* (International Organization for Standardization, 2018).

One commonly used definition is the one given by the US National Building Information Modelling Standard (NBIMS), which defines BIM as *"a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition"* (National Institute of Building Sciences, 2019)

In Australia, the National Guidelines for Digital Modelling gives two characteristics of a BIM model: "*First, it must be a three-dimensional representation of a building (or another facility) based on objects, and second, it must include some information in the model or the properties about the objects beyond the graphical representation*" (Cooperative Research Centre for Construction Innovation, 2009)

BIM Use

There are several ways of applying BIM in all the phases of the project. The BIM model should be done according to the scope in which it is planned to be used. A "BIM Use" case is defined by Penn State (Kreider & Messner, 2013) as *"a method of applying Building Information Modelling during a facility's lifecycle to achieve one or more specific objectives"*. It is a combination of the specific objective to be achieved when applying BIM and characteristics

to define, identify and communicate the BIM use accurately; therefore, it should be defined at the beginning of the project.

When applying BIM for the analysis of the performance of the building in case of fire, it should be specified the clear objective to be achieved when applying BIM. This present study suggests minimum BIM Use purposes in which this activity should be focused on, for developing a BIM model based on the guide from Penn State. It is given a scope of the BIM Use applied in this study as a reference for future works when the user intends to perform a fire CFD simulation. If a fire safety designer wants further purposes, they should be included in his specific approach, such us *quantification, monitoring, visualisation* which are not covered in this study.

The planning team of the project should determine how they will be implanting BIM on the project and make a "go/no go" decision on each BIM Use purposes prior more elaboration. The primary purpose of BIM in this present research is to *forecast*. Its objective is to conduct detailed analysis to predict the future performance of a facility facing a given scenario, in this case, a fire event.

A secondary purpose of the BIM model is to *generate* information during the design phase. Any time that information is authored, modelled or created it is generated. The model should contain the necessary information for performing the CFD simulation. Therefore, it is required to determine the magnitude and scale of the facility elements (*Size*) and to determine the location and placement of those elements (*Arrange*).

A tertiary purpose of BIM is to *transform*; this means to translate the information to be received from one form (or format) into another so that it can be received and used by another process. In this case, this is done by exporting information from Revit into an open source format, IFC, which is later used in the CFD package.

BIM adoption

The adoption of BIM around the world has grown in different ways. Countries such as the United Kingdom, the United States of America, Singapore or Finland, which were the pioneers, have been working with BIM for several years and have mandated its use in public projects. Instead, BIM is less developed in Latin-American countries.

A study conducted by Jung and Lee (Jung & Lee, 2015), outlined the state of BIM around the world in 2014 by a survey with results from 150 respondents. While North America, Europe, Oceania, and Asia were advancing rapidly towards a mature stage of BIM, the Middle East/Africa and South America were just early adopters of BIM.

The International BIM report in 2016 (RIBA Enterprises Ltd, 2016) compared the adoption of BIM across the Czech Republic, Canada, Denmark, Japan and the UK, as it is presented in Figure 1. Several stakeholders were surveyed in their understanding, awareness and adoption of BIM between 2014 and 2015. Both Canada (127 respondents) and Denmark (189 respondents) reported a majority of using BIM, were people from the architectural discipline participated the most: 61% in Canada and 58% in Denmark. From the UK close to 900 responses were received. In Japan, 244 respondents participated for the first time in an international BIM survey, where 60% of them were from the design field. One hundred fifty-seven responses were received from the Czech Republic, which reported the smallest percentage of adoption. Among other reasons, this results in the Czech Republic obey to the high prices in BIM software which just big companies are able to afford. It should be noted that since BIM does not have a single definition, these results are affected by national differences in understanding what BIM is.
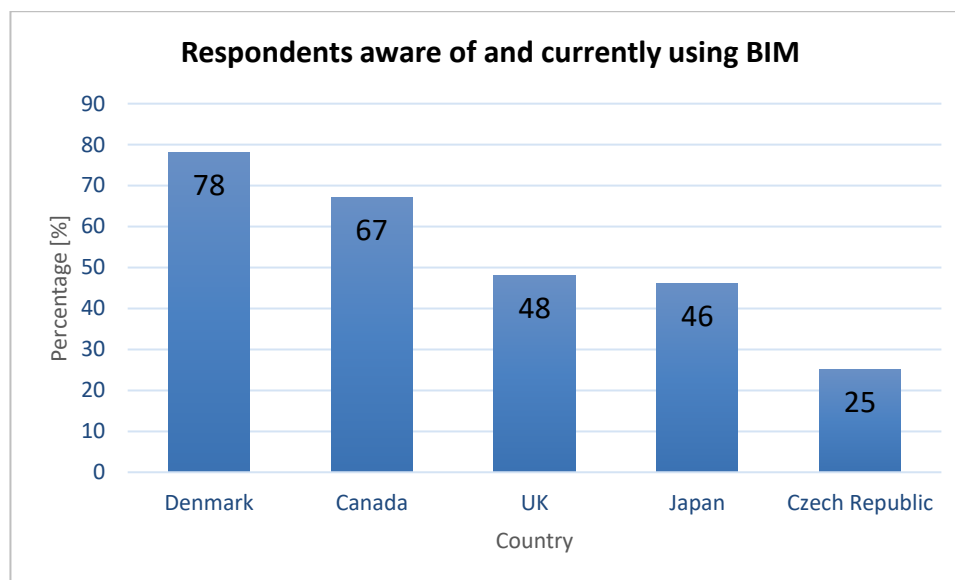
Figure 1. Awareness and use of BIM. Taken from International BIM report 2016 (RIBA Enterprises Ltd, 2016)

Understanding how BIM is adopted in Latin-America is limited by the scarce data about the use of BIM, together with the different dynamics in the industry of each country. Chile is a leader in the region with its strategic plan "Construye 2025" which promotes BIM in the public and private sectors. Additionally, "Plan BIM" a 10-year program created in 2016 is aiming to increase the productivity and sustainability of the construction industry through the incorporation of processes and methodologies using BIM. One of its main objectives is the gradual incorporation of BIM by 2020 in projects developed by public institutions (PlanBIM, 2019).

In countries such as Argentina, Mexico, Panama, Uruguay and Colombia it has been implemented a program called "BIM forum" with independent groups organised on each country. These working groups integrate stakeholders from the construction industry,

engineers, architects and education institutions to promote good practices, research and training on BIM in order to motivate its adoption. In Argentina, for example, "BIM forum" organised a survey in 2017 to 377 professionals in the industry, which reported that 65.2% of them knew about BIM and that 38.1 was using it (BIM Forum Argentina, 2017).

In Colombia, the demand for professionals with knowledge in BIM has been increasing from 2015. National and international construction companies are making efforts on training their employees on BIM for implementing it progressively in their workflows. "BIM forum" was launched in Colombia in 2018 by CAMACOL with the aim of increasing to 50% the use of BIM in construction companies by 2022 (Forero Ramírez, 2018).

The adoption of BIM in the United Kingdom, Sweden and Australia is explained in more detail next.

United Kingdom

In the UK the government plays a crucial role in demanding the introduction of BIM. In 2011, the UK Cabinet Office announced that the government would mandate Level 2 BIM on its projects from April 2016 (Cabinet Office, 2011). In support of this mandate, a BIM Task Group has hosted the development of a series of British Standard and Publicly Available Specification (PAS) documents (British Standards Institution & UK Government, 2019):

- **PAS 1192-2:2013.** It was the first BIM guide released. It was intended for specifying "information management for the capital/delivery phase of construction projects using Building Information Modelling". However, it was recently superseded by EN ISO 19650
- **PAS 1192-3:2014.** Specifies "information management for the operational phase of assets using BIM,". The asset management helps organisations to optimise the life cost of managing portfolios of assets which can be complex and diverse. This PAS focuses on the operational phase of assets regardless of the way how these were commissioned.
- **PAS 1192-4:2014**. It is a code of practice for "fulfilling employer's information exchange requirements using COBie". COBie (Construction Operations Building information exchange) is a conventional structure for the exchange of information throughout the lifecycle of a facility ensuring compliance, continuity and completeness.
- **PAS 1192-5:2015.** Due to increased use of computer-based technologies in support of the management of assets throughout the built environment life cycle, this PAS provides a framework to assist stakeholders in addressing vulnerability issues by sharing information in a security-minded fashion.

- **EN ISO 19650-1:2018.** Recommends principles for business processes in the built environment sector in support of the management of information using BIM during the life cycle of built assets. It highlights that collaboration between participants involved in asset management helps to achieve higher levels of quality and greater use of existing knowledge. Applicable for all size construction projects.
- **EN ISO 19650-2:2018.** Establishes requirements for information during the delivery phase of assets and to produce information in a collaborative environment in a practical way.

With this work, the UK government wants to position the UK to become the world leader in BIM. The National BIM report 2018 (RIBA Enterprises Ltd, 2018) shows that this goal is being accomplished as shown by the growing adoption of BIM in the construction industry. The survey included the responses from 808 wide range type of organisations, from those carrying small to large projects and people from diverse professions, including architects, BIM managers, contractors, service engineers, etcetera. Results from the National BIM report 2018 regarding BIM adoption in the UK are presented in Figure 2.
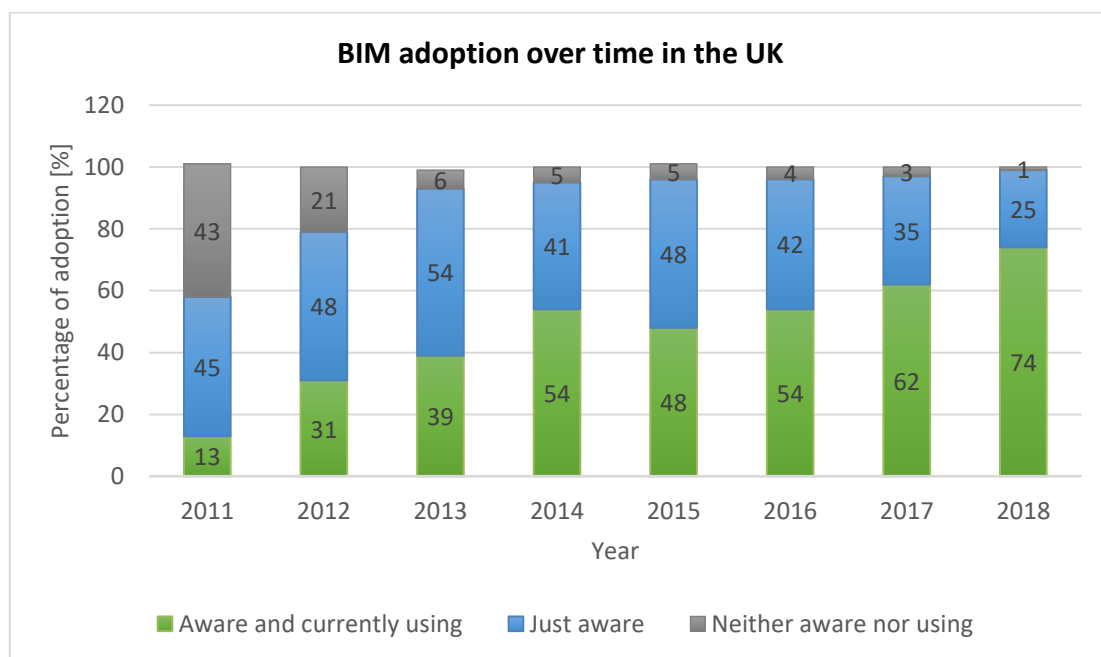
Figure 2. BIM adoption over time in the UK. Taken from National BIM Report (RIBA Enterprises Ltd, 2018)

Data presented in Figure 2 shows that from 2011, when the BIM mandate was first announced, the adoption of BIM in the UK has grown 61% until 2018. After the mandate became effective in 2016, it has increased by 20%. It should be noted that there is still a 25% not using BIM. Some respondents highlighted that the Government needs to continue enforcing the BIM mandate.

Sweden

Sweden is under pressure to increment and materialise mandates to build and optimise BIM and associated standards. Its Nordics neighbours are amongst the pioneers in developing BIM policies and standards to support adoption in the construction sector (Hooper, 2015). In 2009 initiated a sector-wide research and development programme named OpenBIM as a call for state support. Initially, five state organisations started working together, namely Akademiska Hus, Specialfastigheter, Riksdagsförvaltningen, Fortifikationsverket and Statens Fastighetsverksomhet.

Föreningen för Förvaltnings Information (FFI) and the local chapter of BuildingSMART also joined the group changing its name to BIM Alliance Sweden in January 2014. Now the alliance counts with 180 companies and organisations as members. It is responsible for promoting the adoption of BIM in the Swedish AEC industry and for coordinating sector and academic research and development relating to BIM and open standards.

The five state-owned original members of the BIM alliance have motivated an initiative called "BIM i staten" (BIM in the state) which has developed common strategies and guidelines for the use of Building Information Modelling in projects and management (BIM Alliance Sweden, 2017), specifically:

- "Strategi för BIM i förvaltning och project" (2018), Strategy for BIM in management and project.
- "Utvecklingsprocess för BIM" (2014), Development process for BIM.
- "Informationshantering i förvaltning" (2014), Information management in management.
- "Riktlinjer BIM-samordning" (2014), Guidelines for BIM Coordination
- "Riktlinjer digitala leveranser för förvaltning" (2014), Guidelines for digital deliveries for management.
- "Riktlinjer BIM i project" (2014), Guidelines for BIM in projects.

Another public authority has launched initiatives to formulate BIM requirements. The Swedish Transport Authority (Trafikverket) is the largest developer of infrastructure in the country. It is leading an ambitious strategy where all investment projects from 2015 require to be delivered by a pre-defined BIM maturity level. Their goal is to use BIM throughout the project's lifecycle from planning to maintenance and management (Trafikverket, 2017).

The largest Swedish BIM project to date

New Karolinska Solna (NKS) Hospital in Stockholm, is described as one of the most remarkable projects in which BIM has been vital for design, construction and operation (Mills, 2017). The

more than 320,000 m² of indoor space (including 8000 rooms, 38 operating theatres, 168 examinations rooms) and the demanding requirements for a LEED gold certification made the project team to select Building Information Modelling.

During the design phase, a cloud collaboration system was employed for better document management among all parties, from architects, and contractors through mechanical and electrical engineers, including even façade consultants. Through weekly meetings, the team members were able to resolve several clashes, identify risks and analyse costs and programming.

Later, during the constitution works, the latest information was put together for supervisors, site managers, engineers and contractors; this has saved time for printing or searching for information on a large data scale project. On top of that, as-built data will be shared to the partners Skanska and Innisfree, the organisations in charge of operating the facility until 2040. With this BIM model, more optimal operation and maintenance will be possible for the building for all its life.

Australia

One of the first pilots for assessing the benefits of BIM in Australia was done in Sydney Opera House in 2007. The Facilities Management Exemplar project included the integration of 35 years of construction and renovation works in a spatial 3D design and geographical platform. It was found that BIM enables consistency in the data, multiple representations as 2D and 3D reports, and an integrated source of information to support broader organisational objectives (Cooperative Research Centre for Construction Innovation, 2007).

In 2012, the "National Building Information Modelling Initiative (NBI)" was launched, which recommended the Australian Government to work together with industry to accelerate the adoption of BIM in Australia by defining the 1st of July 2016 to require full collaborative BIM and open standards for information exchange. It also endorsed the adoption of a BIM Roadmap, the development of legal and technical instruments to support the mandatory use of BIM and the education of clients and operators on the benefits of BIM (buildingSMART Australasia, 2012)

Several organisations are working together for promoting consistent approaches to BIM. The Australasian BIM Advisory Board (ABAB) was established by the Australasian Procurement and Construction Council (APCC) and the Australian Construction Industry Forum (ACIF), together with standard-setting bodies, NATSPEC, buildingSMART and Standards Australia. This is a government, industry and academia partnership working to maximise the value of BIM. Some key open standards and guides have been developed as shown in Figure 3.

Consistent BIM Object Names & Properties	NATSPEC BIM Object Properties Generator
Clear Project Control	NATSPEC BIM Management (Execution) Plan
Clarity of Project Requirements	NATSPEC Project BIM Brief
Consistent Client Information Requirements	ABAB Asset Information Requirements
Clear Client Information Outputs	Client Asset Management Plan
Consistent Language	NATSPEC BIM Guide

Figure 3. Open standards and consistent practices. Taken from NATSPEC BIM (NATSPEC Construction Information Systems Ltd., 2019)

Some independent studies have been applied in Australasia to create an insight into the level of adoption of BIM throughout the years. In 2010, buildingSMART Australasia surveyed the adoption of BIM in Australia. Four hundred organisations participated in the survey, from which 73% answered the question "Does your company use BIM?". From the total, 49% indicated that they were using BIM, among which engineers and contractors were the highest users; 24% said that they were not using BIM, and 27% did not answer this specific question. However, some limitations should be noted since the survey lacked statistical analysis, control over the respondents, and knowledge about the total number and size of businesses in the industry at the moment (Allen Consulting Group Pty Ltd, 2010).

On the other hand, in 2013 McGraw Hill Construction (MHC) applied a survey on firms located in Australia and New Zealand to understand their engagement with BIM. This survey used accepted industry research standards to produce results with a high level of confidence. The total sample included 435 participants from the design and construction industries. This report showed that 51% of all users had been engaged with BIM for more than three years on more than 30% of their projects. From this study, MHC concluded that in Australia and New Zealand construction industry remains locally driven by small firms characterised by regional differences. This influences the awareness of BIM, which is high but relatively early compared to other regions such as the United States (McGraw Hill Construction, 2014).

2.2   Data-Exchange between BIM and simulation software

In order to understand how data-exchange could be done between BIM software and simulation packages, it should be clear the available approaches for sharing BIM data and workflows across the stakeholders of a project. Bormann et al. (2018) explained some key terms for understanding those approaches.

In one scenario, a project stakeholder applies a specific BIM software for performing a discipline-specific task. The building model is not handed over other stakeholders, and there is no involvement of other software packages. This is called "*Little BIM*", and gives an isolated solution where the external communications are done using conventional drawings.

On the other hand, if constant communication is done between stakeholders from different disciplines and during the whole lifecycle of a project, it is called "*BIG BIM*". For the coordination of this workflow, model servers or databases are often used for sharing information. This is the scenario addressed in this study, where a BIM model is done by a design firm which shares the building model to other stakeholders, such as the structural engineer, electrical engineer and the fire safety engineer. These other parties use their discipline-specific software for performing their simulations.

Later, the challenge is to decide the file formats and software for exchanging information among stakeholders, whether to use file formats readable by software from one vendor ("*Closed BIM*") or vendor-neutral formats ("*Open BIM*") which are usually open source, publicly available and supported by standards.

Several proprietary exchange formats are available for BIM data. The most common example is RVT, the format used by Autodesk Revit. Revit allows interoperability with other Autodesk packages such as Navisworks, used for project review, whose own format is NWD. Other proprietary formats for BIM are PLN by Graphisoft, and DGN by Bentley.

The need for providing interoperability between packages with different internal formats led to the creation of open standards to serve the needs of the AEC industry: Industry Foundation Classes (IFC), for exchanging comprehensive BIM data between software packages, and Construction Operations Building Information Exchange (COBie), for transferring data and documents to facility managers in a human-readable form.

The open-source feature of IFC makes it a preferable format among several software disciplines, which helps in the implementation of "*Big Open BIM*" workflows. IFC is a supported file format by Autodesk Revit and many other BIM software. Unlike RVT format, IFC is also read by Pyrosim, a pre-processor of FDS for the simulation of fire scenarios. IFC features make it a suitable data-exchange format for this study, and it is explained in more detailed next.

Industry Foundation Classes (IFC)

Industry Foundation Classes (IFC) is a vendor-neutral format developed by the international organisation BuildingSMART. It is a data model that represents both the geometry and

semantic structure of the BIM model. IFC is intended to cover a broader range of different data exchange scenarios than the proprietary formats, making easier the interoperability work and avoiding to manually re-enter information previously created.

The idea of using IFC on this research is to be able to communicate the information (geometry and construction properties) from the BIM model (Revit) to the simulation software (Pyrosim) while reducing data losses.

The data modelling language for IFC is EXPRESS, as explained by A. Borrmann et al. (2018), follows object-oriented principles such as the abstraction of objects in the real world into entities, where each entity type is related to attributes and relationships to other entity types.

Many countries have adapted IFC schemas into more customised outputs and have adopted IFC as an obligatory data exchange format for construction bidding and design approvals. Singapore, Finland, Norway, United States of America and Great Britain are among the pioneers (Borrmann, Beetz, Koch, Liebich, & Muhic, 2018)

IFC releases

BuildingSMART presents on its webpage the timeline of the different releases of IFC (BuildingSMART International Ltd, 2019). The first IFC platform released was published in November 2000 and was called *IFC2x.* It introduced the concept of a core model and domain extensions. An addendum followed IFC2x in October 2001, but it was replaced in May 2003 by *IFC2X2,* which introduced sub-models for structural analysis, and electrical, plumbing and building control definitions. It also allowed 2D content.

The third release, IFC2X3, was published in February 2006 which integrated and improved the quality from the previous releases. Since July 2007 it is recommended by Building SMART to use IFC2x3 Technical Corrigendum 1 rather than any other previous release.

The current release, launched in March 2013, is IFC4 (also called IFC2X4) which enhanced the capability of the IFC specification in its main architectural, building service and structural elements. It also improved the readability and ease of access to documentation. A first addendum was introduced in July 2015 (IFC Add1) followed by Addendum 2 in July 2016. The main change in IFC Add 2 is related to improvements in the *Model View Definitions* (explained next), for example, in the tessellated geometry for the *Reference View*, and the advanced boundary representation geometry for the *Design Transfer View.*

The future IFC5 is currently in a planning phase, but it is expected to include further support for infrastructure domains.

IFC Model View Definition

According to Jakob Beetz et al. (Beetz, Borrmann, & Weise, 2018), when the exchange of information is based on an IFC model, a Model View Definition (MVD) helps to determine which information is necessary and which is optional for a particular aspect, process or stakeholder views. The MVD specify what parts of the overall IFC model is narrowed down and the classes, attributes, properties and relationships that are required for a specific purpose. This makes it easier to implement specific use cases (such as structural or fire simulations) and application areas (like tendering or design approval).

A standardised subset of the IFC schemas has been predefined by BuildingSMART to specify further the content expected from the building model:

- **IFC2x3 version**

  o **Coordination view:** It was the first Model View Definition developed by BuildingSMART. First implemented for the IFC2x release, and currently available as Coordination View Version 2.0 for IFC2x3. It allows sharing BIM information between the architectural, mechanical and structural engineering disciplines. It contains definitions of spatial structure and building service elements needed for coordinating these disciplines. Other semantic information can be assigned to those elements, such as property sets and material definitions. It introduced some extensions by the following add-on views:
    - **Quantity take-off add-on:** It transmits base quantities for all spatial, building, building service and structural elements.
    - **Space boundary add-on:** It describes the additional IFC support required for the exchange between architectural and building service modelling software and thermal analysis software. The space boundary definition (also called thermal boundary) is Influenced by "what is on the other side". The two levels of space boundaries are explained as follows (Borrmann, Beetz, et al., 2018):
      1st Level space boundaries disregard any changes in building elements or spaces on the other side.
      2nd Level space boundaries consider changes in building elements or spaces on the other side. Additionally, it also considers the material of the building element, providing thermal properties (Autodesk Inc., 2019h).
    - **2D annotation add-on:** It allows the exchange of 2D element representations such as annotations, dimensioning and remarks.

  o **Structural Analysis View:** it is used to send a structural analysis model, from an application to other structural analysis applications, which might use different analysis methods or codes. It supports that the same structural analysis model can

be evaluated regardless of the primary construction type (either steel, concrete or timber).

- o **Basic Facility Management Handover View:** It aims to improve the interoperability of the building information life-cycle by enabling the integration of planning, design, construction and commissioning applications with Computer Aided Facility Management (CAFM) and Computerized Maintenance Management System (CMMS) applications.

- **IFC4 version**

  - o **Design Transfer View (DTV):** It is used in workflows where the models are handed over to perform further processes. It provides building information that allows modifications of the content by inserting, deleting, moving and modifying elements and spaces. In IFC DTV the source of the BIM information can be shared.

  - o **Reference View:** It is particularly suitable for BIM workflows based on reference models, where the exchange is mainly one-directional. Some of the common characteristics in the workflow when using IFC4 Reference View is that the source of the BIM information remains in the original author and the receiver of the model can analyse and extract the information from it but is not supposed to modify the model. It is mainly intended for visual checking, clash detection and Quantity take-off.

IFC structure

This sub-chapter presents some concepts of the IFC structure which are required to understand the activities of analysis of relevant data from the IFC file. This allows the extraction of information from the BIM model using the Scripting Tool and results in an enhanced FDS file.

Borrmann et al. (2018) described the structure and inheritance hierarchy of the IFC format. IFC is a data model structured into several layers, where the upper ones can reference elements in the layers below, but not vice versa. It is divided into the Core layer, Interoperability layer, Domain layer and Resource layer.

The Core layer contains elementary classes that define basic structures, key relationships and general concepts which can be re-used in more detail by the upper layers. One scheme extension contained in the Core layer is the "Product Extension" which describes the physical and spatial objects of a building and their respective relationships. It consists of subclasses

like *IfcBuilding*, *IfcElements*, *IfcOpeningElement* among others. Additionally, it comprises relationships classes such as the *IfcRelAssociatesMaterial*.

The Interoperability layer lies above the Core layer and represents a connection with the Domain layer. There, derived classes can be used for different application schemes, such as *IfcWall*, *IfcSlab* or *IfcWindow*. Above them, the Domain layer contains highly specialised classes that apply to a particular domain, such as electrical, heating, ventilation and fire protection elements.

Below the Core layer, it is found the Resource Layer which provides basic data structures that can be used in the entire IFC model. Some of these schemes include the Geometry Resource (elements such as points, vectors, curves or swept surfaces), and the Material Resource.

The inheritance hierarchy defines specialisation relationships which links the attributes and classes that can be inherited from other classes. The starting point in the inheritance tree (see Figure 4) is the *IfcRoot* class which provides objects with a unique identification, describes ownership, origin and history of changes made to it.
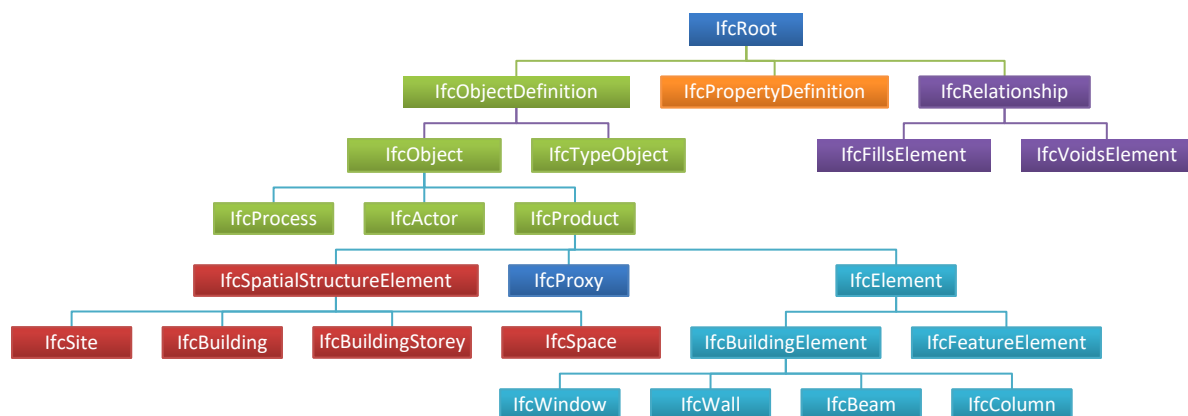
Figure 4. Inheritance tree of a part of the IFC data model. Taken from Borrmann et al. (2018)

From the *IfcRoot* it is found the next derived super-classes:

- **IfcObjectDefinition**: It is an abstract superclass for classes representing physical objects, spatial objects or conceptual elements. It contains three subclasses, namely *IfcObject*, *IfcTypeObject* and *IfcContext*.

   Under the *IfcObject* class, it is found the *IfcProduct* class, which is an abstract object representation to which it can be assigned a geometry and a location within the coordinates system of the project. In turn, it contains:

- **IfcElement:** which is a superclass for all important basic classes including IfcBuildingElement, which contains elements such as *IfcWall, IfcSlab, IfcWindow*, etcetera.
- **IfcSpatialElement:** used to describe non-physical spatial objects, such as *IfcSite* or *IfcBuildingStorey.*
- **IfcProxy:** used for the representation of objects that do not match in any predefined semantic type, such as topography elements.

- **IfcPropertyDefinition:** Defines properties of an object that are not already part of the IFC data model.

- **IfcRelationship:** It is the root in which every relationship object is defined. It is a crucial aspect of a BIM model because it does not stop in the mere creation of building elements as isolated entities but describes the function and interaction between objects. These associations are established as objectified relationships which means that an intermediary object represents the relationship itself. Some relevant relationships in this study are:

  - **IfcRelAssociates:** It is used to relate a source of information with an object or its properties. Besides other relations, it is significant for specifying materials. In this case, it is used the relationship class *IfcRelAssociatesMaterial* which links an *IfcElement* with an object of the class *IfcMaterialDefinition*. In turn, *IfcMaterialDefinition* contains some relevant subclasses for this research:
    - **IfcMaterial:** Specifies the attribute *Name* as a unique identification of materials.
    - **IfcMaterialLayer:** This class contains the attribute *LayerThickness* and relates to the *IFCMaterial.*
    - **IfcMaterialLayerSet:** This class includes a set of *IfcMaterialLaye*r classes. It is an important ability of an IFC model to represent elements form by several layers.

  - **IfcRelDefines:** It connects an object with a Property Set Definition or a Type Definition. Individual *IfcPropertySingleValue* definitions are grouped in an *IfcPropertySet* which is linked to an object by the relationship *IfcRelDefinesByProperties*. An *IfcProperty* can be added as required to any instance in the model. It is here where thermal properties such as Heat Transfer Coefficient, Thermal Mass and Thermal Resistance are defined. Those are found in the Property Set called "Analytical Properties", as Revit names it.

3   Software used in this study

Three software packages were mainly used in this study, Autodesk Revit 2019 for the Building Information Modelling part, FDS for Computational Fluid Dynamics, and Pyrosim as a pre-processor of FDS. Autodesk Revit is the most used BIM software around the world. In the UK, for example, Revit is the most popular software for producing models with 44%, while Graphisoft ArchiCAD is following with 19% (RIBA Enterprises Ltd, 2018). Because of its popularity, more literature is found about its employment in several projects and how IFC is supported on it. Additionally, this study counted with assistance from Autodesk developers for a better understanding of best practices for its use.

FDS is one of the most common CFD software used in research teams for the analysis of thermodynamics, heat transfer, combustion, fire science, among others, due to its focus on fire driven flows. Pyrosim is a pre-processor of FDS; its tasks are crucial for reading IFC files from BIM software in this study. Pyrosim is a commercial programme, but an educational license is available at Lund University for conducting research and promoting training among students.

This chapter also comprises how thermal properties of materials are defined and calculated in FDS, Revit and the IFC format.

3.1   Autodesk Revit 2019

Autodesk is known worldwide for being a leader in architecture and engineering software. It was founded in 1982 by John Walker together with a team who developed the first version of AutoCAD, their first Computer-aided design (CAD) software, used for drafting, design and analysis of building and infrastructure projects. The significant impact of AutoCAD brought the introduction of discipline-specific versions of the software, and other products such as Inventor, Maya and Revit. Nowadays, Autodesk complements its software services together with a significant commitment to education, sustainability and entertainment (Scan2CAD, 2017).

In 2002, Autodesk acquired "Revit Technology Corporation" for an amount of 133 million dollars (Autodesk Inc., 2002). The software was launched in 2000 by Irwin Jungreis and Leonid Raiz who wanted to create an architectural software that could handle more complex projects than ArchiCAD, the first BIM software made available for personal computers (Bergin, 2012).

Autodesk Revit is a Building Information Modelling software used to plan, design, construct and manage buildings and infrastructure. It allows the parametric modelling of elements in a project to enable better coordination and change management. It also allows multiple team members to work simultaneously in a centralised model. It facilitates the communication of

designs thanks to the tools offered for three-dimensional drawing and rendering, and the possibility of adding and presenting semantic data in the model, for example through material take-offs. Additionally, Revit offers fully certified import and export of IFC files (Autodesk Inc., 2019c)

In this research, it was used Autodesk Revit 2019 (19.0.1.1) to generate the model of a basic building and a two-room building, as described later. One key feature in this version is the improvement for IFC4 support. Additionally, this version of Revit enhanced some tools, such as those for applying custom parametric cuts in steel connections; improved capabilities for primary/secondary hydronic networks; maximised working space with tabbed views and multimonitor support (Brumm, Crotty, Molloy, & Piechnick, 2018).

The latest release of the software was already announced: Revit 2020. This enhanced version contains new features such as: support of PDF files; advanced elliptical walls; improved rebar copy and movement, and "Path travel", a useful tool for the Fire Safety field for the analysis of movement of people in buildings based on travel distances and times between two points in the model (Brumm, Crotty, Molloy, & Piechnick, 2019).

3.2 Fire Dynamics Simulator (FDS)

Computational fluid dynamics (CFD) is the study of fluid flows in systems to analyse associated phenomena such as chemical reactions or heat transfer by scenarios simulated in a computer-based environment. CFD solving power is structured around numerical algorithms that can address fluid flow problems. It offers unique advantages over experiment-based approaches in the sense that it allows a reduction of time and costs of new designs. Additionally, it has the ability of study complex scenarios which might be expensive or impossible to perform in controlled experiments or to challenge the capabilities of a system above normal limits (Verteeg & Malalasekera, 2007). Three-elements are usually part of CFD software: a pre-processor, a solver and a post-processor.

Fire Dynamics Simulator (FDS) is a Computational Fluid Dynamics software released in February 2000 as a collaborative work led by the National Institute of Standards and Technology (NIST) in the United States and VTT Technical Research Center of Finland. It is aimed as a tool for solving practical fire safety problems and for the study of fundamental fire dynamics and combustion (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019b).

FDS includes several models for specialised applications. The Hydrodynamic Model numerically solves a form of the Navier-Stokes equations for thermally-driven flows. Turbulence is solved by means of Large Eddy Simulation (LES), which is its default mode of operation, but Direct Numerical Simulations (DNS) are also possible if the mesh is fine enough.

The Combustion Model in FDS uses a single step, mixing-controlled chemical reaction and the Radiation Transport is solved by the Finite Volume Method (FVM).

One notable feature of FDS is the approximation of geometry obstructions to rectilinear meshes, and bounding surfaces to flat planes. FDS allows the use of multiple meshes to handle cases where the geometry does not fit a single mesh and for taking advantage of its parallel processing options.

FDS acts as a CFD solver without a graphical user interface (GUI). Input can be written in a text editor (such as Notepad ++) or by third-party software (like Pyrosim). Smokeview is used as a post-processor of FDS and is designed for visualising time-varying fire phenomena. It has been developed by Glenn P. Forney at NIST. With this software, it is possible to display animated contour slices for time-dependent variables, such as temperature, velocity or visibility, and contour and vector planes for static data at a fixed time (Forney, 2019).

Version 6.7.1 of FDS and 6.7.5 of Smokeview were used in this study.

3.3 Pyrosim

Pyrosim is a commercial pre-processor of FDS, developed by Thunderhead Engineering Consultants. It provides an easier way to input complex 2D or 3D geometries in FDS through a user-friendly interface. It also facilitates the selection of simulation conditions and parallel processing. Pyrosim ensures that the desired simulation scenario is written in the correct format as an FDS input file. Also, the visualisation tool "Results" that accompanies PyroSim works as a post-processor of FDS.

One of the main features of Pyrosim version 2018.3.1210 that was used in this research is the capability of importing BIM files as well as formats like CAD and images types (.png, .jpg, .tif, .bmp). According to Pyrosim's User Guide (Thunderhead Engineering Consultants Inc, 2018), the software can import data from Autodesk Revit by the following formats:

- **IFC:** It provides advanced BIM data related to the objects in a building, although it is currently used only for geometry import in Pyrosim.
- **DXF:** CAD format which handles complex geometry types but does not support appearance information.
- **DWG:** It also supports geometry data but has basic support for mapping textures.
- **FBX:** Outstanding support for appearance information and texture mapping, but PyroSim treats the objects as collections of thin faces instead of solid objects. The best results for importing this file format in Pyrosim are achieved by the used of third-party plugins such as Simlab Soft.

3.4 Material properties in FDS and Revit software

Material properties in FDS

To consider the heat transfer through solid materials when a fire is simulated in FDS, it is required to include some properties of the material(s) that form the elements of the building. In the MATL line, the following properties can be defined:

Thermal conductivity (k): It is a physical property of a material that in general depends on temperature and the nature of the substance. In solids, heat is transmitted by the elastic vibrations of the atoms and molecules and by free electrons which acquire an increased velocity when the temperature at one end of an object is raised. While these electrons move, they collide with other particles and transfer their energy to them. A high value of thermal conductivity means a higher rate of heat that moves to other parts of the solid, and then, this tends to reduce temperature gradients (Karwa, 2017). The units used in FDS are [W/m*K], and it can be defined in the input file with the name CONDUCTIVITY.

Specific heat capacity (c): Sometimes referred to as Thermal Capacity (Drysdale, 2011), is a measure of the variation with temperature of the stored energy of a substance (Pitts & Sissom, 1998). The units used in FDS are [kJ/kg*K], and it is called SPECIFIC_HEAT.

Density (ρ): It is defined as the mass per unit volume. The units used in FDS are [kg/m³], and it is written in the code as DENSITY.

These properties have been determined experimentally for several engineering materials, and some of these values can be found tabulated in literature sources, such as the ones by Shaum's (1998) or Karwa (2017)

Even though that these parameters are temperature dependent and can be set in FDS to take into account this variation, it was not considered for this project since its influence in solid materials is slight, and the data stored in the BIM model does not include information about this dependence.

Additionally, in order to get the heat transfer calculation in FDS, it is necessary to add a line under the SURF line which establishes the material (MATL_ID), thickness (THICKNESS), emissivity (EMISSIVITY) and the material mass fraction (MATL_MASS_FRACTION) when a mixture of solid materials are found in the same layer. However, in this project, the emissivity that was used for FDS is the one by default (0.9), and it was considered materials just with one component per layer.

Material properties in Revit and IFC

Autodesk REVIT 2019 and IFC assign other derived thermal properties to the building elements of a BIM project which are explained next:

Heat transfer coefficient (h): Also referred to as U-value. It is the constant of proportionality linking the heat transfer per unit time and unit area to the overall temperature difference (Pitts & Sissom, 1998).   In Revit is calculated using the following equation (Autodesk Inc., 2019d):

$$U\ Value\ = \frac{Thermal\ Conductivity}{Thickness} = \frac{1}{R\ value}\left[\frac{W}{m^2 * K}\right]$$

Thermal Resistance (R) = Sometimes called R-Value. It is the resistance that the material offers to the flow of heat by conduction (Karwa, 2017). The Thermal Resistance in Revit is defined by the following equation (Autodesk Inc., 2019j):

$$R\ Value\ = \frac{Thickness}{Thermal\ Conductivity}\left[\frac{m^2 * K}{W}\right]$$

Thermal mass (C)= In Revit, the thermal mass value of an element is equivalent to thermal capacitance or heat capacity (Autodesk Inc., 2019l). When heat is applied in a surface, the solid absorbs heat locally at a rate depending on its heat capacity. The higher the heat capacity, the higher the temperature gradients (Karwa, 2017). In Revit, the thermal mass is calculated as follows (Autodesk Inc., 2019g):

$$C = Density\ x\ Volume\ \times Specific\ heat = Mass\ x\ Specific\ heat\left[\frac{kJ}{K}\right]$$

Where the volume is calculated as the thickness of the material layer times one square foot (0.0929 m²).

In the other hand, when an IFC file is exported, the value of thermal mass is given as [J/(m²*K)], and it is calculated in the following form:

$$C = Density\ x\ Thickness\ \times Specific\ heat\left[\frac{J}{m^2 * K}\right]$$

Revit offers three different ways to assign the mentioned thermal properties to element types. These can be selected in the Advanced Energy Settings dialogue and used to suit different stages in the design process:

Conceptual types: This is the configuration used by Revit when no other option has been selected for an element in a building model. It is intended for energy analysis based on conceptual masses. It uses a series of tabulated data for different conceptual constructions.

For example, for an exterior wall the values presented in Table 1 are available in the International System of units:

Table 1. Mass Exterior Wall Metric (SI) Values (Autodesk Inc., 2019k)

Conceptual Construction	R-value	Unit density	Heat capacity
Lightweight Construction - High Insulation	4.47	139.54	0.234
Lightweight Construction - Typical Cold Climate Insulation	3.05	155.97	0.214
Lightweight Construction - Typical Mild Climate Insulation (default)	1.73	184.15	0.193
Lightweight Construction - Low Insulation	1.38	301.46	0.196
Lightweight Construction - No Insulation	0.49	455.55	0.193
High Mass Construction - High Insulation	2.91	495.67	1.116
High Mass Construction - Typical Cold Climate	2.58	477.14	1.081
High Mass Construction - Typical Mild Climate	1.91	512.67	1.08
High Mass Construction - No Insulation	0.24	669.35	1.075

Schematic Types: It is intended for the schematic design stage. It assigns defined thermal properties for building element categories and overrides the default Conceptual Types when it is selected. It includes a series of thermal properties for predefined analytic constructions.

The following are the categories for which a schematic type can be selected: Roofs, Exterior Walls, Interior Walls, Ceilings, Floors, Slabs, Doors, Exterior Windows, Interior Windows and Skylights. For example, for the category of doors, it is possible to select between the next analytic construction options:

- Wooden (U=2.1944 W/(m²*K))
- Metal (U=3.7021 W/(m²*K))
- Timber flush-panel hollow-core (U=2.3256 W/(m²*K))
- Solid hardwood (U=2.5572 W/(m²*K))
- Hollow core wood (U=3.1796 W/(m²*K))
- Door – wood – hollow core – wood storm (U=1.8737 W/(m²*K))

Detailed elements: It is used when the model contains building elements whose material thermal properties have been carefully selected to represent real construction properties and overrides the Conceptual Types and Schematic Types options. It gives more realistic results when an energy analysis is carried out.

Autodesk Revit 2019 has a library of common materials used in the AEC field. This library includes information on physical and thermal properties. Inside of the Material browser, Revit allows to include three different assets per material: Appearance, Physical and Thermal.

The Thermal asset includes nine configuration options as shown in Figure 5. It can be noted that the required thermal properties of materials for performing simulations in FDS are included in the information contained in the Revit model.
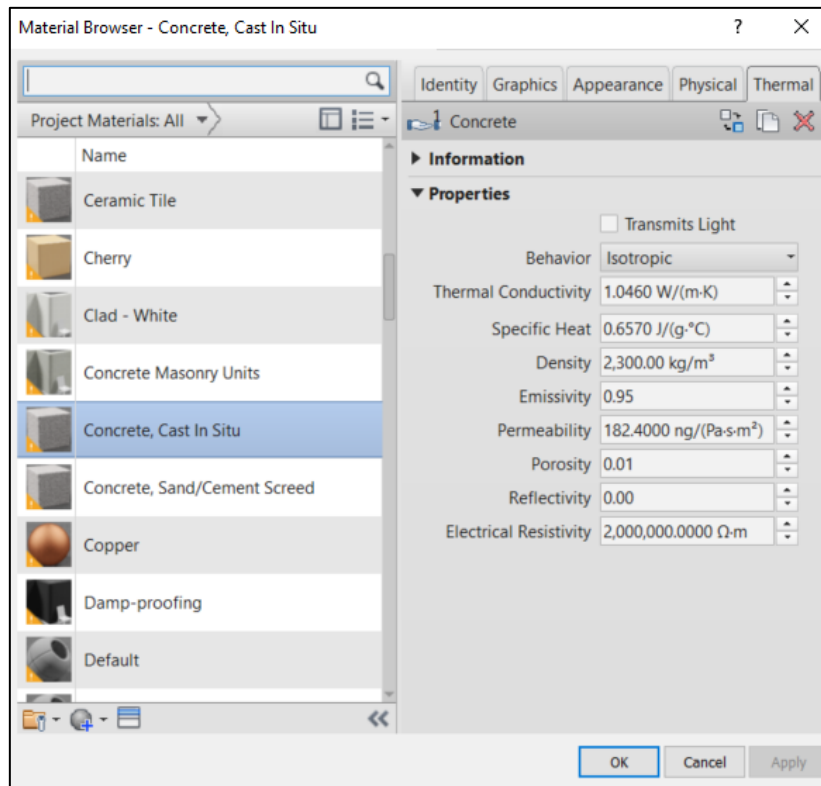
Figure 5. Material Browser in Revit 2019. Thermal Properties for "Concrete, Cast In Situ".

Revit automatically calculates Heat Transfer Coefficient (U), Thermal Resistance (R), and Thermal mass for each element type depending on the thickness of the material layers and its material thermal properties, using the equations mentioned before. However, these three properties are only calculated when the Detailed Elements option is selected and for the next specific element types: Roofs, Ceilings, Floors, Walls, Foundation Slabs, Structural Floors and Structural Walls. These values are stored in the "Analytical Properties" and can be found in the "Edit type" window for each element type.

For other elements, such windows and doors, the values of the Schematic types are used (if this option has been selected instead of the Conceptual Types) since the complexity of such elements makes it difficult for Revit to calculate thermal properties from the Detailed Elements.

4 Evaluation of parametric definitions and adjustments in different building models

The evaluation of different parametric definitions was made in building models with three levels of complexity. It was chosen to start with a simple model to facilitate the understanding of the structure of the IFC format and the data losses during export and import activities. This first model, the Basic Building, facilitated the analysis of variations in the construction materials and the interpretation of these changes when imported in Pyrosim. The second level of complexity, the Two-room building, was intended for the analysis of openings, windows and doors. The third and more complex building was the Health Center, selected as a case study for the evaluation of the complete workflow from getting BIM data and using it into a CFD simulation. In this chapter is presented more information on the features of the building models and the parametric definitions studied.

4.1 Building models analysed

Basic Building Model

In order to analyse an adequate pathway for exporting information from a BIM model, and to perform fire simulations, it was done a basic building model in Autodesk Revit. The geometry of the room is based on the Reaction to fire test – Room corner test, according to the standard SS-ISO 9705-1:2017 (International Organization for Standardization, 2017). The dimensions of the room are shown in Figure 6.

Using this simple geometry made more straightforward to identify changes in the IFC file text while modifying the geometry or parametric definitions from Revit and the subsequent results when importing to Pyrosim.
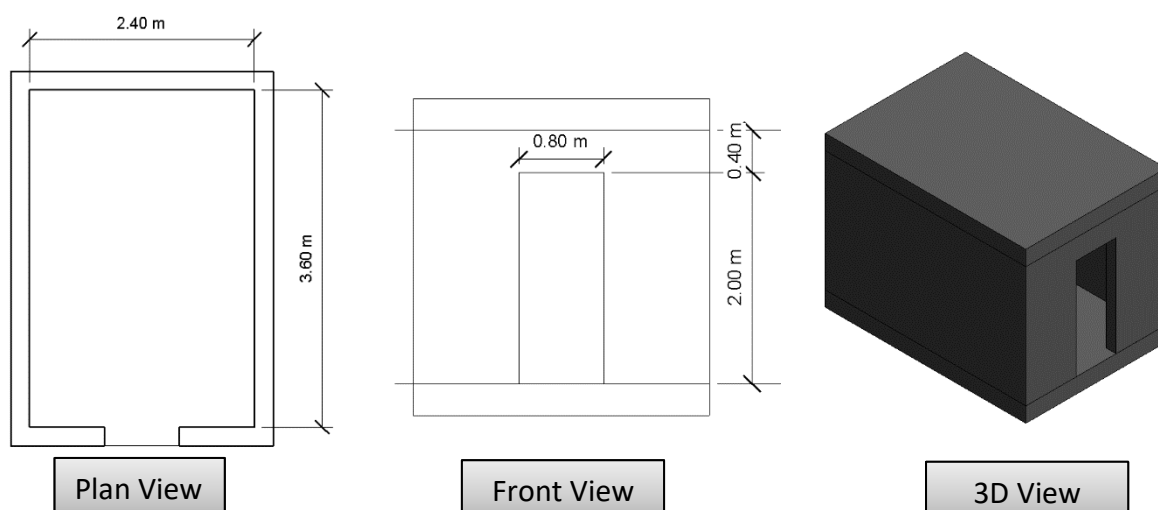
Figure 6. Dimensions of the Basic Building Model according to SS-ISO 9705-1:2017

Two-room Model

A second model was created with more elements and characteristics than the Basic Building Model. The Two-room model has double the area than the first one and includes additional elements such as a closed door, an open window and a closed window. This model allowed the analysis of the IFC file when doors and windows are included, as well as the capabilities of Pyrosim and FDS for performing simulations involving heat and smoke spread to further areas that the room in fire. The dimensions and geometry of this room are shown in Figure 7.
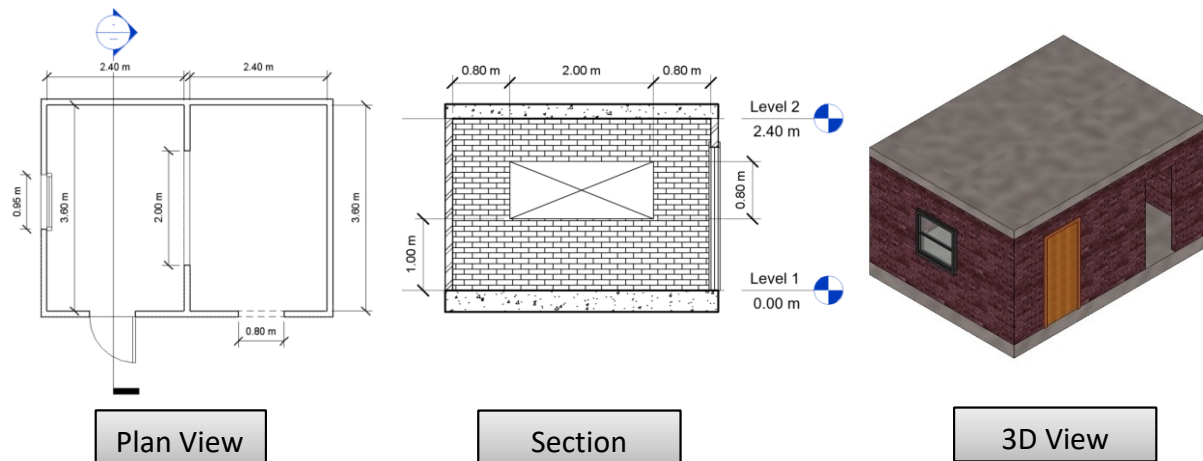
Figure 7. Dimensions of the Two-room model

Case study: Health Center Model

A more complex building was selected to evaluate a case study with the characteristics of a real building model. Autodesk provided the "Health Center model located in San Francisco", a BIM model in Revit that is frequently used for the explanation of Energy Analysis tools in software from Autodesk (Autodesk Inc., 2019f). This model is presented in Figure 8 and Figure 9.
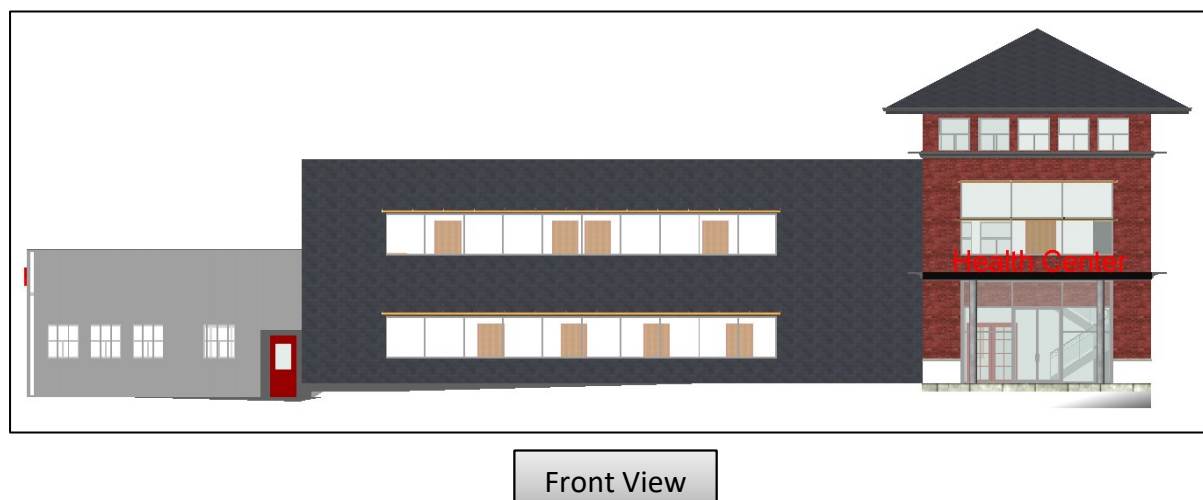
Figure 8. 3D Front view of the Health Center

| South-East View | North-West View |
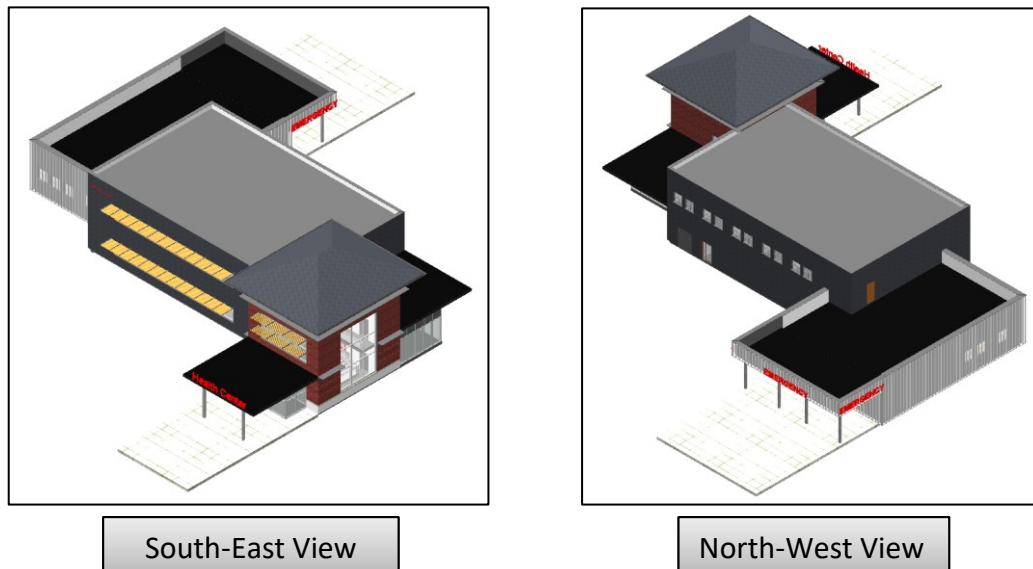
Figure 9. 3D South and North views of the Health Center

An overview of the components of this building is presented in Table 2.

Table 2. Features of the Health Center model

Number of floors	2 floors
Number of rooms	68 rooms
Total area	998.62 m²
Doors types	11 families
Window types	2 families
Floors types	2 types
Ceiling Types	3 types
Roof types	4 types
Wall types	12 types
Curtain wall types	9 types

In the scope of this research, the most relevant information in this model is the one related to the materials and their thermal properties. The model has eighty-four (84) different materials from which thirty-one (31) materials have a thermal asset already included. Some of these materials are taken from the library in Revit and others were explicitly made for the project. Since not all the materials include thermal properties, the information imported into FDS is not complete to analyse the heat losses through all boundaries. However, this is a regular scenario that a Fire Safety Engineering might encounter when receiving a BIM project from other Designers, Architects or Engineers, who might not be aware of the need to include further characteristics of the materials proposed for the project.

Even though the model was set in Imperial units, these settings were changed in Revit to the International System of Units in order to match the configuration of the Scripting tool.

4.2 Parametric definitions and adjustments

In order to isolate the best step by step in the process of exporting the BIM model into the CFD software, several parametric definitions were changed. First regarding the materials of the construction elements, later related to the type of openings, and last, changes in the file format and version for the data exchange. All the adjustments studied are shown in Figure 10.
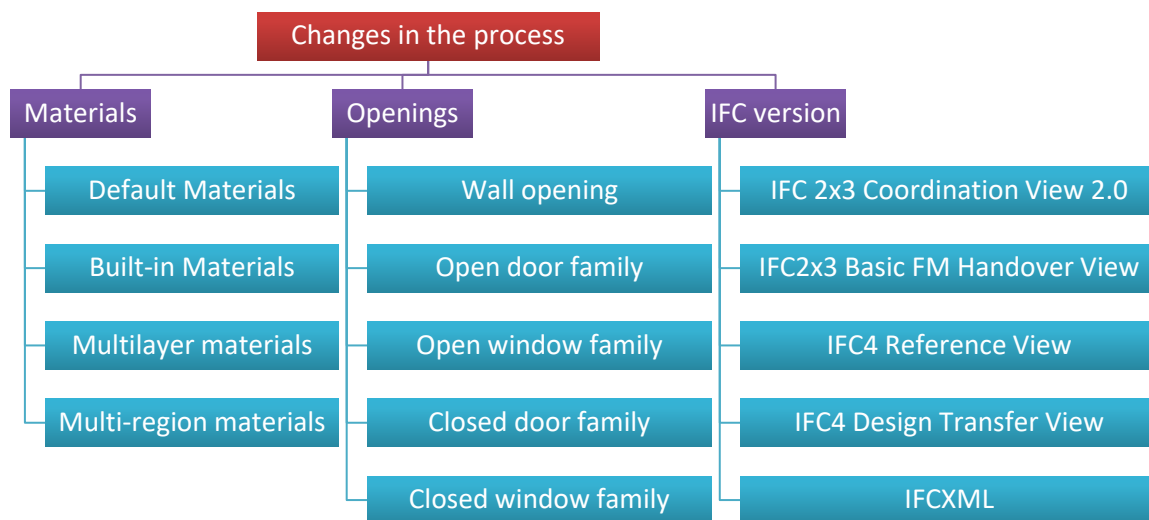
Figure 10. Parametric definitions that were evaluated.

Materials

The family types selected for the first model created in Revit consisted of the generic families included in the template "Construction-DefaultMetric" of Revit 2019. These correspond to the Basic Wall called "Generic – 200 mm" and the Floor called "Generic 300mm" whose materials were set as "By Category". These means that the applied material for those elements was based on their category (Autodesk Inc., 2019b). Since on this template, the default values were not modified, the material that corresponds to the categories of Walls and Floors are "Default Wall" and "Default Floor", respectively.

These default materials do not have any information regarding physical or thermal properties, and their Graphics and Appearance settings are a raw grey colour without any pattern or rendering information, as it can be seen in Figure 11.

Figure 11. Basic building model with default materials.

An IFC file from the Revit model was imported into Pyrosim which was able to generate geometry and assign a surface to each element depending on the material name. Consequently, two surfaces were created: Default Wall and Default Floor. Both have a colour "Grey 50" and a "Basic" surface type in Pyrosim which means that the default FDS boundary conditions are set in those surfaces. As a result, these surfaces have a fixed temperature (depending on the ambient temperature set in the software) and emissivity.

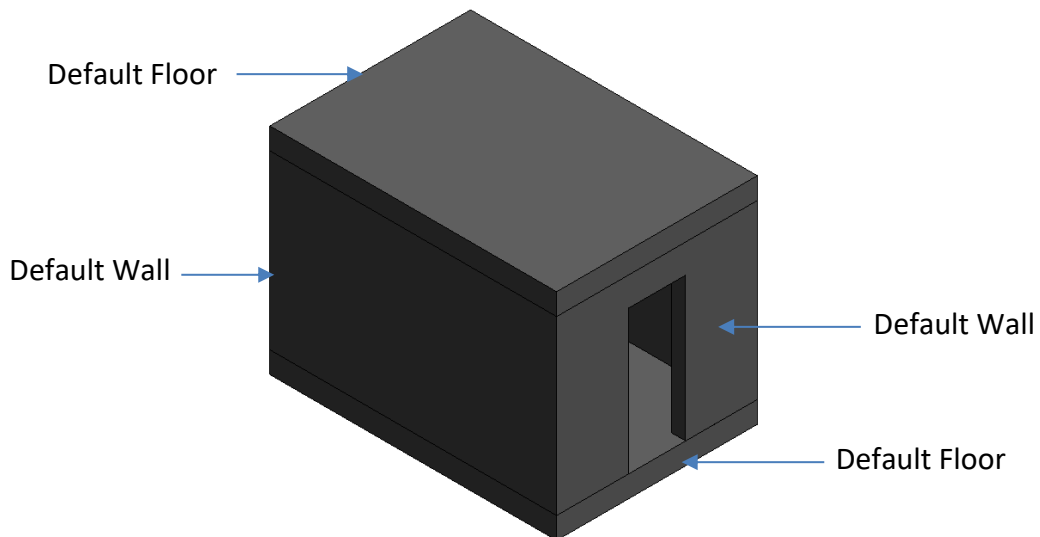**Homogeneous material, Concrete, Cast In Situ:**

The first change in materials to be introduced was assigning "Concrete, Cast In Situ" to floors and walls instead of the "Default Floor" and "Default Wall". This concrete included information regarding physical and thermal properties from the built-in library of Revit. Among others, this material has the next thermal properties:

Thermal conductivity: 1.0460 [W/(m*K)]
Specific Heat: 0.6570 [J/(g*°C)]
Density: 2300 [kg/m³]

Revit calculates some "Analytical Properties" for each family based on their materials. That information is included in the IFC file when it is selected the checkbox of "Export Revit property sets" in the Export IFC tool.

The information in the IFC file was explored by using IFC viewers such as DDS-CAD Viewer (Data Design System, 2017) and BIM Vision (Datacomp Sp. Z o.o., 2018). There, the model appearance did not include any texture, except for the distinctive grey colour of the concrete. Additionally, the "Analytical Properties" of Revit were found in the IFC file besides other

properties for each one of the family types in the model. Some of these values are shown in the next table:

Table 3. Thermal properties for the Basic Building model in the IFC file

Family Type	Wall	Slab
Thickness	0.2 m	0.3 m
Material	Concrete, Cast In Situ	Concrete, Cast In Situ
Heat Transfer Coefficient (U) [W/(m^2*K)]	5.23	3.486667
Thermal mass [J/(m²*K)]	302220	453330
Thermal Resistance (R) [(m^2*K)/W]	0.191205	0.286807

However, it should be noted that the current Revit IFC export tool does not export values for density, which is required for the calculation of Specific Heat from Thermal Mass values. At this stage, Density is a missing value required for the calculation of thermal parameters in FDS. Later, this issue is addressed when defining the scripted enhancement to FDS data from IFC data.

This IFC file was imported into Pyrosim. Even though the software detected the name of the material and created a surface with that name, it did not bring any information related to the material properties. Every element had assigned the surface "Concrete, Cast In Situ" since in this case every object had the same material. The geometry in Pyrosim contains all the elements drawn in Revit, including the door opening, but as in the IFC viewers, the textures are lost. This geometry can be seen in Figure 12.

Additionally, it was also possible to identify that BIM Vision offered a representation of the IFC model similar to the one brought into Pyrosim. Instead, DDS-CAD Viewer often showed a gap in the walls at the door opening.
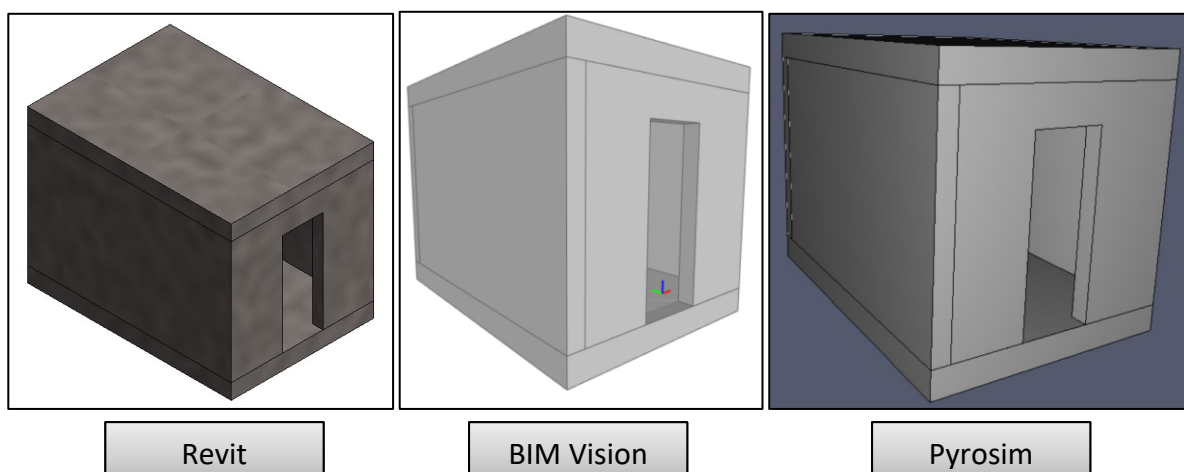

| Revit | BIM Vision | Pyrosim |

Figure 12. Basic Building model with "Concrete, Cast In Situ" material.

Three different materials:

The second change consisted in introducing different materials for the elements in the room. Walls were selected as "Brick, Common", the upper slab as "Metal Deck", and the Floor was kept as "Concrete Cast In Situ". For all of them it was selected thermal properties from the Revit library, as follows:

Table 4. Thermal properties for Basic Building model with three different materials

Family Type	Walls	Top Floor	Bottom Floor
Thickness	0.2 m	0.3 m	0.3 m
Material	Brick, Common	Metal deck	Concrete, Cast In Situ
Thermal Conductivity [W/(m*K)]	0.54	45.0	1.046
Specific Heat [J/(g*°C)]	0.84	0.48	0.6570
Density [kg/m³]	1550	7850	2300

When importing to BIM Vision and Pyrosim, it was possible to identify differences between elements by the colour they had assigned. This colour corresponds to the one selected in the Graphics tap in the Materials browser in Revit. Having a particular colour assigned to each material gives a better understanding of the model when it is imported into Pyrosim since the software creates a surface for each material name, in this case: "Brick, Common", "Metal Deck" and "Concrete Cast In Situ". This geometry can be seen in Figure 13.

As in the previous model explained, the "Analytical properties" are found in the IFC file when explored in BIM vision or read in Notepad ++. Each element has thermal properties which are relevant for a fire simulation but are not imported into Pyrosim. After consulting a developer of Pyrosim, he confirmed that at this time, Pyrosim does not import information regarding material properties from Revit.

This IFC file contains the next properties:

Table 5. Thermal properties in the IFC file for Basic Building model

Family Type	Walls	Top Floor	Bottom Floor
Heat Transfer Coefficient (U) [W/(m²*K)]	2.7	150	3.486667
Thermal mass [J/(m²*K)]	260400	1130400	453330
Thermal Resistance (R) [(m²*K)]/W]	0.37037	0.006667	0.286807
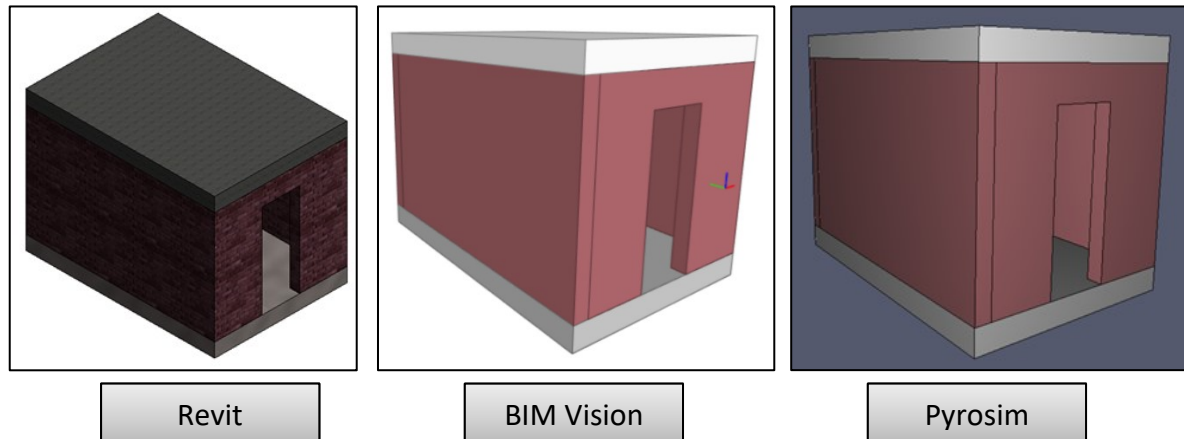
Figure 13. Basic Building model with three different materials.

This test showed that having a particular colour assigned to each material gives a better understanding of the model when it is imported into Pyrosim. The developer of Pyrosim that was consulted stated that the different colours in the objects could be used for selecting items by right-clicking on an object and then selecting all objects with the same colour by clicking "select by colour".

Multilayer materials:

The third change in materials introduced in the model were multilayer walls selected for the ISO room. Revit includes some built-in multilayer materials, from which "CW102-50-100p" was selected. Its appearance and layer thicknesses are shown in Figure 14.

Figure 14. Multilayer material.

Revit automatically calculated the "Analytical Properties" for this material assembly giving the next results:

Heat Transfer Coefficient (U) = 0.8723 [W/(m²*K)]
Thermal mass = 28.78 [kJ/K]
Thermal Resistance (R) = 1.1263 [(m²*K)]/W]

When opening the IFC file in BIM Vision, it was possible to identify that it contains the Thermal properties of the multilayer wall as a wh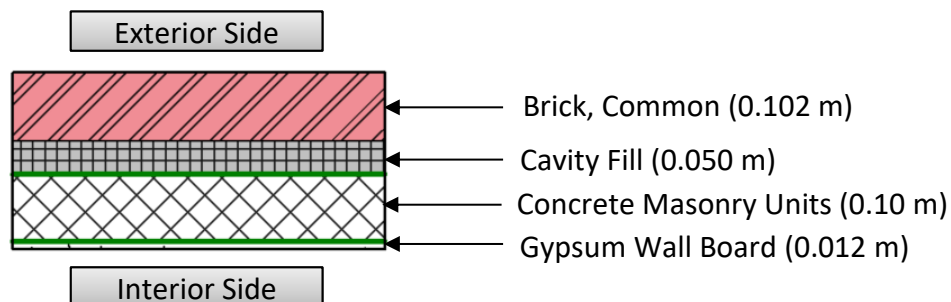ole, in the same way as it was shown in Revit. It also identifies the names of each layer and its thickness, but not separated material properties for them. Additionally, the colour at the surface that is shown in BIM Vision is the one in the core layer, in this case, the one for the Concrete Masonry Units, as presented in Figure 15.

| Revit (section) | BIM Vision | Pyrosim |
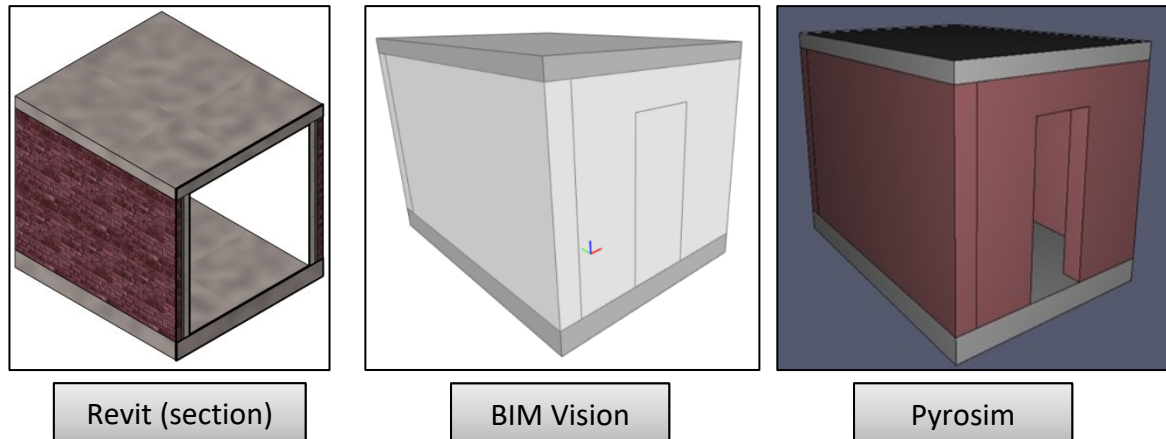
Figure 15. Basic Building model with multilayer material.

The IFC file in Pyrosim shows different colours than in BIM Vision. This program detects the material in the exterior side, creates a surface based on its name and assigns its colour to the entire element. In Pyrosim, it is not possible to distinguish between elements made by multilayer materials and those with one layer, since other layers behind the external one are neglected. This is an important issue that was considered when coding the Scripting tool.

The thickness of the objects is kept as the total thickness of the layers altogether (0.264 m for the walls).

Multi-region materials:

The last test made with the materials of the BIM model was including Multi-region walls; this refers to the option in Revit to modify the vertical structure of a layer, as shown in Figure 16.

The exterior side of the wall was divided into two regions. On top of the walls it was selected "Softwood Lumber", and on the bottom, it was selected "Brick, Common". Both materials share the same layer and the same thickness (0.102 m) and were part of a multilayer material. Other materials in the wall were set as in the Multilayer case.

| Revit | BIM Vision | Pyrosim (One portion of wall selected) |

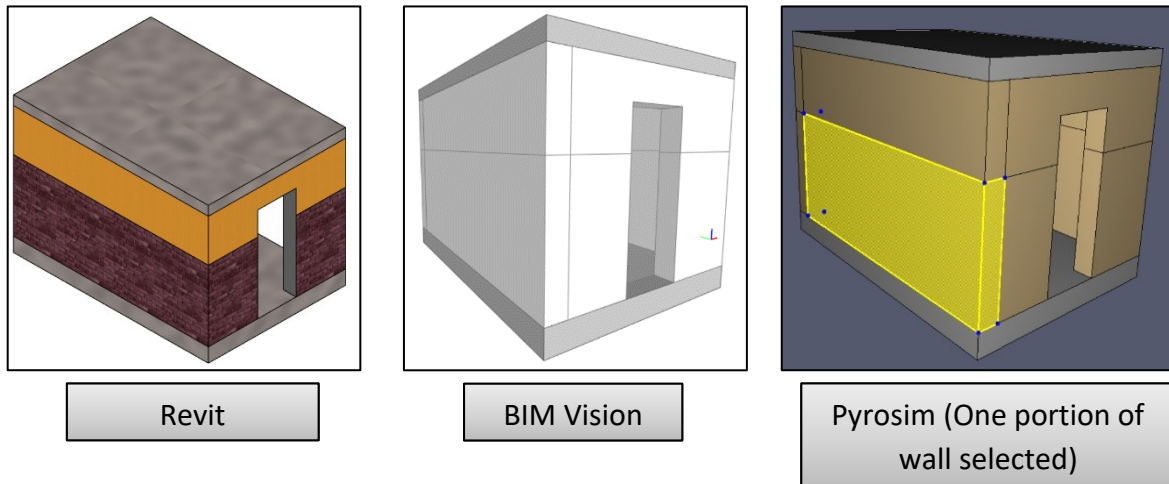*Figure 16. Basic Building model with Multi-region walls.*

Revit recalculated the thermal values for the new configuration, giving the next results:

Heat Transfer Coefficient (U) = 0.5009 [W/(m²*K)]
Thermal mass = 29.67 [kJ/K]
Thermal Resistance (R) = 1.9963 [(m²*K)]/W]

The IFC file in BIM Vision showed similar characteristics to the one for the multilayer wall, regarding the appearance (Colour from the material in the core layer), but the surface in Pyrosim had the colour from the Softwood, Lumber, who appears first in the outer layer in the material layer assembly. When reading the IFC file in Notepad++ it is the first material written in the code, and as a result, Pyrosim creates a unique surface with this name.

As an additional trial, it was included an intermediate level exactly in the interface between the Softwood and the Brick. When exporting the IFC file from Revit in the Export IFC tool, it was selected an additional checkbox "Split Walls, Columns, Ducts by level". With this, it was expected to have a different result for each portion of the wall, either in the appearance or in the thermal properties. Although BIM Vision and Pyrosim detected separated walls on each side of the level (see the third image in Figure 16), it made no difference in their properties.

Type of openings

Revit offers different ways for creating an opening in a wall, either by a "Wall opening" in the "Modify Wall" tab or by adding a door family who just includes the opening itself, such as the family called "M_Door-Opening" from the Revit library. Both result in the same graphical representation, but unlike the Wall Opening, the door family allows the creation of a "Space" in the building. Being able to establish this Space is a step in selecting 2nd Level Space boundaries when exporting the IFC file.

In the Two-room building, four kinds of openings were set: open door family (M_Door-Opening), closed door family (M_Single-Flush), open window family (Window-Square Opening) and a closed window family (Windows_SCO_Horz_Bar_Sgl). This configuration can be seen in Figure 17.
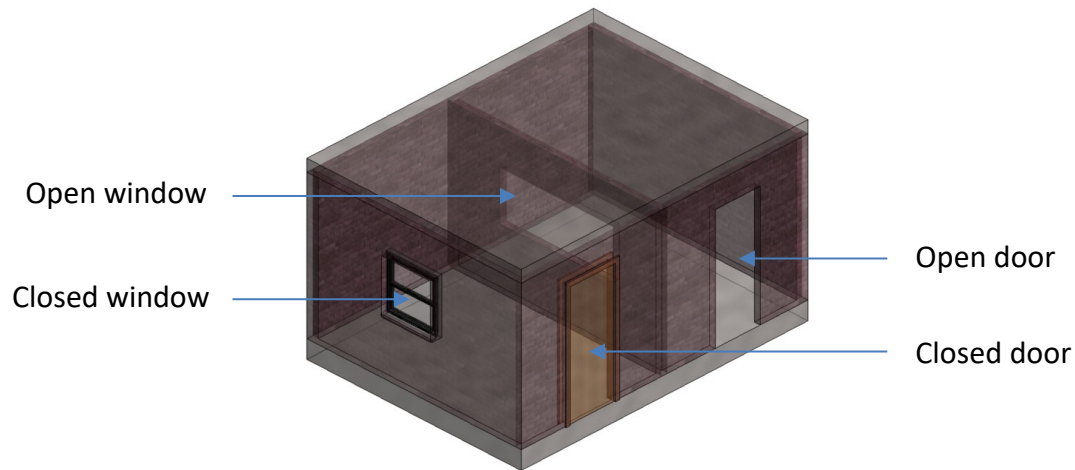

Open window

Closed window

Open door

Closed door

Figure 17. Two-room building. Half-Transparent view.

In the cases with closed doors and windows, the appropriate thermal properties were selected in the materials that form the family. However, this type of families does not calculate the same Analytical Properties as for Walls and Slabs. Doors include Heat Transfer Coefficient (U) and Thermal Resistance (R), but no the Thermal mass (Autodesk Inc., 2019e) which is essential for calculating Specific Heat. In the case of windows, Revit assigns just a Heat Transfer Coefficient (U) (Autodesk Inc., 2019m). These values, are set in Revit either by Conceptual Types or Schematic Types (See section: Material properties in Revit and IFC) since the complexity of the elements and materials that can form these families makes it difficult to calculate properties from the Detailed Elements option.

Thus, when this model is exported into IFC, just the mentioned properties are written in the file. As a result, it is not possible to include these properties in the translation tool and therefore, no further information is included in the FDS file regarding materials properties of doors and windows.

The door and window openings are useful when it is required an open inlet or outlet of air and gases in the fire simulation. Even though sometimes these openings might create unexpected gaps in the wall (as it is explained in section: IFC format, version and add-on's), the right selection of the IFC version overcomes this problem.

IFC format, version and add-on's

Autodesk Revit includes a Built-in tool for exporting BIM files in the IFC format which is found in the "Export" option inside the "File" menu. The export tool in Autodesk Revit 2019 is the

called "Export IFC (v.19.1.0)" but a newer beta version, IFC v19.2.0 Beta 4 (Autodesk Inc., 2019i), was used during this research.

The Export IFC tool allows the selection of the IFC version, File type, Space boundaries, Property sets, among other options according to the user needs. It includes a series of predefined configurations according to the available IFC versions by BuildingSMART (see section: IFC Model View Definition) and other organisations which require specific information for sharing BIM models in the IFC file format described in the Help platform of Revit 2019 (Autodesk Inc., 2019h) as follows:

- **IFC 2x3 GSA Concept Design BIM 2010:** A variant of the standard IFC 2x3 used for submitting files to the US Government Services Administration. Additional property sets are included.
- **IFC 2x2 Singapore BCA e-Plan Check:** A certified variant of IFC 2x2 used for submitting files to the Singapore BCA e-Plan Check Server.
- **IFC2x3 Basic FM Handover View:** A variant of IFC 2x3 that follows the general requirements to enable the handover of facility management information, used primarily in Bavaria.
- **IFC2x3 COBie 2.4 Design Deliverable View:** IFC COBie (Construction Operations Building Information Exchange) format required by the UK government's BIM mandate for collaboration on public-sector work.

Additionally, the beta release of the Export IFC tool (IFC v19.2.0 Beta 4), includes an extra IFC version called "IFC4 for General Use".

In this phase, the ISO-room model was exported into the IFC format by selecting different settings in the Export tool in Revit in order to verify how it changed the content of the BIM model and how it was read in Pyrosim. The following versions were tested, giving similar results:

- IFC 2x3 Coordination View 2.0
- IFC 2x3 Basic FM Handover View
- IFC4 Design Transfer View
- IFC4 General Use

The above mentioned IFC versions gave a good transfer of geometric data from the BIM model to Pyrosim and were readable by BIM Vision. They gave results like the ones described in the section "Materials", more specifically, in the way how the surfaces created in Pyrosim were named after the outer material layer. Even though there was no noticeable difference between them, the IFC4 Design Transfer View was mainly used because it is intended for transferring information from a BIM model to any other design or simulation software.

Unlike other IFC versions, IFC4 Reference View gave a different input into Pyrosim since the names of the surfaces created in Pyrosim correspond to the type of elements in the BIM model. For example, for a model of the ISO-room, Pyrosim assigned two random colours to the surfaces, one for the slabs (Grey) and another for the walls (Beige), and gave them the names of *IfcSlab* and *IfcWall* instead of the material name in the objects, in this case "Metal Deck", "Concrete, Cast In Situ" and "Brick, Common".

A drawback was found when selecting IFC4 Reference View, since the door opening created gaps in the wall at the frame of the door, as it can be seen in Figure 18.
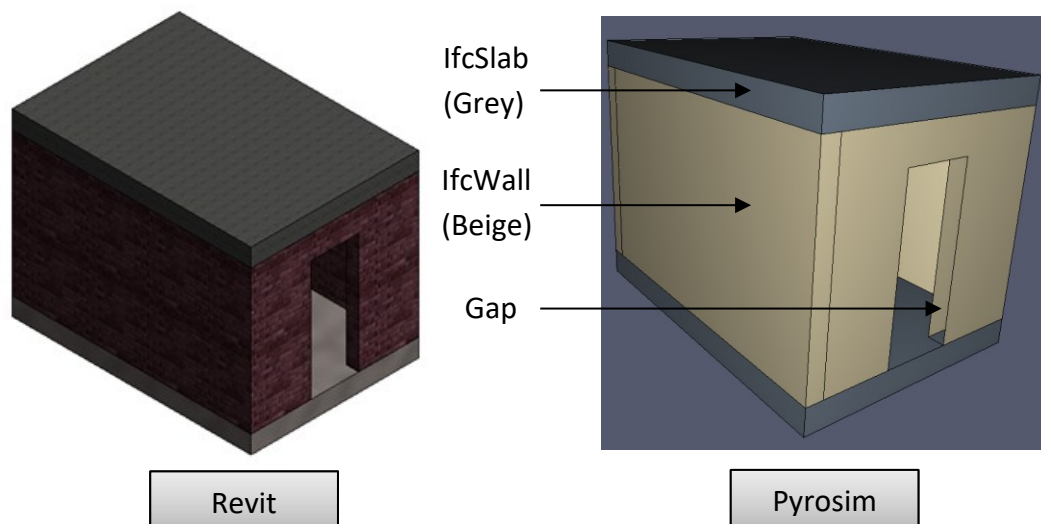

Figure 18. Basic Building model exported as IFC4 Reference View

This result goes in accordance with the purpose of the Reference View IFC version since it is mainly intended for visual checking. Therefore, it is not an appropriate version to be considered when a Fire simulation is required. Additionally, since the Scripting Tool of this research relies on the surfaces created in Pyrosim from the material names in the BIM model, it is unfeasible the use of an IFC Reference View format in the tool.

Add-on's

Some additional options are essential for getting thermal properties in the IFC file: "Export Revit property sets" and "Export IFC common property sets". When the first-mentioned checkbox is selected in the Export IFC tool, it includes the thermal property set "Analytical properties" from the Revit elements into the IFC file. If this setting is not selected before exporting the IFC file in Revit, no information regarding Thermal mass and Thermal Resistance (R) is written, except for Heat Transfer Coefficient which can be found in the IFC file labelled as "Thermal transmittance".

Another add-on is 2nd Level Space boundaries, which was explained in chapter 2.2. Autodesk Revit developers suggested this setting in order to get a better geometry export suited for the

activities of this project. It is needed that each room in the building has a "Space" in Revit, and then it should be selected the Space Boundaries to "2nd Level: in the options for IFC Export.

Finally, a last feature of the IFC Export tool was tested, called "Export only elements visible in view"; this is a useful option which facilitates the selection of the desired content to be exported into the IFC file. For example, if a Section box is created in the three-dimensional view in Revit, it will be exported just the geometry inside the box. Also, if specific elements are hidden in the view, they will not be included in the IFC file. This can be used as a way of filtering information from objects which are not relevant for a fire simulation, without affecting the original BIM model, its quantities, settings or planes.

IFCXML

Even though that Pyrosim shows IFC and IFCXML as formats that can be imported in the software, the IFCXML format was not supported when a test was done in this IFC type. Pyrosim gives the next error message: *"Cause: IOException: File contains no geometric data".*

However, when the IFCXML file was reimported into a new Revit project, it showed that the geometric data was readable from the file. In the other hand, neither BIM Vision nor DDS-CAD were able to open the IFCXML file.

Revit also offers the option to export Zipped IFC and Zipped IFCXML files, but these were not tested since they do not appear as suitable formats in Pyrosim.

5 Scripted enhancement to FDS data (from IFC)

Pyrosim showed to be a handy software for creating three-dimensional geometries from BIM models using IFC files. However, semantic information from the material properties contained in the IFC file is not recognised by Pyrosim yet. In this research, it is proposed a scripting tool for enhancing FDS files exported from Pyrosim by including values of Heat Transfer Coefficient, Thermal Mass and Density of the material layers that form elements in a BIM model.

The scripted enhancement to FDS data proposed in this study is made by a scripting tool, which reads the information from an IFC file in search of values of Heat Transfer Coefficient and Thermal mass. These values are used by the tool for the calculation of Specific Heat and Thermal conductivity, which are re-written in the FDS format and inserted in the appropriate lines in an FDS file obtained from Pyrosim.

Python was used for writing this scripting tool. It a programming language released in 1991 by Guido Van Rossum. This software is recognized by its open source license and easy to learn structure. It is currently administered by the Python Software Foundation (Python Software Foundation, 2019). Additionally, PyCharm was used as an integrated development environment (IDE) for Python. It offers assistance while writing lines of code by flying errors, suggesting quick fixes and facilitating the navigation through projects (JetBrains s.r.o., 2019).

Input

In order to create an enhanced FDS file, it is required to have two input files: an IFC file exported according to the appropriate parametric definitions as discussed in chapter 4; and an FDS file exported from Pyrosim after setting up all the scenario conditions such as fire size, fire reaction, mesh size, open boundaries, simulation time and others as it is further explained in chapter 6.

It is required to create a duplicated of names in Revit before using the scripting tool. This is to avoid the situation in Pyrosim where materials with different thicknesses receive the same surface name. A similar situation occurs with material assemblies with the same outer layer, but different core and internal layers since Pyrosim assigns the name of the outer material to all of them.

Pre-define density values in the tool

Since density values are not included in the property sets of IFC files from Revit, it was necessary to create a list in the Scripting Tool of pre-defined values of density for several

materials. The library of physical assets in Revit was used as a reference for the Material names and density values that might be used in a BIM model.

The tool can search for the material names contained in the IFC file. If this name coincides total or partially with any of those in the pre-defined list in the tool, a function will return the corresponding value of density. If a match is not found, the function automatically returns a default value of 200 kg/m³. Nevertheless, the user is free to edit the code and append material names and density values according to his needs.

Process section

The main tasks of the tool are focused on finding material names and values for Heat Transfer Coefficient and Thermal Mass by searching for entities and relationships through the lines in the IFC file. It was explained in chapter 4.2 that these values are defined just for specific element types in Revit: Roofs, Ceilings, Floors, Walls, Foundation Slabs, Structural Floors and Structural Walls.

The standard mapping of IFC files in Revit establishes a connection between a Revit Category and an IFC Class Name given by the settings selected in the "IFC options" inside the "File" menu in Revit. This correspondence is shown in Table 6.

Table 6. Correspondence between Revit Category and an IFC Class Name

Revit Category	IFC Class Name
Wall	*IfcWall*
Structural Wall	*IfcWall*
Floor	*IfcSlab*
Structural Floor	*IfcSlab*
Foundation Slabs	*IfcSlab*
Ceiling	*IfcCovering*
Roof	*IfcRoof*

Thus, just four IFC Classes are searched by the tool: *IfcWall*, *IfcSlab*, *IfcCovering* and *IfcRoof*. For each one of them, it was analysed the inheritance hierarchy structure in order to find values of Heat Transfer Coefficient, Thermal Mass, material layer thickness and material layer name, for every entity type in the model. Figure 19 shows this structure for *IfcWallType* and *IfcSlabType.*
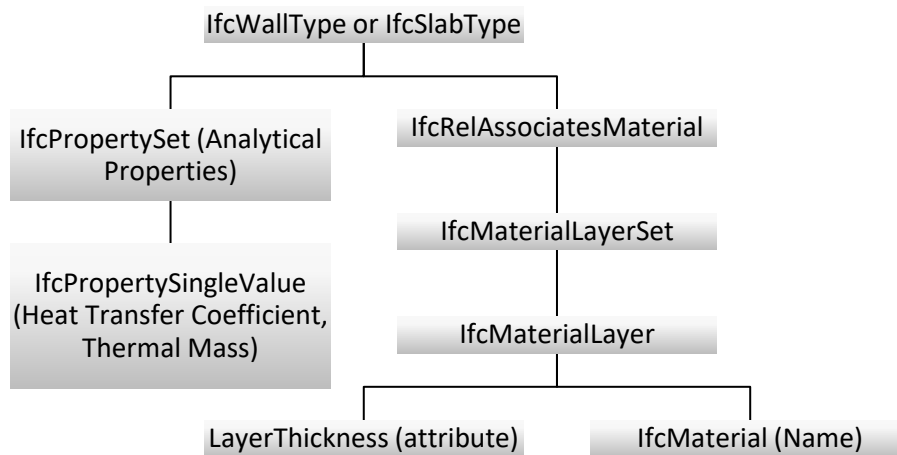
Figure 19. IfcWallType and IfcSlabType structure followed

For ceilings, the structure includes additional relationships, that should be followed to find the required information, as it is presented in Figure 20.
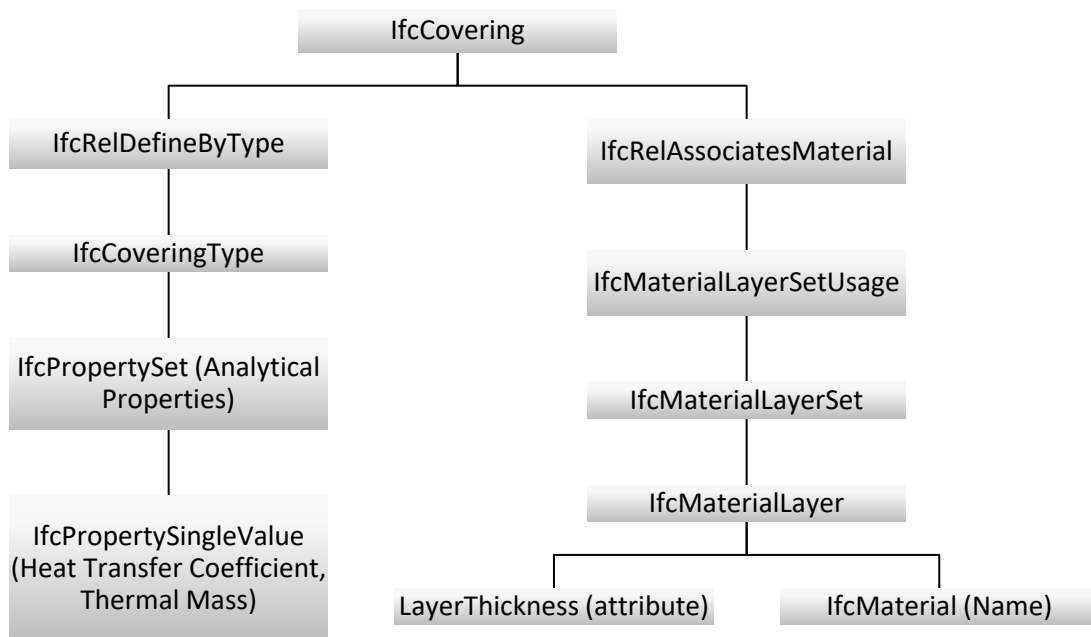

Figure 20. IfcCovering structure followed

In the case of roofs, IFC introduces a method for representing general spatial zones taking into account functional considerations. This relationship is *IfcRelAgregates* and links IfcRoof with IfcSlab. The IFC structure followed in this case is shown in Figure 21.
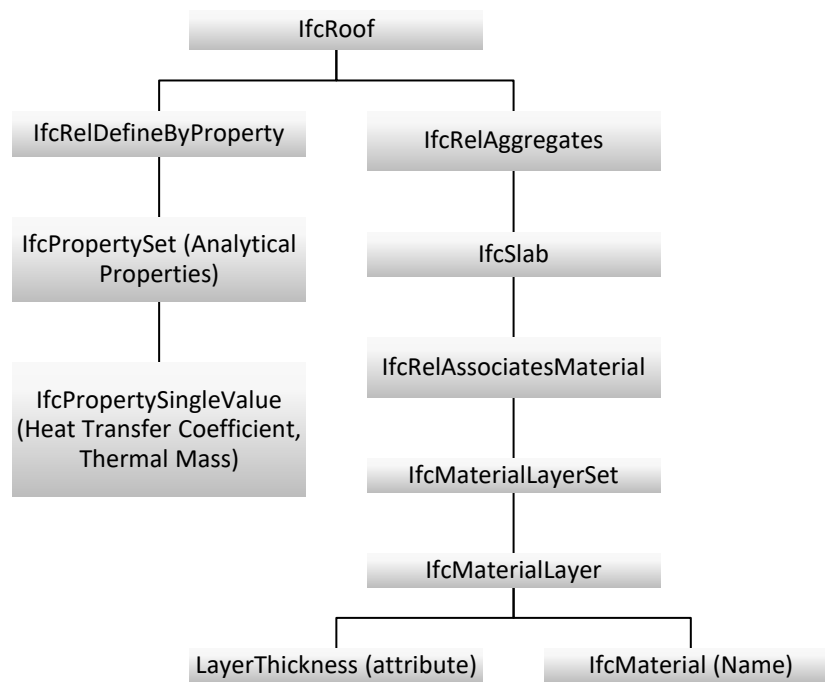
Figure 21. IfcRoof structure followed

The tool is also able to handle cases where entity types are supposed to have thermal properties, but this information was not included in the Thermal asset in the Revit file. When the tool finds that an entity does not contain IfcPropertySingleValue's for Heat Transfer Coefficient or Thermal Mass, it neglects the information from this element and the materials attached to it. Therefore, just those elements that contain all the required information are further processed and included in the enhanced IFC file.

It was identified during the evaluation of parametric definitions that Pyrosim detects the name of the material in the exterior side of a multilayer element, and from this, it creates a surface that matches the same name. Hence, the scripting tool associates the Heat Transfer Coefficient, and Thermal Mass values to the first *IfcMaterialLayer* written in the IFC file, which corresponds to the one in the external face.

Calculations

Considering that an element type can be related just to one value per property, the scripting tool does additional calculations for those elements form by multilayer materials. It sums up the thicknesses of all the *IfcMaterialLayer's* that form an element type, in order to get one total thickness value. Additionally, the tool finds a weighted density according to the thicknesses of the material layers that are part of the element for getting a representative value per element type.

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Subsequently, the tool calculates Thermal Conductivity and Specific Heat for each element type based on the data found in the IFC file and the pre-defined density values in the tool. The tool performs the following calculations from the equations presented in chapter 3.4:

$$Thermal\ Conductivity = \ U\ Value\ \times\ Thickness\ \left[\frac{W}{m\ \times K}\right]$$

$$Specific\ heat = \frac{Thermal\ mass}{Density\ x\ Thickness\ \times 1000^*}\left[\frac{kJ}{kg\ *\ K}\right]$$

Output

In this section, the scripting tool identifies the REAC (Reaction) and SURF (Surface) lines in the FDS file that was read in the input section. Between these lines, it is inserted the information related to the materials that were identified during the process section. An example of the inserted MATL line is presented next:

```
&MATL ID='Concrete, Cast In Situ',
      SPECIFIC_HEAT=0.65,
      CONDUCTIVITY=1.046,
      DENSITY=2300.0/
```

The SURF lines are already written in the FDS file exported from Pyrosim but require a link to the information regarding the material properties, by using MATL_ID. Additionally, it should be written the total thickness of the element(s) in connection with the surface. An example of a SURF line is presented next, where the appended lines are highlighted in blue colour.

```
&SURF ID='Aluminum',
      BACKING='VOID',
      MATL_ID(1,1)='Aluminum',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.0572,
      COLOR='GRAY 97'/
```

One minor change is introduced in the HEAD CHID line to match the names with the new enhanced FDS file. Finally, the tool creates a new directory that contains the enhanced FDS file and gives a notification in case the tool is run when an output directory has been created already.

WinMerge was used as a way for quickly verifying the changes introduced in the FDS file. It is an open source differencing and merging tool (Grimm et al., 2014). This software compares a maximum of three text files and highlights the differences between them. Figure 22 shows a

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[*] This value was included for getting consistent units.

comparison made in WinMerge between an original FDS file (left) and an FDS file with enhanced data (right). At the left side, it is possible to see a Location Pane which schematically represents the two files. The yellow colour means a difference in the text in both files, and the grey colour means that in those spaces it was introduced new content. The Location Pane also shows the portion of text that is displayed at the moment. The figure shows new MATL lines on top and appended attributes inside the SURF line.
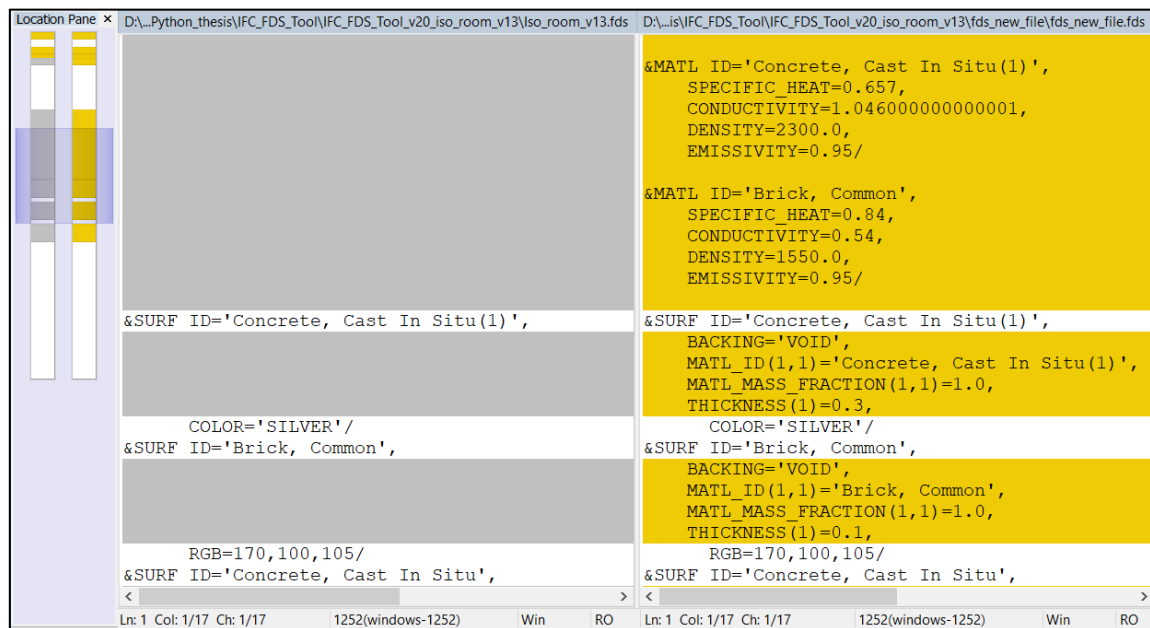

Figure 22. Comparison in WinMerge between an original FDS file and an FDS file with enhanced data

6   Implementation of strategies for simulation of fires in enclosures

In this chapter, it is explained the overall process applied in the three building models for exporting information from BIM files and performing simulations of fire events. It focuses on the settings and tools used for writing an FDS file based on geometrical and thermal data from BIM models. All this is performed using Autodesk Revit, Pyrosim and the Scripting Tool. The completion of the workflow is demonstrated by the results obtained from the simulations performed in FDS.

The general workflow implemented for all the models is shown in Figure 23. First, Autodesk Revit was used for creating the geometry and assigning appropriate semantic data according to the BIM Use specified for the project (forecast, generate and transform). Since a fire simulation is to be performed, thermal properties of the materials should be included beforehand in the BIM model; from this, it is exported an IFC file selecting the appropriate version. The IFC file is imported into Pyrosim, which creates solids with the information read from the .ifc file. It assigns a surface to each solid named after the first material layer. In Pyrosim it should be shaped the fire scenario by selecting an appropriate fire size, fire location, fire reaction, mesh domain, mesh cell-size, contour planes, and any other additional elements or features required for assessing the fire development. Then, from Pyrosim a .fds file is exported.
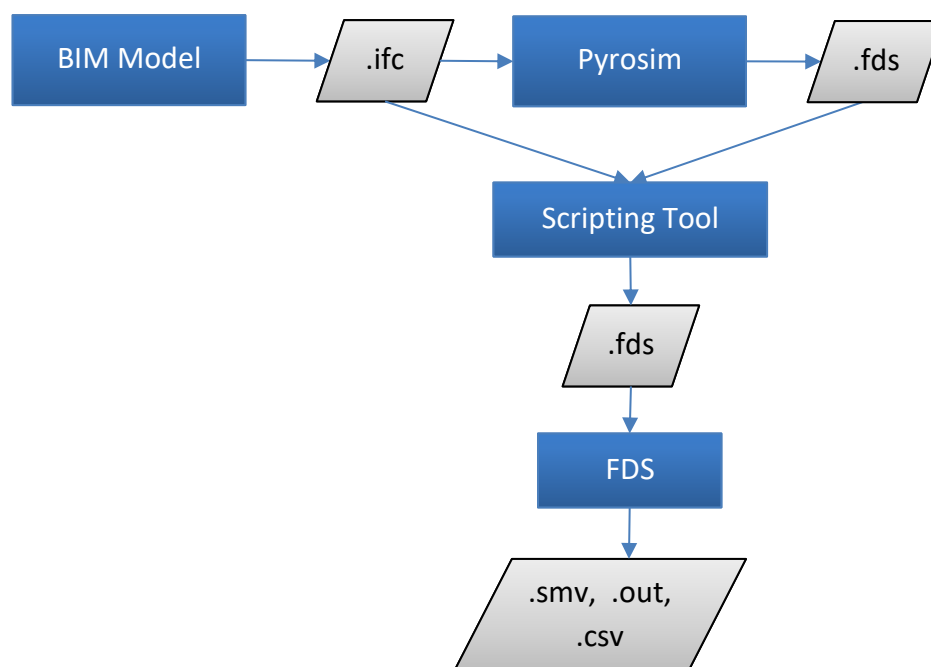

Figure 23. General Workflow implemented

Since the information regarding the thermal properties of the materials is contained already in the BIM model, and as a result in the IFC file, it is not necessary to input this data in Pyrosim. Instead, the Scripting Tool proposed in this study reads the information from the IFC file and

enhances the data contained in the .fds file exported from Pyrosim. This is done by searching through the IFC structure into those element types that contain Heat Transfer Coefficient and Thermal Mass values, which are required by FDS if assessing the heat transfer through the boundaries is wanted.

Fire simulations were performed in the three building models following standard practices for the use of FDS, getting results in the way of temperature, velocity and visibility slices. For the Health Center, it was used the computational resources of Aurora offered by LUNARC, the center for scientific and technical computing at Lund University.

Later in this chapter, it is explained more in detail how the implementation of this strategy was approached for the three building models and the results obtained from the simulation of fire events.

Mesh size considerations

Apart from the geometry and input parameters, the computational conditions, such as mesh size, have profound effects on the simulation results. Although in this study it is not intended to obtain precise results from the FDS simulations, appropriate basic parameters were considered for assessing an acceptable mesh size without performing a mesh sensitivity analysis. A finer mesh is to be applied to the areas of interests, such as the fire location, while the interconnecting meshes were bridged correctly to yield reasonable results while complying to the various grid size requirements imposed by FDS.

According to the FDS user's guide (McGrattan et al., 2019b), for buoyant plumes, the non-dimensional relationship $D*/dx$ is a measure of how well the flow field is resolved for a given mesh size and is a good indication for calculating cell sizes. The characteristic fire diameter D* was calculated using the following equation:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5}$$

Where,
D*: Characteristic fire diameter
Q: Heat Release Rate
ρ∞: Ambient density = 1.2 kg/m3
cp: Heat capacity coefficient 1.0 kJ/kg K
T∞: Ambient temperature = 20°C = 298 K
g: Gravity = 9.81 m/s2

Then, $D*/dx$ was calculated with the appropriated cell sizes, getting the results shown in Table 7. In the cases of the Two-Room model and the Health Center, a finer mesh was selected for the mesh in the fire location and a less fine mesh for the surroundings. All the cases of this

study complied with the suggested interval 4<*D*/dx*<16 for the relationship *D*/dx*, according to the FDS user's guide.

Table 7. Cell sizes selected for the building models and their D*/δx values

Building	Heat Release Rate	δx	D*/δx
ISO-Room	100 kW	0.05 m	7.66
Two-Room	500 kW	0.1 m	7.29
		0.05 m	14.58
Health Center	1000 kW	0.2 m	4.81
		0.1 m	9.62

Additionally, it was taken into account that an important part of the FDS calculation uses a Poisson solver based on Fast Fourier Transforms (FFTs) in the "y" and "z" directions. This means that the second and third dimensions of the mesh should each be of the form $2^l 3^m 5^n$, where l, m and n are integers.

Performance criteria

Performance criteria are thresholds that indicate when unacceptable conditions are reached. During fire safety assessments it is often evaluated the time that it takes to reach those untenable conditions in order to ensure the life safety of occupants of a building in case of fire. The performance criteria evaluated in this study should be understood as an example that these simulations from FDS can be interpreted in a Life Safety context, but not as conclusive fire performance results for the buildings analysed.

Thermal injuries might occur in people immersed in a heated atmosphere. When someone is exposed to hot gasses, the primary hazard tolerance is limited by hyperthermia, where the thresholds are approximately 120°C for dry air or 80°C for humid air. Above this temperatures pain followed by burns become important. Conduction from heated bodies at 60°C cause pain after 1 s and burns after 10 s, while at 80°C pain occurs at 100 ms and burns after 1 s contact (Purser & McAllister, 2016). Taking into account the skin burn threshold, 60°C is considered as performance criteria for this study.

Several studies have been performed to assess the influence of visibility reduction in the egress of occupants of a building on fire. Visibility can have an impact in the movement of people through an egress route, their speed and their wayfinding abilities. Some studies suggest a minimum visibility distance of 3-5 m for people who are familiar with the building and 15-20 m for people unfamiliar with the building. Others suggest minimum visibility distances of 10 m (Hurley & Rosenbaum, 2015), being this last threshold one of the most used performance criteria in the Fire Safety field and the one selected for this study.

6.1 Implementation of strategies in the Basic Building Model

Geometry and setup in Autodesk Revit

The three-dimensional model used for this analysis is based on the dimensions of the ISO-room presented in chapter 4.1. Alternative parametric definitions were set in this model for the evaluations made in chapter 4.2, but the specific characteristics used for the implementation of strategies for the simulation of a fire event are described in Figure 24.
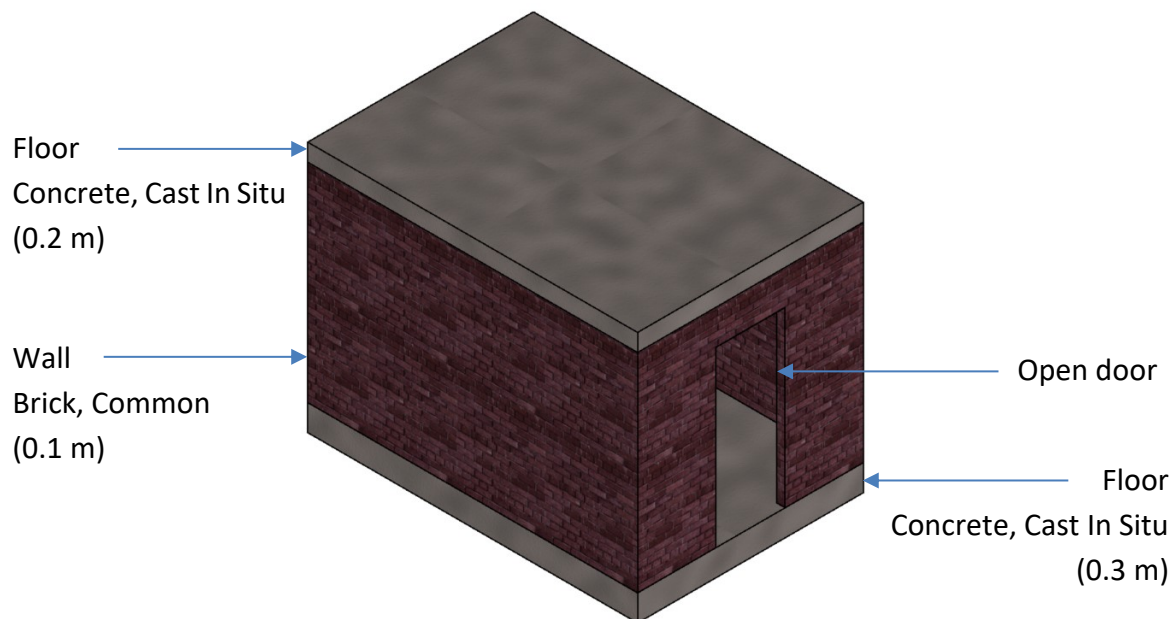

Floor
Concrete, Cast In Situ
(0.2 m)

Wall
Brick, Common
(0.1 m)

Open door

Floor
Concrete, Cast In Situ
(0.3 m)

Figure 24. Basic Building Model

In order to facilitate the import of the model in Pyrosim, it was selected the corner of the building as the origin of the coordinates system by moving the *Survey Point* in Revit, as shown in Figure 25 (left). Thus, the origin of the coordinates system in Pyrosim coincides with the selected point in Revit, making easier the location of a rectangular mesh.

Afterwards, a *Space* was set in the building by using the tool Analyze→Spaces & Zones→Space in Revit. This tool identifies when the configuration of walls and doors is enclosing a space, as presented in Figure 25 (right). This step is required in order to enable the 2nd Level space boundaries.
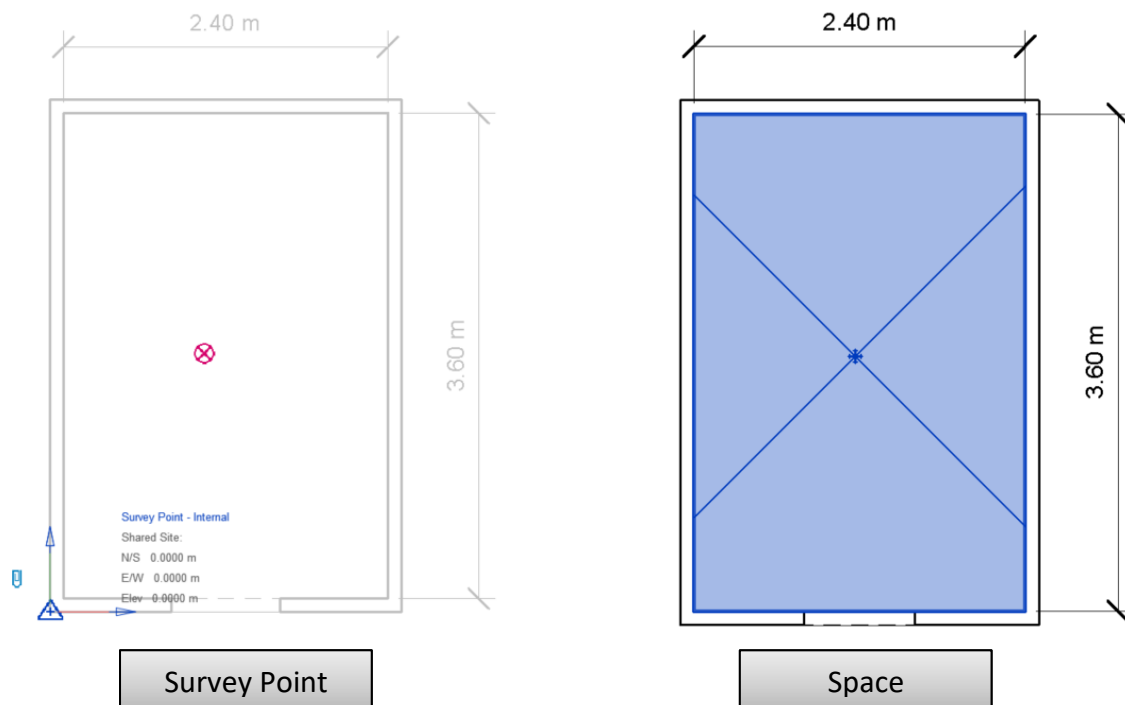
Figure 25. Selected Survey Point (left) and Space identified (right) for the Basic Building

IFC settings

For this step, it should be first explored the IFC options in Revit. These are found in File→Export→Options→IFC options. There, it is possible to select an IFC Class Name for every Revit Category, but this is not recommended for this case since the Scripting tool is working with a standard mapping of the IFC file. Then, the button "Standard" should be pressed, or it should be verified that at least it is kept the correspondence between IFC Class Names for the Revit categories as it was shown in Table 6.

Later, the IFC Export tool in Revit (File→Export→IFC) was used according to the findings in chapter 4.2 (IFC format, version and add-on's). The following settings were chosen for all the cases in this study:

File type: IFC
IFC version: IFC4 Design Transfer View
Space boundaries: 2nd Level
✔ Export Revit property sets
✔ Export IFC common property sets

After exporting the IFC file, it is possible to explore it using Notepad ++ for reading the text content or by BIM Vision for visualising the model and interpreting the properties attached to it. Figure 26 presents an extract from the IFC text which comprises the

IfcPropertySingleValue's for a wall selected in the model. Additionally, the three-dimensional geometry and the "Analytical Properties" are shown as presented in BIM Vision.
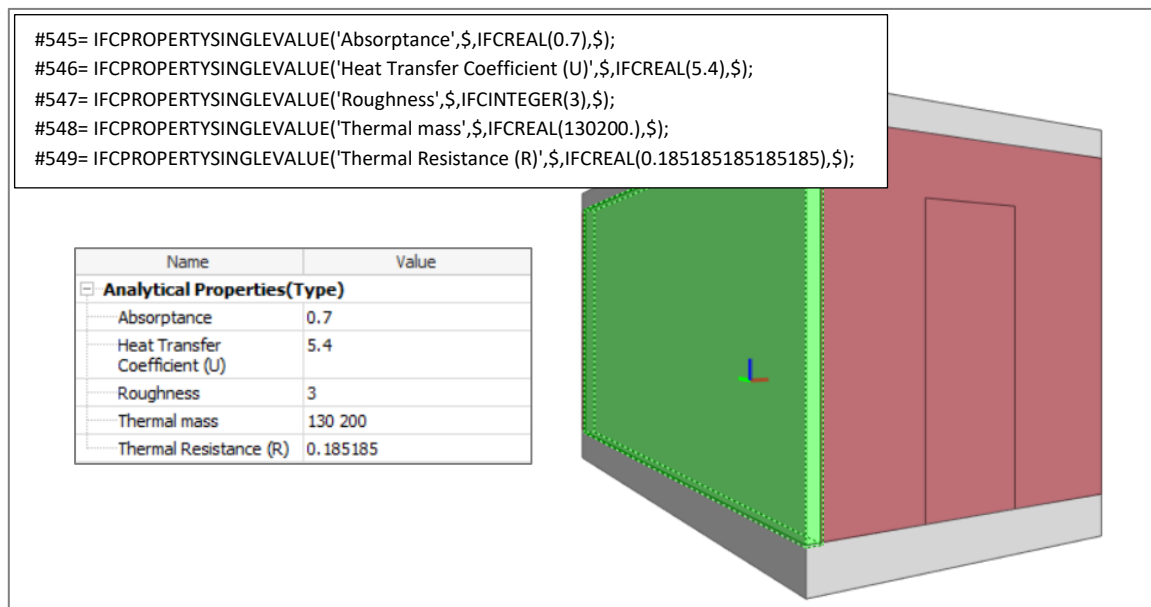


```
#545= IFCPROPERTYSINGLEVALUE('Absorptance',$,IFCREAL(0.7),$);
#546= IFCPROPERTYSINGLEVALUE('Heat Transfer Coefficient (U)',$,IFCREAL(5.4),$);
#547= IFCPROPERTYSINGLEVALUE('Roughness',$,IFCINTEGER(3),$);
#548= IFCPROPERTYSINGLEVALUE('Thermal mass',$,IFCREAL(130200.),$);
#549= IFCPROPERTYSINGLEVALUE('Thermal Resistance (R)',$,IFCREAL(0.185185185185185),$);
```

Name	Value
Analytical Properties(Type)	
Absorptance	0.7
Heat Transfer Coefficient (U)	5.4
Roughness	3
Thermal mass	130 200
Thermal Resistance (R)	0.185185

Figure 26. Analytical Properties of a wall in the Basic Building Model

Pyrosim Settings

Here the IFC file is imported by the tool File→Import FDS/CAD file. This software automatically detects the length units of the IFC file (meters in this case). No other setting was changed for this step, although this import tool allows changes regarding lighting, object grouping or location in the Z axis. Since the origin of the coordinates system was selected previously in Revit, Pyrosim positioned the (0, 0, 0) coordinates at the corner of the building.

Most of the configurations related to the fire scenario were set in Pyrosim. The reaction consisted of Poly(methyl methacrylate) PMMA whose parameters were set from the library in Pyrosim, which are based on the SFPE Handbook, 3rd Edition. The following are its main characteristics:

ID: PMMA   **Oxygen atoms:** 0.4   **Soot Yield:** 0.022

Carbon atoms: 1.0   **Nitrogen atoms:** 0.0

Hydrogen atoms: 1.6   **CO Yield**: 0.01

A surface of the type "Burner" was created for defining the fire size with a Heat Release Rate Per Unit Area (HRRPUA) equal to 1000 kW/m². This surface was assigned to a Vent component with an area of 0.1 m² (0.5 m x 0.2 m) which gave a Heat Release Rate equal to 100 kW. This HRR is constant over the entire simulation, and no RAMP was introduced on it. The vent was located over an obstruction with the same area and 10 cm high located in the back corner of the room, as shown in Figure 27 (left).
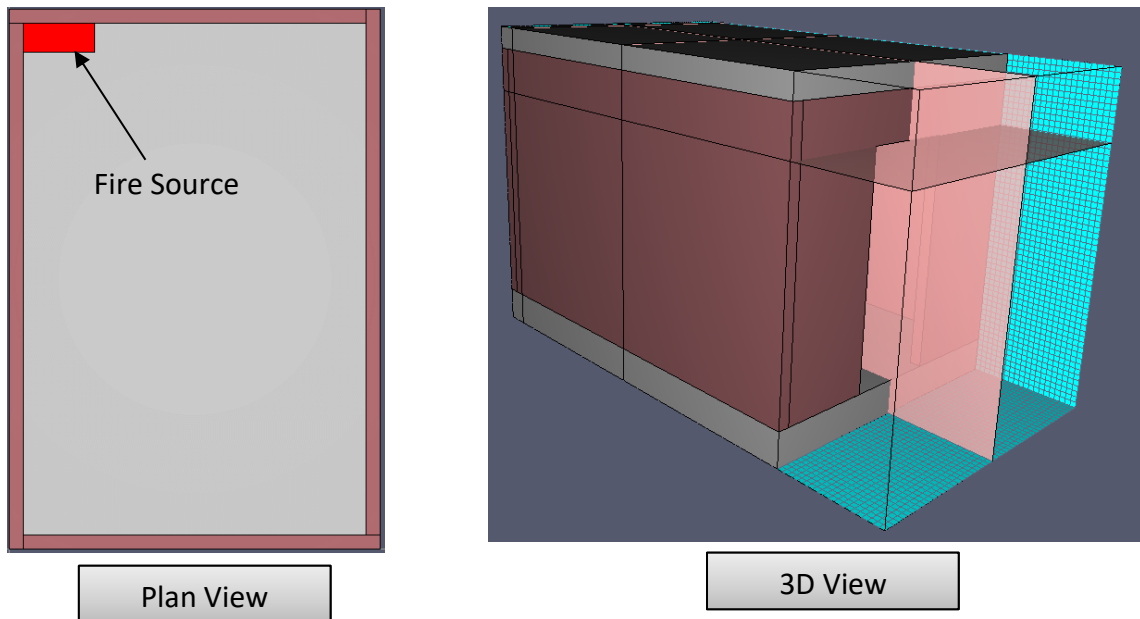
Figure 27. Plan and 3D view of the Basic Building model in Pyrosim

A mesh was drawn to fit the geometry of the room and was extended outside of it to allow better visibility of the smoke behaviour when leaving the room. This mesh has 52 cell divisions in the X direction, 96 divisions in the Y direction and 58 divisions in the Z direction. All of them with the same cell size equal to 0.05 m, giving a total of 289,536 cells in the mesh. It can be noted that the Y and Z directions contain a number of cells that can be factored down to 2's, 3's and 5's, required for the Poisson solver as explained before. Subsequently, all the boundaries were open.

In order to understand the behaviour of the fire by the measurement of different variables, 2D slices were configured to show temperature, velocity and visibility contours. Additionally, "Wall Temperature" was included in the output as a boundary quantity.

The simulation time was set as 300 seconds, which was found to be enough for achieving critical conditions. Finally, a .fds file was exported.

Scripting tool

When the .ifc and .fds files were ready, the Scripting tool was used. It read the contents in both files and looks throughout their structures to match the names of the materials in the IFC which have thermal properties on it.

The Basic Building model does not have Ceilings, one of the Revit element types that might contain Heat Transfer Coefficient or Thermal Mass values on it. After doing some tests on this model, the tool was configured in such a way that it can handle cases when any specific type of element is not part of the project.

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For running the Scripting tool, it is required to locate the two files (.ifc and .fds) in the same folder as the tool. The name of these files should be changed in the Input section of the tool. Subsequently, a name should be selected for the output directory and FDS file. Running the tool for the Basic Building model takes few seconds and returns a .fds file with the information set in Pyrosim, including the material properties (MATL lines) and their attachment to the surfaces (SURF lines).

Running the FDS simulation

The simulation was run using conventional procedures for running FDS files. In this case, the Command Prompt of Windows was used. A regular laptop was employed in this study with a processor Intel Core i7 – 8550U CPU @ 1.80 GHz 1.99 GHz and an installed memory of 8 GB. The Basic Building FDS file had just one mesh, so it was used one MPI process and four OpenMP threads (see FDS User Guide for more details) for using the most of the four cores available in the laptop. It took around 15.7 hours for completing the simulation.

FDS Simulation Results

Fire simulations performed in FDS showed that material properties from the BIM model were successfully used for the calculation of "Wall temperature" in the boundaries of the Basic Building, as shown in Figure 28. After 30 s the interior side of the walls made by Brick, Common, reach temperatures higher than 203°C at the corner exposed directly to the fire.
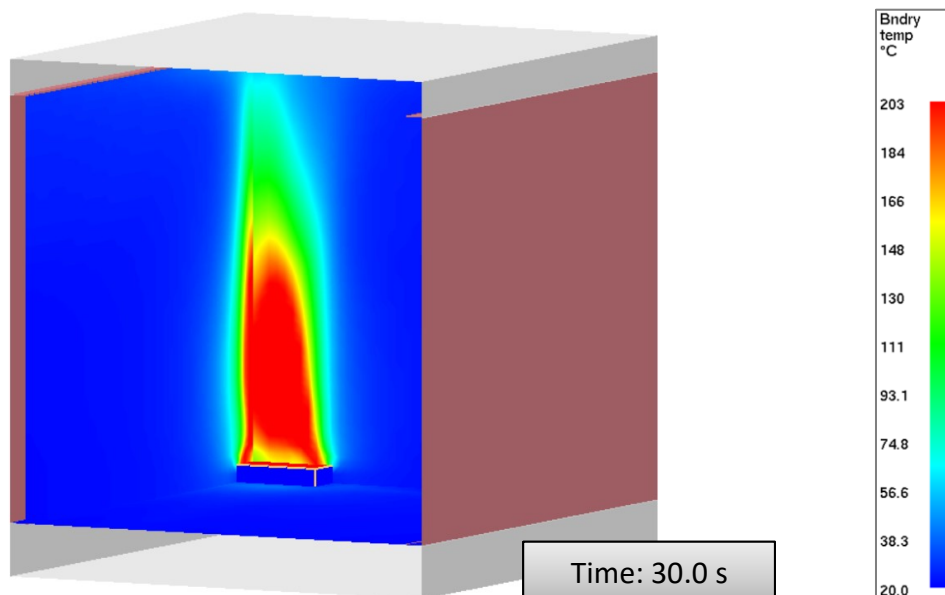

Figure 28. Boundary temperatures in the Basic Building.

The development of gas temperatures in the Basic Building was analysed by temperature contours. Figure 29 shows the initial time at which temperatures higher than 60°C start

reaching 2m height (measured from the floor of the room) and the time when all the area is already under temperatures higher than 60°C at the same 2m height.
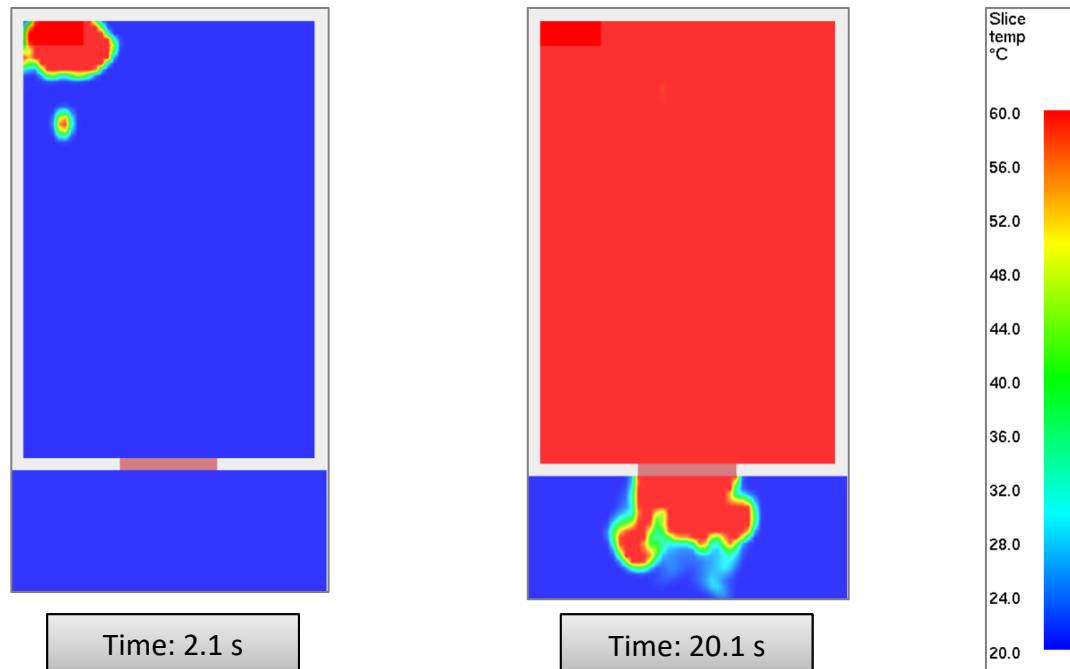

Figure 29. Gas Temperature in the Basic Building at 2m height. Plan View

At 2 m height, the visibility conditions start dropping below 10 m at 2.1 s. After 12.6 seconds after ignition, the visibility conditions are already reduced below 10m in the whole area as shown in Figure 30. This building has a reduced area of 8.64 m². This makes the fire to grow fast and achieve high temperatures and low visibilities in a few seconds. The hot layer stabilises at 1.4 meters after 30 s and continues in similar conditions during the remaining time of the simulation.
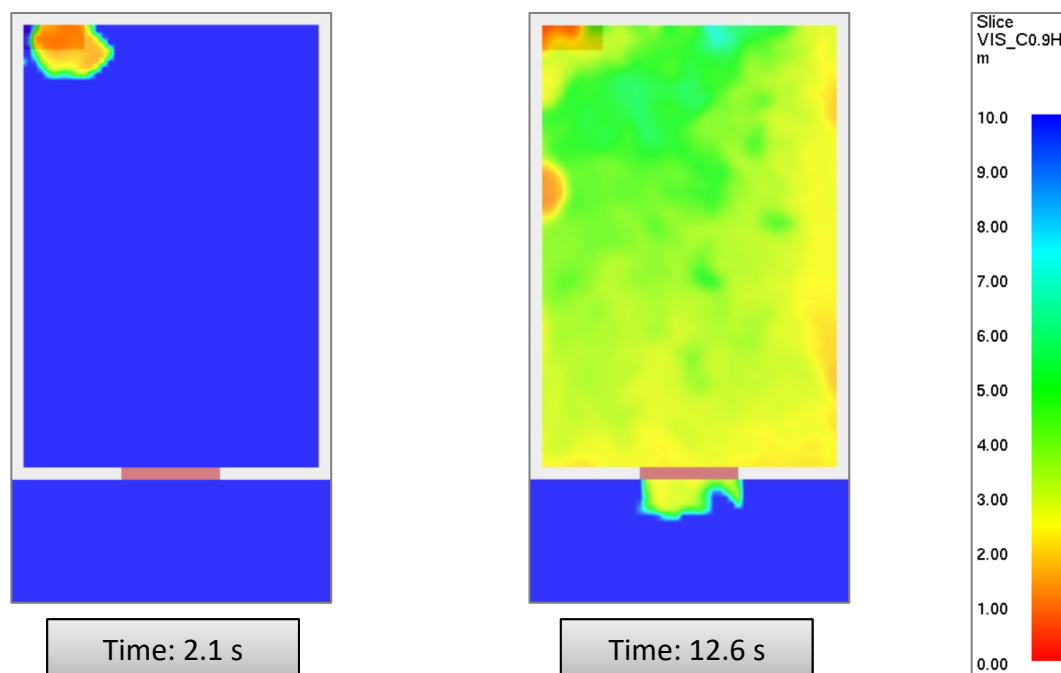

Figure 30. Visibility in the Basic Building at 2m height. Plan View

6.2 Implementation of strategies in the Two-room Model

Geometry and setup in Autodesk Revit

The geometry of the Two-room Model corresponds to the one described in chapter 4.1 (Two-room Model). Doors and windows are those evaluated in chapter 4.2. The materials assigned to floors and walls are presented in Figure 31. Materials of doors and windows are not specified since they are treated as Schematic Types by Revit. This means that their thermal properties are set from predefined analytic constructions and values of Thermal Mass are not included in the IFC file.
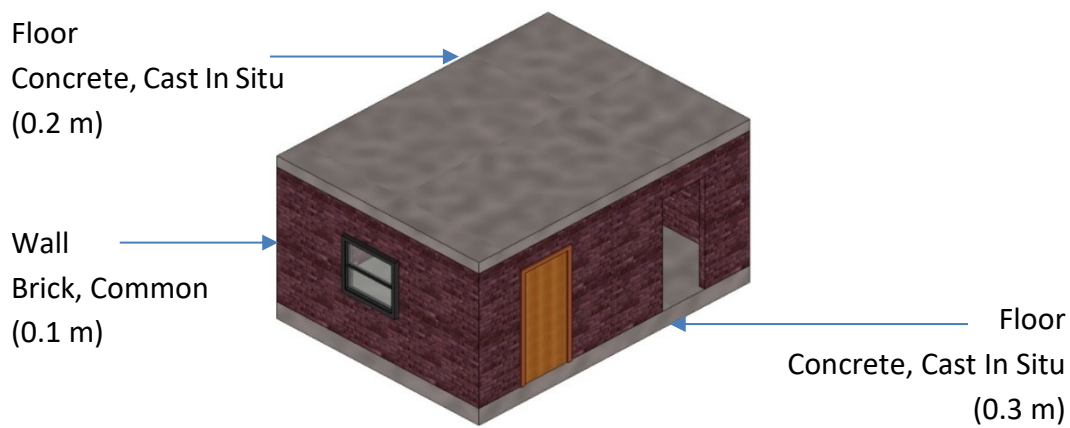

Floor
Concrete, Cast In Situ
(0.2 m)

Wall
Brick, Common
(0.1 m)

Floor
Concrete, Cast In Situ
(0.3 m)

Figure 31. Two-room model

As in the Basic Building, a Survey Point and a Space were set in the model to facilitate the importing activities into Pyrosim. The origin of coordinates (0, 0, 0) was positioned in the front corner of the building, and two spaces were set for it. This is illustrated in Figure 32.
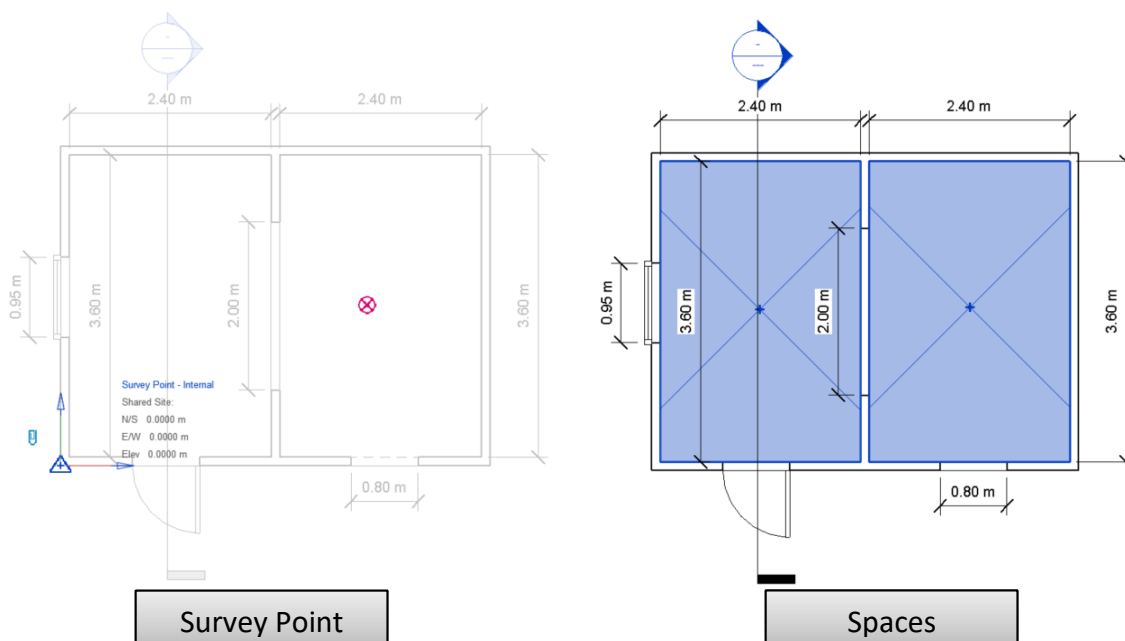

Survey Point

Spaces

Figure 32. Selected Survey Point (left) and Space identified (right) for the Two-room building

IFC settings

The same options selected for the Basic Building were applied in the Two-room model for exporting the IFC file. Just one additional outcome should be noted for this case which included element types such as windows and doors. The IFC data of a door (as an example) contains values in the "Analytical Properties" from the Schematic Types from Revit, but do not have Thermal Mass defined, as it is detailed in Figure 33.
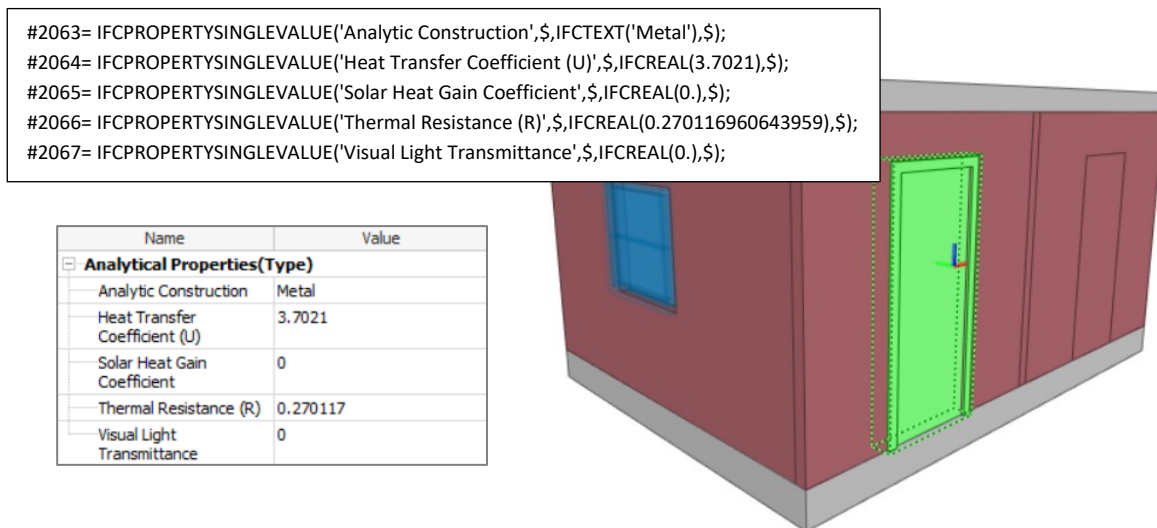

Figure 33. Analytical Properties of a door in the Two-room Model

Pyrosim Settings

The specific fire scenario used for the Two-room model consisted of a fire bigger in size than the one used in the Basic Building, but the same fuel. The Heat Release Rate Per Unit Area (HRRPUA) was kept in 1000 kW/m², but the area of the fire's vent was change to 0.5 m² (1.0 m x 0.5 m) which gave a Heat Release Rate equal to 500 kW. The vent was located in the back corner of the room with the closed door, as shown in Figure 34 (left). This setup was intended for observing the influence of a fire in an adjacent room.
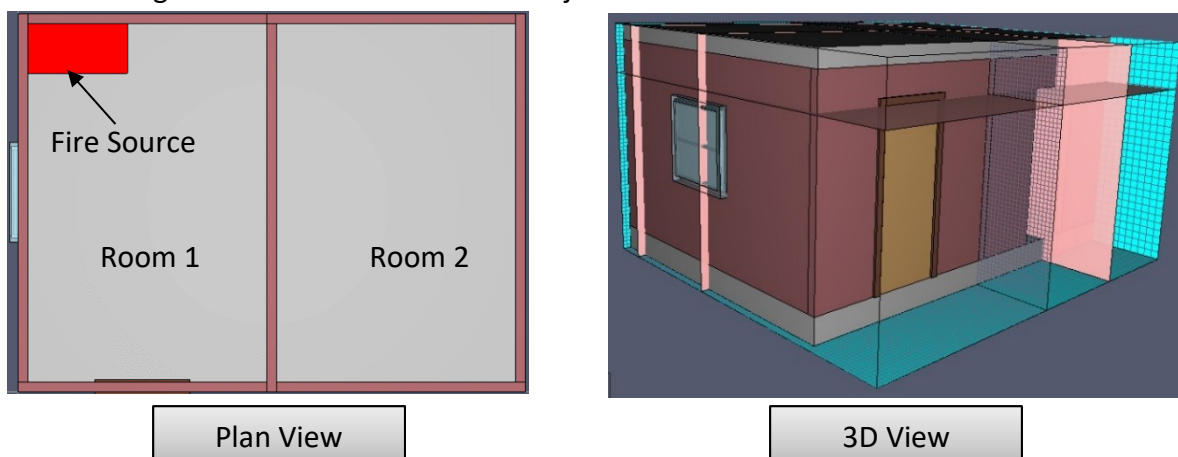

Figure 34. Plan and 3D view of the Basic Building model in Pyrosim

Two meshes were drawn in this model to take advantage of the computational resources by having a finer mesh in the room with the fire. Both meshes were extended outside of the building to allow better visibility of the smoke. The first mesh has a total of 289,536 cells distributed among 52 cells in the X direction, 96 cells in the Y direction and 58 cells in the Z direction, all of them with the same cell size equal to 0.05 m. The second mesh has bigger cells of 0.10 m in a total of 37440 cells divided into 26 cells in the X direction, 48 cells in the Y direction and 30 cells in the Z direction.

Other settings and FDS results

Running the Scripting tool and the simulations were performed following the same setting as in the Basic Building. The same laptop run the simulation of the Two-room model with two MPI processes and two OpenMP threads, taking 22.3 hours to finish the simulation successfully.

The fire simulated in the Two-room building developed high gas temperatures in both rooms which increased the temperatures in the boundaries as shown in Figure 35. This figure shows that the corner exposed to the fire reaches temperatures higher than 168°C after 90 s. These walls are made of Brick, Common, whose properties are taken into account by FDS for calculating heat transfer. Additionally, boundaries in the second room are also heated up by the hot gasses coming through the internal open window in the building.
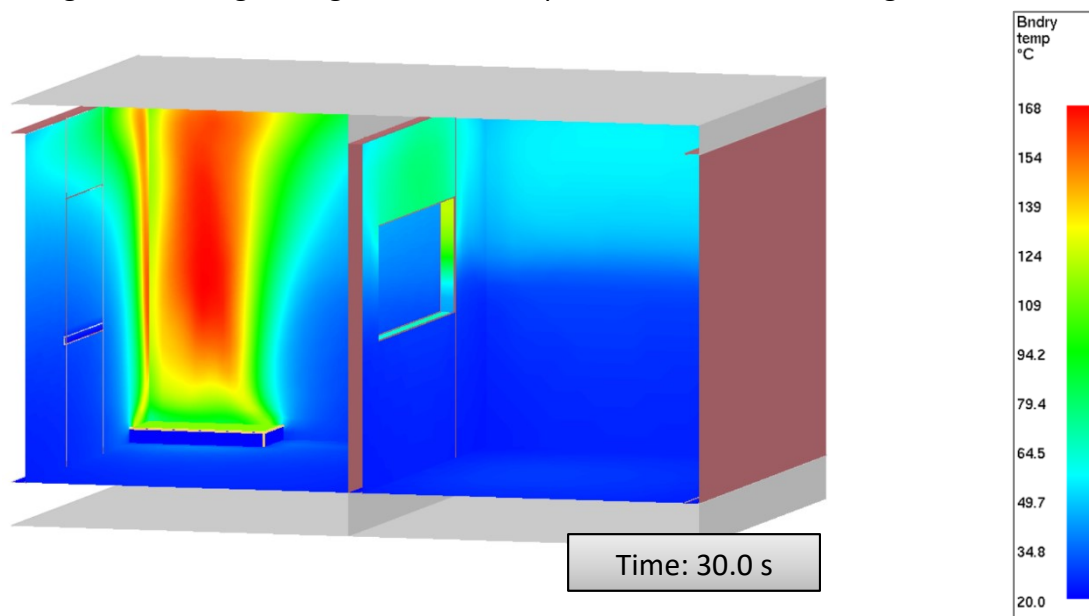

Figure 35. Boundary temperatures in the Two-room Building.

Temperature contours were analysed in order to identify the time it takes to achieve untenable conditions at 2m height in the two rooms. After 12.6 s, a uniform temperature higher than 60°C covers the whole area as shown in Figure 36.
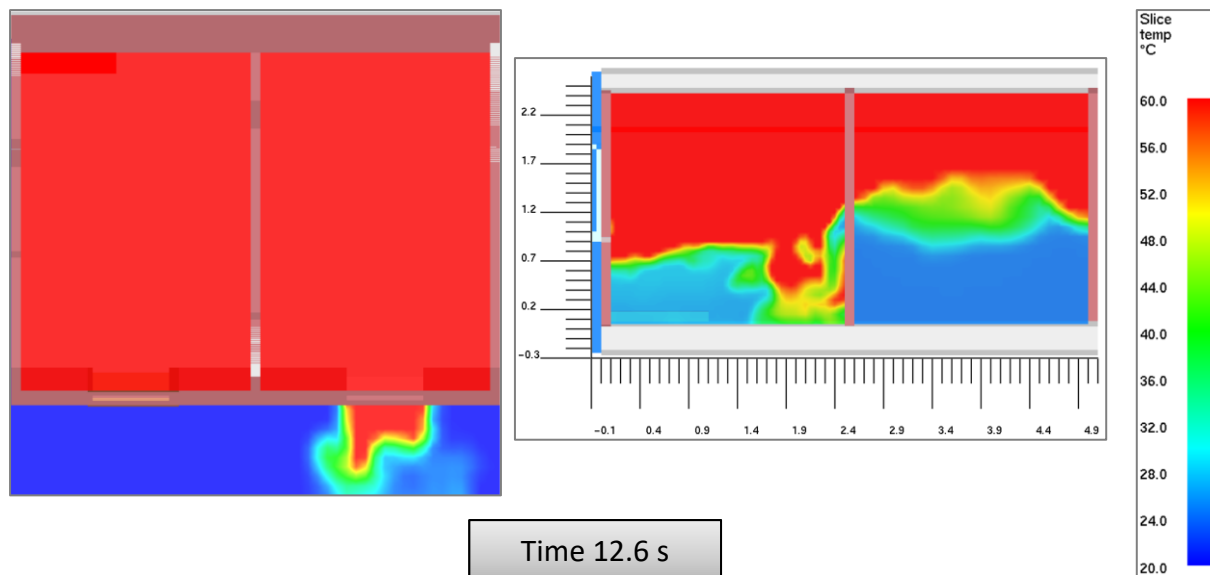
Figure 36. Gas Temperature in the Two-room Building at 2m height. Plan View (left) and Section Y axis (left)

The visibility is reduced in both rooms of the building. After just 6.3 seconds the visibility at 2 m height is lower than 10 m in room 1 and after 11.7 s in room 2, as shown in Figure 37.
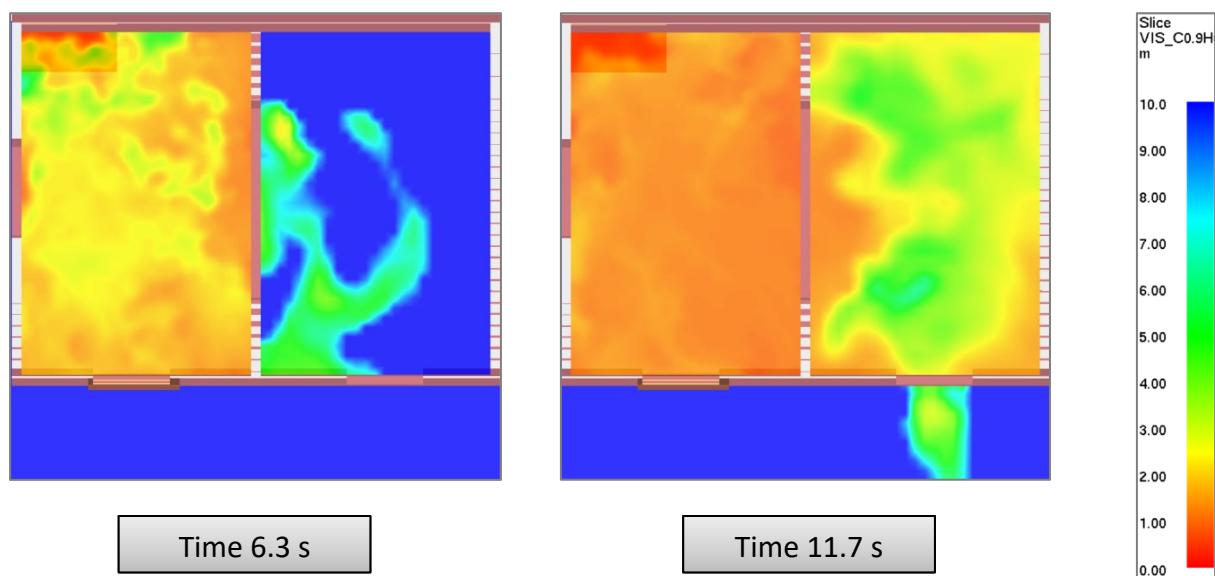

Figure 37. Visibility in the Two-room Building at 2m height. Plan View

It should be considered that when a fire is located in a corner, the fire plume is attached to the wall and develops four times the energy release rate. These conditions besides the reduced area of this building (17,28 m²) allow the fire to grow rapidly and generate untenable conditions in a few seconds.

After 90 s, the conditions in the room stay constant during the remaining time of the simulation. The hot layer stabilises at 1.0 m height from the floor of room 1 (left) and around 1.5 meters in room 2 (right).

6.3   Implementation of strategies in the Health Center

In the AEC field, it is usual that the fire safety engineering analysis and design are done by a third party separated from the architectural and structural designs. Thus, a BIM model might be share to fire safety firms without careful planning on the information that they might require from the model in order to use not only the geometry but also the data contained in it. This Health Center model was found as a good example to understand how to deal with a BIM model that was not intended to be used for fire simulations. With this model is it possible to explain how to overcome difficulties in transferring information from a BIM model to FDS and the kind of information that should be set in the BIM model to get thermal properties from it.

Geometry and setup in Autodesk Revit

A model of a Health Center was used as a case study to evaluate the workflow from getting information from a BIM model until performing a fire simulation in FDS. The geometry of such a model was described in chapter 4.1 (Case study: Health Center Model) but required additional settings to be adapted to other steps in the process.

The model was created in Imperial units, but the calculations inside the Scripting tool were set for the International System of Units (SI). Revit allows choosing the desired units per discipline in Manage→Project Units. All the properties shown in the Common and Energy disciplines were changed. For example, the "Coefficient of Heat Transfer" was changed from "BTU per hour square foot degree Fahrenheit", to "Watts per square meter kelvin". This action automatically re-calculates the thermal properties and any derived value for all the materials in the project.

As in the Basic Building, a specific origin for the coordinates system was selected, although this had not such significant impact later in Pyrosim since the irregular shapes that form the building make it difficult to assure a good insertion point. The selected origin point is shown in red colour in Figure 38.
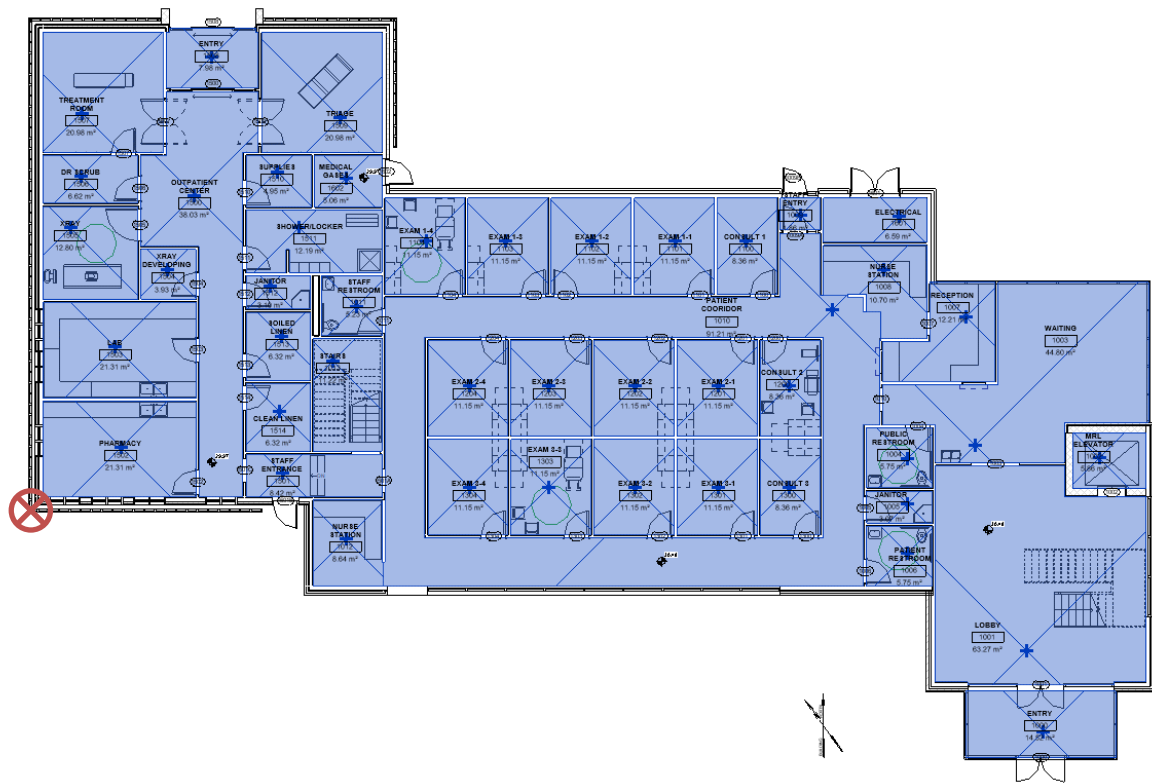
Figure 38. Origin of coordinates and Rooms in the Health Center. Ground floor.

For this project, it was not necessary to manually select the spaces in the building since the model contained rooms already defined, as presented in Figure 38. It should be clear that, in Revit, the data contained in Rooms is different from the one in Spaces. Any of them can be selected for performing an energy analysis in Analyze→Energy Settings→Other Options→Room/Space Data→Export Category. When Rooms is selected, Revit transfers the Room object name and number to the corresponding Analytical Space name. Instead, when Spaces is chosen, Revit uses the following information: Space object name and number, Occupancy, Lighting, Equipment, and Zone (Autodesk Inc., 2019a).

Another issue that was addressed in this project was its rotated orientation towards the north. In order to locate the model in an orthogonal position in agreement with the coordinates system in Pyrosim, it is required to verify beforehand if a project is rotated in Revit. This can be done in Manage→Location→Site. For the Health Center, the angle from the Project North to the True North is 35 degrees.

The original conditions in which the Health Center model was created did not include all the thermal properties in the materials of the elements that are addressed in this study (walls, floors, ceilings and roofs). A second model was created in which the missing information was included to compare the results from FDS simulations. This comparison was made between the Health Center with partial information and a copy with complete thermal properties in the materials of walls, floors, ceilings and roofs.

One key difference between the Health Center and the models previously described are its multilayer materials in walls, ceilings and roofs. An issue with this kind of materials was described in section 4.2, where it was said that Pyrosim identifies the name of the material in the external layer and assigns the material name to the surfaces that it creates. So, for example, the Health Center has the following two wall types: "E_0HR_BRCK ()-(6" Mtl Stud, 5/8" GWB" and "Elevator Wall 2" (shown in Figure 39 and Figure 40). Both materials have Brick, Common (Red) as the one in the exterior side. As a result, Pyrosim assigns the same surface name to all elements that have these two wall types, regardless of the differences in the other materials, thicknesses or thermal properties.
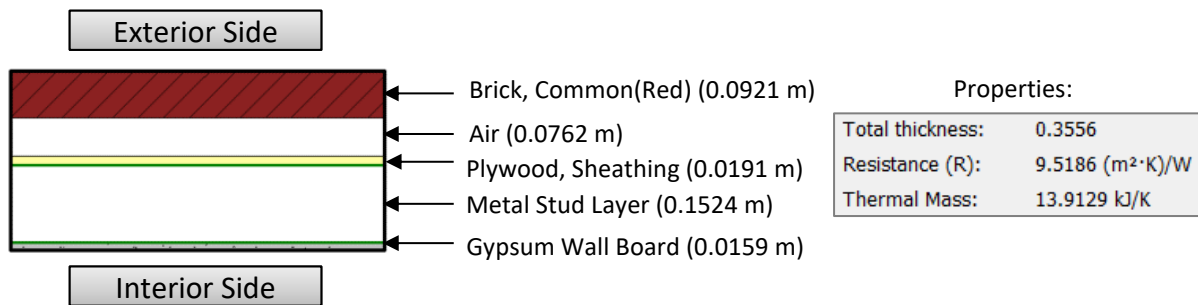

Figure 39. Materials assembly for "E_0HR_BRCK ()-(6" Mtl Stud, 5/8" GWB"
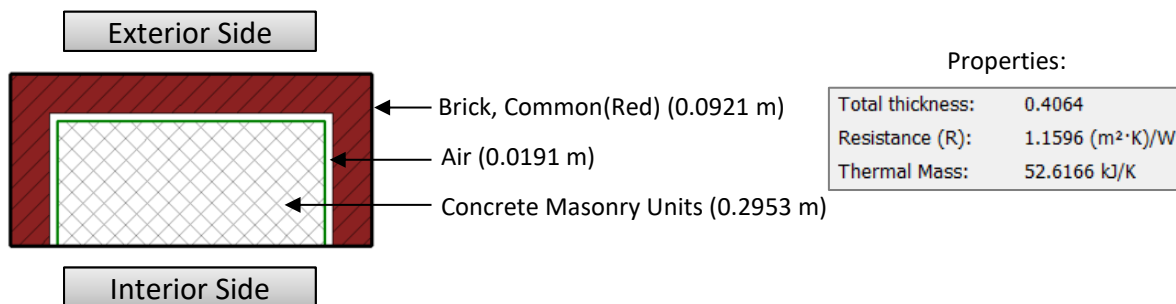

Figure 40. Materials assembly for "Elevator Wall 2"

In order to overcome this issue, a duplicated material with a slightly different name was created for one wall type (or the required ones according to the number of material assemblies in similar conditions). For this case, a new material called "Brick, Common(Red)(2)" was created and selected for the external face of the "Elevator Wall 2". Subsequently, Pyrosim creates two surfaces, one named "Brick, Common(Red)" and another one named "Brick, Common(Red)(2)". This facilitated the job of the Scripting Tool making it able to assign the pertinent thermal properties to each kind of surface, for instance, a Thermal Mass equal to 13.9129 [kJ/K] for "Brick, Common(Red)", and 52.6166 [kJ/K] for "Brick, Common(Red)(2)".

Some last adjustments were required since the model was created in such a way that all doors and windows were closed, creating an unlikely air-tight building. However, a more realistic and critical fire scenario involves some air entrainment, and smoke spread throughout the

building. Then, for assessing the development of a fire and smoke in the building, some doors and windows were opened. This could be done either in Revit or in Pyrosim, but in this case, Revit was used.

Figure 41 shows two windows whose family types were changed to an open window family with the same size as the adjacent windows, 1.4 m x 1.5 m. These windows were selected because of its distant location to the fire source in the atrium. Additionally, four doors were opened, two in the lower floor and two in the upper floor. Later in the results from FDS, it can be observed the influence of these changes in the development of the fire.
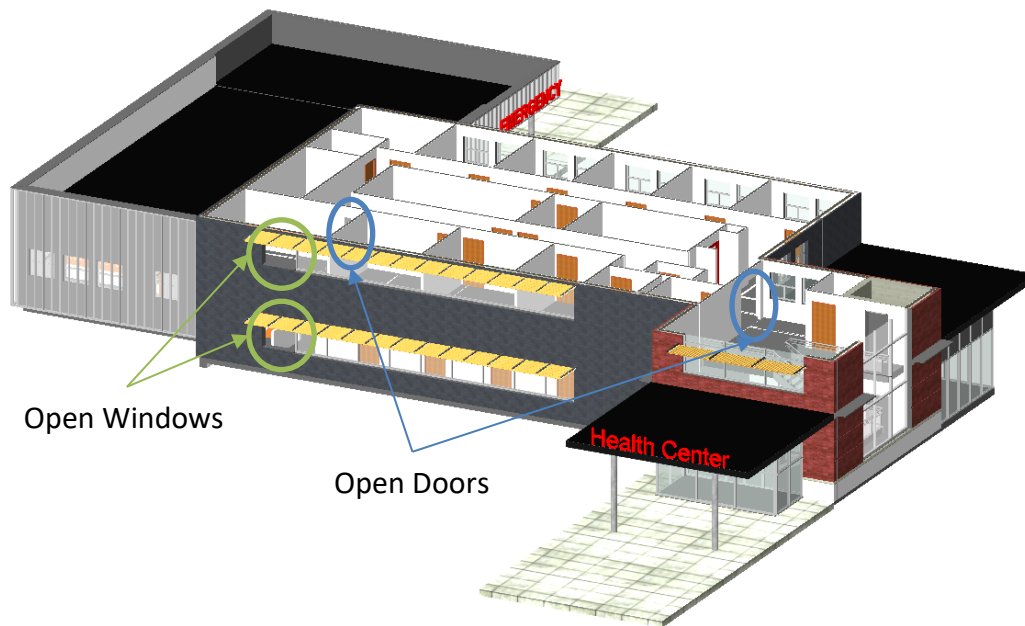

Figure 41. Open windows and doors in the Health Center. (Section applied at the upper floor)

IFC settings

Besides the construction geometry, other objects might not be of significant interest in performing a fire simulation. Topography, trees and other site components were hidden from the 3D view to avoid undesired information to be exported into the IFC file. Figure 42 shows a rendered picture of the site components in this project.

Figure 42. Rendered 3D view of the site components of the Health Center project.

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Another option is to use a Section Box to crop the geometry in a 3D view to select the elements of the building that are wanted to be exported. After using either a Section Box or hiding elements, it is selected the checkbox "Export only elements visible in view" in the IFC export tool, which filters the information of the hidden objects from the IFC file. Other settings were established as it was explained in section 6.1.

Pyrosim Settings

Importing the IFC file into Pyrosim was done in the same way as it was explained for the Basic Building model. After this process, it was necessary to rotate the geometry 35° in order to make it orthogonal to the north to facilitate the alignment of the mesh. The reaction was selected again as PMMA, but the fire scenario for this building is different. The HRRPUA was kept equal to 1000 kW/m², but the fire area was changed to 1 m² (1.0 m x 1.0 m) for getting a Heat Release Rate equal to 1000 kW. This HRR is constant over the entire simulation, and no RAMP was introduced on it. The fire vent was located in the atrium at the entrance of the building (Figure 43) considering that this location might be critical due to the possibility of smoke spread to the entire building. This scenario does not consider any heat and smoke control or fire suppression system.
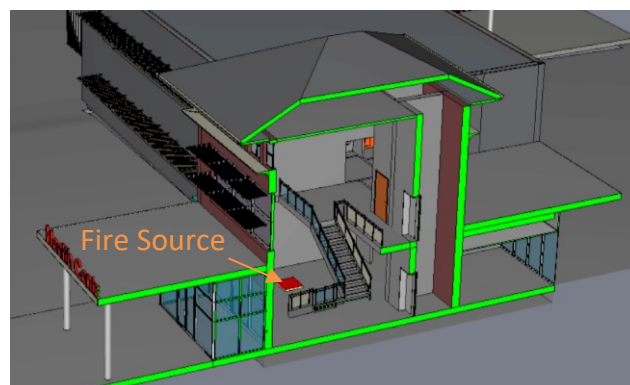

Figure 43. Location of the fire source in the Atrium of the Health Center

The geometry of this building required the distribution of several meshes to fit an adequate domain of analysis. Additionally, in order to maximise de use of the available computational resources at Lund University, ten meshes were distributed and numbered as shown in Figure 44. Meshes number 1 and 5 are located on the back side of the building.
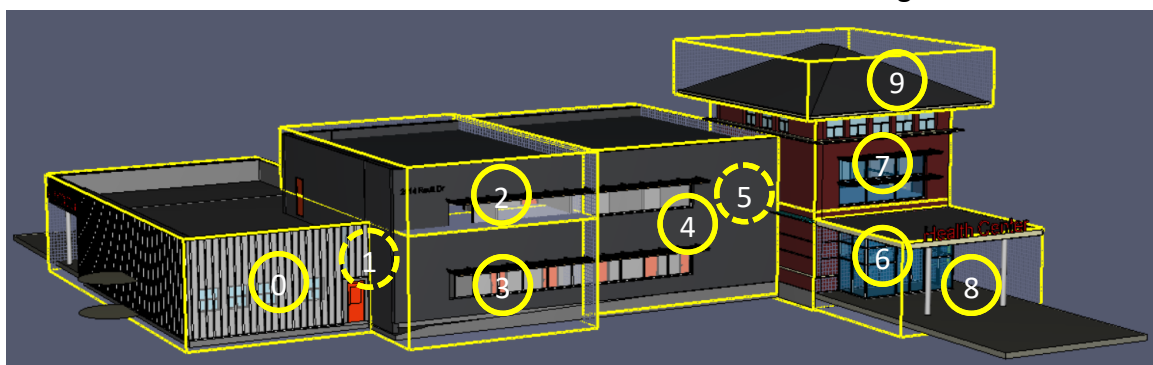

Figure 44. Computational meshes in Pyrosim for the Health Center

In total 1,875,789 cells were required to cover the entire building including some extensions in front of the open windows. Meshes 6 and 7 are located in the atrium where the fire is located. Each one of them required 534,600 and 515,160 cells with a size of 0.10 m in order to better capture the fire behaviour in the zone. Other meshes were set in 0.20 m for being conservative with the calculation time and the level of mesh refinement.

Other settings

The Scripting Tool did not need any further enhancements to process the IFC and FDS data for the Health Center; this procedure is similar to the one described for the Basic Building. In the other hand, more capable computational resources were used for running the simulations in FDS for the Health Center due to a large number of cells used.

LUNARC is the center for scientific and technical computing at Lund University. LUNARC has several clusters, but in this case, Aurora was used to perform the fire simulations.

Aurora cluster consists out of 50 compute nodes funded by research groups at Lund University. Each node has two Intel Xeon E5-2650 v3 processors, offering 20 compute cores per node. The nodes have 64 GB of DDR4 ram installed (LUNARC, 2016). One node was available for performing this simulation.

When starting the simulation in FDS, 10 MPI processes and two OpenMP threads were set to solve the 10 meshes in which the Health Center was divided. It took 25.17 hours to complete the simulation for the original model and 25.46 hours for the model with additional thermal properties.

FDS Results

Two simulations were performed for the Health Center, one for the original model with incomplete information about thermal properties, and a second model with complete information in the materials of walls, floors, ceilings and roofs. For both cases, the fire development was similar.

The simulation of the fire located in the atrium of the building shows the development of the fire and smoke spread as it can be seen in Figure 45. After ignition, the smoke plume raises and impinges the ceiling and generates a hot layer which grows with time. Later, smoke goes through the open door on the upper floor and gradually spreads along the corridor. Almost at the end of this corridor, the intentionally open door allows the fire to enter in one of the rooms and to go out of the building by the open window. Figure 45 and Figure 46 show temperature contours based on a maximum percentile temperature equal to 107°C.
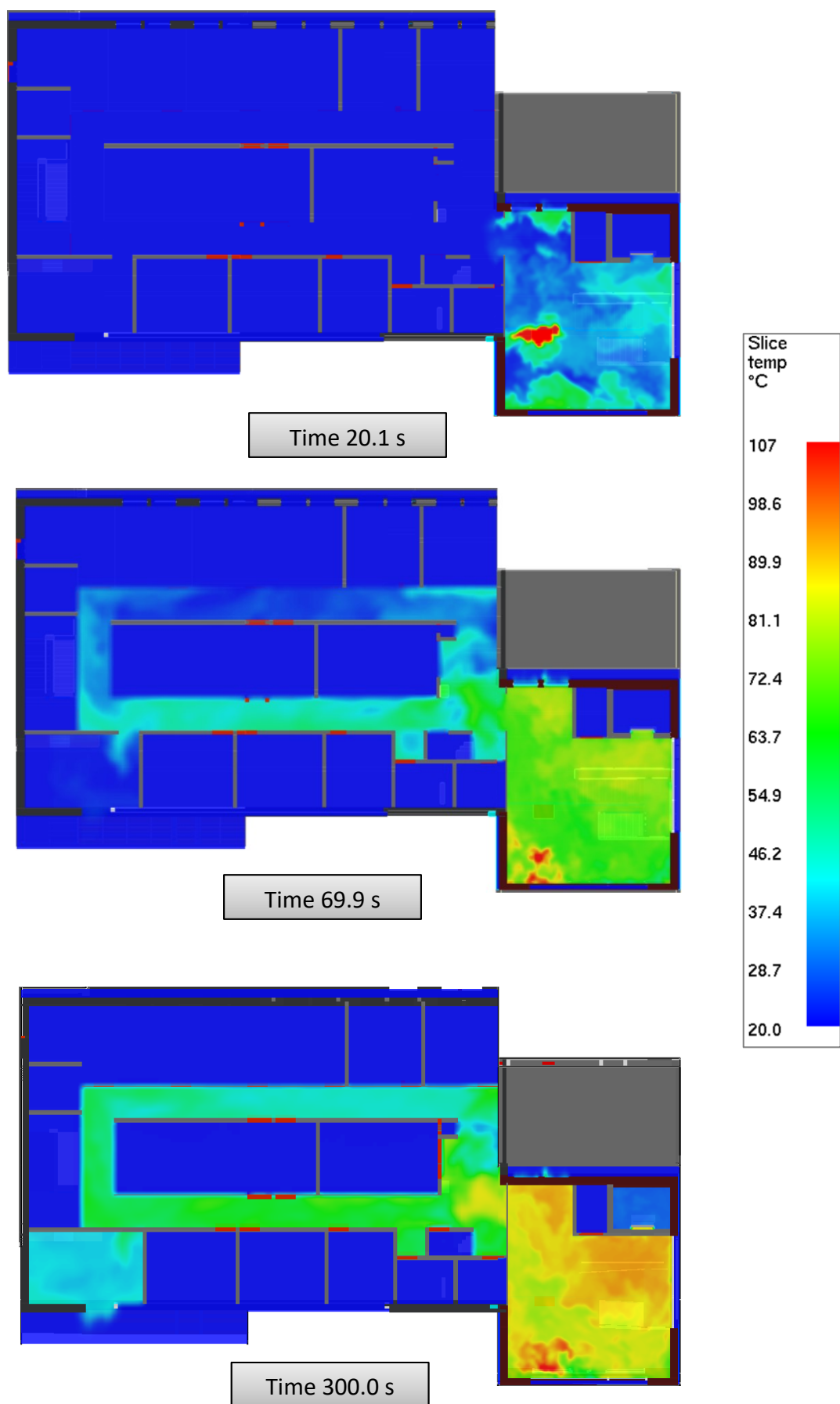
Figure 45. Development of the fire in the Health Center. Temperature slice at 36.2 m height.

Fresh air goes into the building from the open window in the ground floor and enters the atrium by an open door. This fresh air tilts the fire plume and contributes to the entrainment of oxygen in the fire. In this scenario, the movement of the fresh air avoids the spread of smoke on the ground floor which is not affected by hot gases. The fire behaviour continues stable since time equal to 140.1 s for the rest of the simulation and is observed in Figure 46.
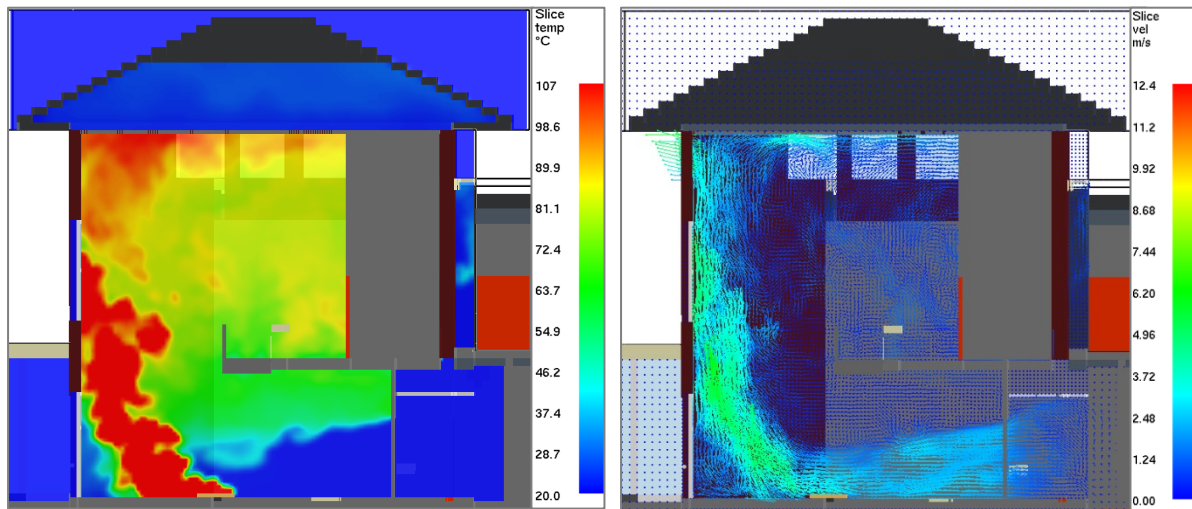

Figure 46. Temperature (left) and velocity contours (right) at the atrium of the Health Center.

Even though the behaviour of the fire in both models is similar, there are some differences in the results of Wall temperatures in the boundaries. One clear example is perceived in the model with additional properties whose results include further information of temperatures in floors as it can be seen in Figure 47. Additionally, the maximum percentile temperature calculated for FDS for the original model is 70.8°C, while for the modified model is slightly higher, 72.2°C.
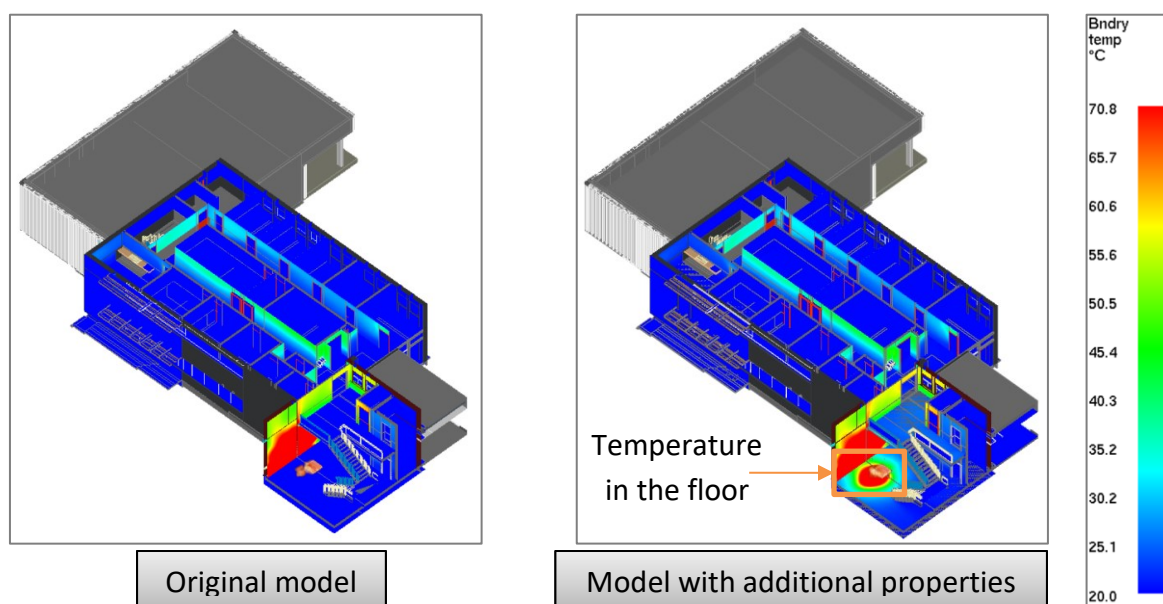

Figure 47. Temperature in the boundaries for the two models of the Health Center at 140.1 s.

The time that it takes to achieve untenable conditions was verified against temperature and visibility slices at 2m high on each floor (32.4 m and 36.2 m). After 35.1 s, gases with temperatures higher than 60°C start reaching the corridor from the atrium (which at this height is unoccupied). Later, at time equal to 95.1 s the corridor experiences temperatures higher than 60°C and hot gases start going into the room with open door and window. All of this can be seen in Figure 48.
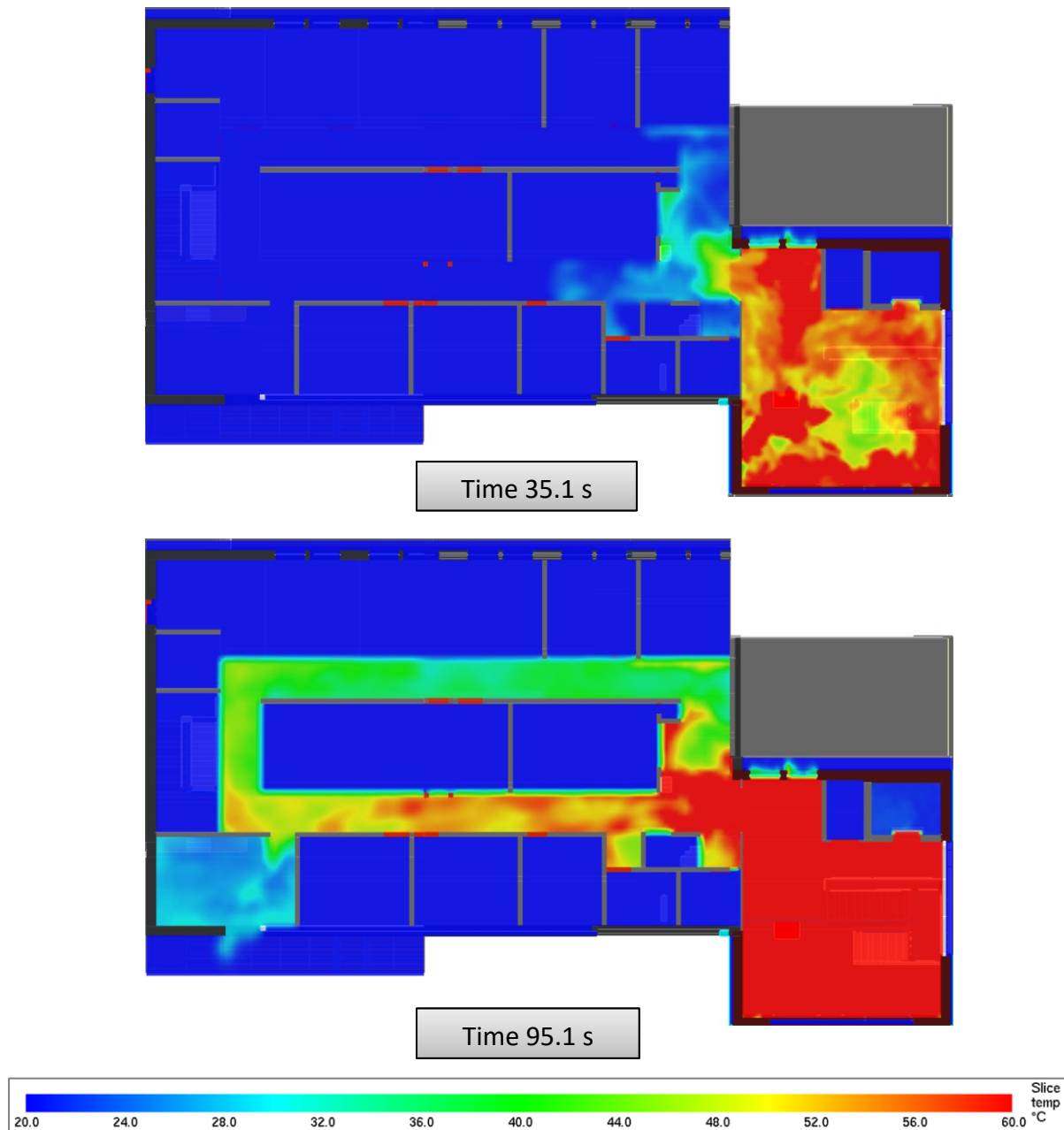

Time 35.1 s

Time 95.1 s

Figure 48. Performance criteria. Temperature in the Health Center. Plan view

Visibility is compromised after 30 s when smoke goes from the atrium into the corridor. At time 65.1 s visibility is reduced to less than 10 m in the corridor and continues decreasing. Figure 49 shows these two stages in the scenario.
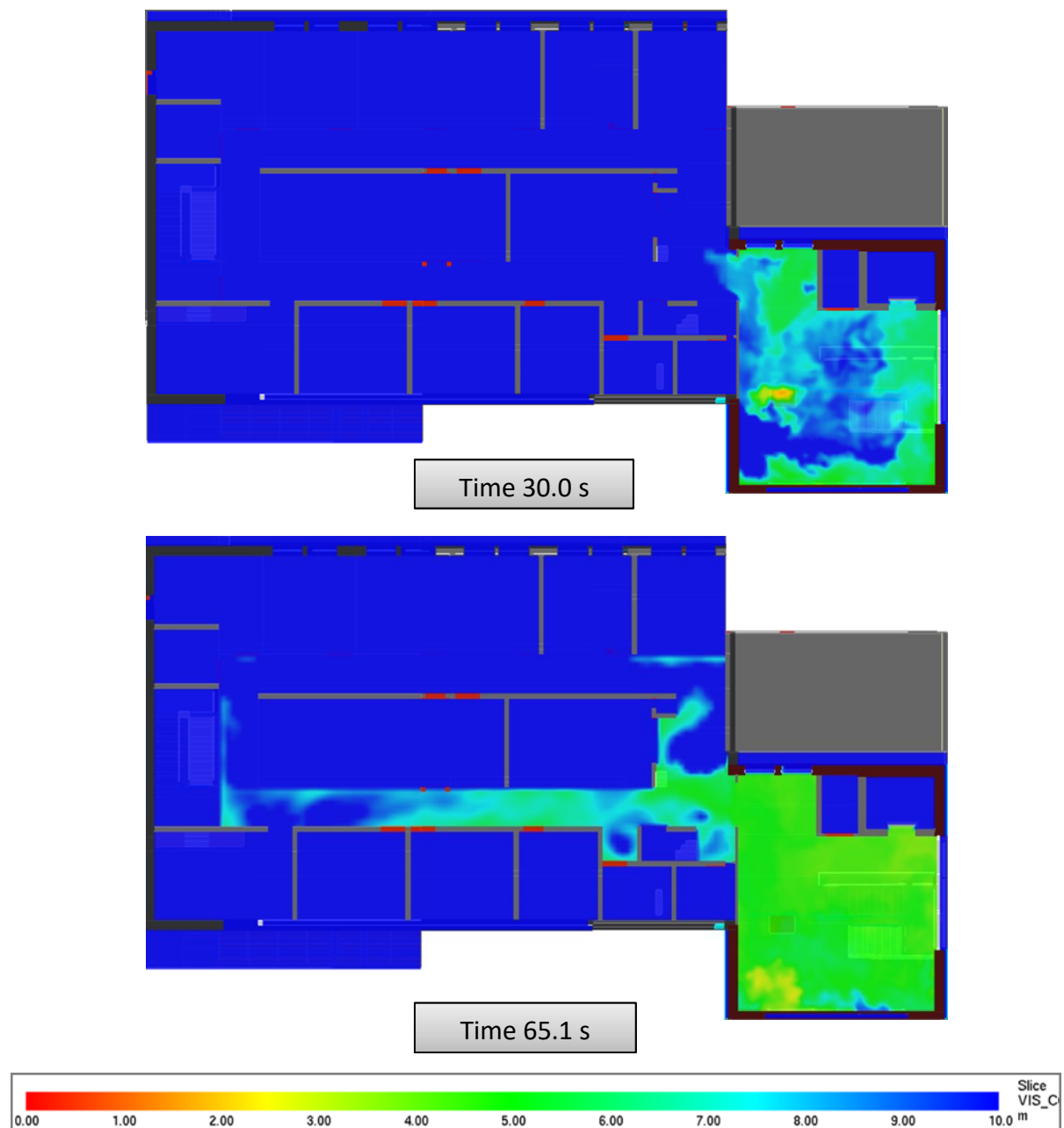
Figure 49. Performance criteria. Temperature in the Health Center. Plan view

If this scenario represented real conditions in the building, it would mean that occupants in the rooms of the upper floor of the Health Center should evacuate this area before 65.1 s (which is considered as Available Safe Egress Time, ASET). However, it should be noted that this scenario did not consider a growing phase of the fire and its characteristics might not represent the contents of the building.

7   Evaluation and conclusions

The work in this study led to several findings that should be outlined for a better understanding on the use of BIM for the simulation of fires in enclosures and the application of the strategies described in the previous chapters.

A key idea of the use of BIM besides the three-dimensional representation of complex buildings is the information contained in it. Programs such as Pyrosim seem to do good work on taking the data from a BIM model for the construction of obstructions for the analysis of fire scenarios. The most outstanding characteristic of BIM is its information; this is what makes BIM a powerful tool. However, this transfer of information from BIM into CFD is still limited. In this research, it was analysed different parametric definitions and strategies to get the most from a BIM model in its geometrical sense, and it was proposed a Scripting Tool to take a step further in obtaining information from the thermal properties of construction materials.

A typical scenario that a Fire Safety Engineering might encounter when receiving a BIM project from other professionals, such as Architects or Engineers, is that this model does not contain further information besides the three-dimensional geometry. These designers might not be aware of the need to include further characteristics of the materials proposed for the project. After doing this study, the author finds a need to encourage an earlier involvement of the Fire Safety Engineer during the design or modelling phase, so that the BIM Use of the model is correctly addressed and relevant information for the Fire Safety analysis is introduced in the model. This helps in fire safety related tasks but also sets a complete building information model useful for construction, maintenance and facility management.

Regarding the IFC format, it should be noted that it is not intended for transferring information about textures and render appearance, but its capabilities make it a good way for doing an open data exchange between BIM and CFD software. Its "open" feature allows getting information from any BIM software and being supported by the Scripting Tool proposed in this study. This means that, since IFC is not attached to be used only with Autodesk Revit models, the workflow described here could be applied to BIM models from different software vendors as long as the IFC file keeps a standard mapping. Though, this present study did not test BIM models from other software than Revit.

When an IFC file is imported in Pyrosim, this interprets the elements of the building and creates solid obstructions and surfaces which makes it easy the work of creating the geometry of a complex building for using FDS. However, those surfaces are named after the outer material layer of an element and assigned to its corresponding obstruction. This is a drawback in the process since it is not possible to notice a difference between material assemblies whose components in the core and interior layers are different, and subsequently, have

different thermal properties. Similar happens to element types with the same material but different thicknesses.

To overcome those inadequacies, it was necessary to duplicate the material in the first layer of elements sharing the same material, in order to get different surface names per material assembly. This issue leads to duplicated names which are not desirable, for example, when calculating construction quantities. Although this strategy does not affect the total quantities of materials in a general view, might alter the information flow. For instance, if a change is made in the characteristics of a material (e.g. density should have been 2300 kg/m³ instead of 2400 kg/m³), it will be required to make the same change in every duplicated material. Therefore, this strategy should be applied just in a copy of the original BIM model and not in a collaborative source. Additionally, users who decide to apply this strategy should be aware that it is not possible to consider the differences in heat losses when one side is exposed to fire instead of the other. In the way how the Scripting Tool was set, it is possible to assign thermal properties for the whole material assembly neglecting the differences of materials in each face of an element.

The Scripting Tool can read and convert the information about thermal properties from an IFC file to an FDS file, which reduces some steps in setting the parameters of a fire scenario. BIM models might contain further information about the fire scenario, such as possible fire source or an appropriate size for the simulation domain, but currently, these should be set beforehand in the FDS input file using Pyrosim. More software development should be done to allow information about the fire scenario to be obtained from the BIM model and to achieve an even higher degree of automation for its integration with CFD.

Using the information from a BIM model for the simulation of fires in enclosures should be performed together with clear fire safety engineering concepts and understanding the limitations of both, BIM and CFD. This means that the supervision and knowledge from a Fire Safety Engineer is required for analysing the appropriateness of the BIM model for being used in fire simulations.

The following conclusions were made in relation to the objectives of this study, based on the evaluations stated before:

Identify model transfer from BIM to CFD

Building Information Modelling (BIM) facilitates the creation of complex building geometries and couples detailed physical data with it. This information is useful for assessing a fire scenario by Computational Fluid Dynamics. In this study, it was evaluated that the Industry Foundation Classes (IFC) format is a suitable data-exchange format to share information from BIM to CFD software. Its vendor-neutral feature allows getting information from any BIM

software and being supported by Pyrosim and the Scripting Tool proposed in this study. Unlike proprietary formats, IFC helps in the implementation of "Big Open BIM" workflows by allowing communication among different disciplines during the lifecycle of a project.

Identify specific BIM data input for CFD

For setting up a BIM model useful for the simulation of fires in CFD, the BIM model should be planned by specifying an appropriate BIM Use. In this case, the BIM model is used to *forecast* the future performance of the building by a fire scenario; to *generate* information during the design phase, and to *transform* this information into an open format such as IFC. For doing this, the model should have the geometry of the building that represents the scenario to be analysed, which requires a proper understanding of the arrangement of openings such as windows and doors and obstructions such as walls and floors. Additionally, material assemblies should represent the ones that are intended for the construction, including appropriate physical and thermal properties.

Test the workflow from BIM to CFD

Two basic building models were used for isolating strategies to get the most from the geometry in the BIM model. Several parametric definitions were studied in the Basic Building and the Two-room building. First, it was evaluated different materials for the construction elements; later, it was analysed the differences between openings, doors and windows, and lastly, it was compared the IFC versions for data exchange.

It was found that the IFC file exported from Revit does not contain material properties for each material layer (Thermal Conductivity, Specific Heat Capacity and Density) but includes other derived thermal properties such as Heat Transfer Coefficient, Thermal Resistance and Thermal Mass for each element type. However, these properties are not recognised by Pyrosim. This shortcoming is overcome with the Scripting tool created in Python which allowed continuity in the workflow (as explained in the next section). It was found that it is feasible to perform CFD simulations with information partially taken from a BIM model, as shown in the implementation process on the three different buildings: the Basic Building, the Two-room and a more complex building, the Health Center.

The guidance received from Autodesk developers was crucial for applying best practices in getting information from BIM into the IFC format. Likewise, the assistance from Thunderhead Engineering Consultants helped to understand the available IFC import options in Pyrosim.

Create and evaluate a prototype tool to address shortcomings in the model data transport

This study proposed a Scripting Tool in the Python programming language to take a step in obtaining information from the thermal properties of construction materials by using information in the IFC file exported from Revit. This tool enhances the FDS input file from Pyrosim which includes other configurations of the fire scenario and the building geometry. The simulations performed using this FDS input file showed that the information is successfully read by FDS and used for the calculation of heat transfer in the boundaries and presented in the form of Wall Temperature contours.

Evaluate limitations and challenges, and communicate outcomes to developers and researchers

The transfer of information from BIM into CFD is mainly limited by the software capabilities and the practices applied during the creation of a BIM model. Further software development should be done in order to use all the potential of BIM, not only in the geometry creation but also in storing and sharing valuable data related to each building elements, such as their material properties. Some potential future work was identified in this study (chapter 8), and communicated to developers and researchers in order to promote better integration of BIM with the simulation of fires in enclosures.

8   Potential future work

After carrying out this study, some potential future work and recommendations were identified. These were communicated to developers and researchers in order to promote further development in the integration of BIM with the simulation of fires in enclosures.

Recommendations for enhancements to the Python Scripting tool:

- The list of densities in the Scripting Tool may be enhanced by creating a link between the library of physical assets in Revit or any other database that contains typical densities for a wider group of materials. In the case of Revit, it uses the file format ".adsklib" for storing information related to thermal assets.

- The Scripting Tool was focused on searching for information regarding thermal properties in the IFC file, but further information of interest might be already included in the IFC file. The tool could be enhanced to search and script information related to fire size, type of fuel, or mesh domain size.

- The Scripting tool was configured for performing calculations in the International System of Units. Even though it is possible to select SI units in Revit before exporting the IFC file, it might be useful to include the capability of working either in Imperial units or SI units.

Recommendations for enhancements to Pyrosim:

Pyrosim detects the name of element types and uses this information for identifying obstructions. It also assigns a unique name from the outer material layer to the surfaces that it creates. However, it should be noted that FDS allows having an assembly of materials on the same surface. Therefore, a surface should not be related to an individual material name, but a "material assembly". Since in IFC does not exist the definition of "material assembly" but "entity type", it would be more appropriate to relate the ID of a surface to the entity type instead to a material name. This would allow in the future the connection of materials from IFC files (ifcMaterial) to the materials in FDS (MATL).

Additionally, if a surface were named after the element type instead to the outer material, it could be overcome the issue when two element types have different material assemblies but the same name in the outer material layer. Every entity type might have different thermal properties, but when they are identified with the same name, this difference is unnoticed. That is why, in this study, it was required to

duplicate the materials in the outer layer in assemblies that were using the same name.

Recommendations for enhancements in Revit:

Currently, the IFC Export tool in Revit does not support exporting material properties in IFC format, though it is a request already know by Autodesk Developers who suggested the next possible ways to overcome this issue:

- To customise the IFC Export tool in Revit to support material properties (or the thermal properties for this case) for being exported in the IFC file. The open source of this exporter is available in GitHub (Autodesk Inc., 2019i)
- To use the Revit Application Programming Interface (API) to get the desired information from materials in a Revit project, and then export it to an IFC file.

These processes require knowledge in programming, Revit elements and materials, Revit API and IFC format.

If Revit supports exporting material thermal properties, the next will be the recommended enhancements to Pyrosim or the Scripting tool:

It would be ideal if the capabilities of the Revit IFC export tool were increased to allow exporting material properties for each material layer (Thermal Conductivity, Specific Heat Capacity and Density) besides the "Analytical properties" for an element type (Heat transfer coefficient, Thermal Resistance and Thermal mass). This would open the possibility of writing an FDS input file including thermal properties per material in the MATL line. For this, either Pyrosim or the Scripting Tool should be enhanced. If any of these programs were able to interpret material names (*IfcMaterial*) as the materials used for FDS (MATL_ID), it would be possible to distinguish between materials in the core, exterior and interior layers of an assembly and to understand the differences in heat losses when one side of an element is exposed to fire instead of the other.

The IFC file contains a class called *IfcMaterialLayerSet* associated with an entity type (*IfcWallType*, *IfcSlabType*, etcetera); this comprises information of each *IfcMaterialLayer* that form a material assembly. *IfcMaterialLayer* contains attributes of Thickness and *IfcMaterial* per material layer. This information could be interpreted in the same format as FDS does.

The next FDS example refers to an assembly of materials, BRICK and INSULATOR, where each material has a thickness of 0.20 m and 0.10 m. If the material properties were exported by the IFC export tool in Revit, it would be possible for Pyrosim or the

Scripting tool to write the MATL lines including thermal properties. The information for the SURF line is currently found in the IFC class *IfcMaterialLayer,* as explained before.

```
&MATL ID = 'BRICK'
CONDUCTIVITY = 0.54
SPECIFIC_HEAT = 0.84
DENSITY = 1550. /

&MATL ID = 'INSULATOR'
CONDUCTIVITY = 0.041
SPECIFIC_HEAT = 2.09
DENSITY = 229. /

&SURF ID = 'BRICK WALL'
MATL_ID = 'BRICK','INSULATOR'
THICKNESS = 0.20,0.10 /
```

Recommendations for enhancements to FDS:

One of the remarkable features of Building Information Modelling is the capability of creating complex building geometries in a three-dimensional representation. However, the current Cartesian coordinate system used by FDS restricts the representation of curved and sloped elements.

The FDS Road Map (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019a) states that plans for FDS 7 include the ability to handle complex, unstructured geometry via high-order immersed boundary method. If this enhancement is introduced, it will be encouraged the use of BIM models for the analysis of fire scenarios in FDS, and further research could be done in this area.

9   Acknowledgements

10 References

Allen Consulting Group Pty Ltd. (2010). *Productivity In The Buildings Network: Assessing The Impacts Of Building Information Models*. In. Retrieved from http://buildingsmart.org.au/wp-content/uploads/2014/03/BIM_Economic_Study_Final-Report_29Oct2010.pdf

Autodesk Inc. (2002). Complementary Technology Expands Building Industry Division Business to New Customer Segments. *STAMATS COMMUNICATIONS, INC.* Retrieved from Buildings website: https://www.buildings.com/news/industry-news/articleid/777/title/autodesk-completes-acquisition-of-revit-technology-corporation

Autodesk Inc. (2019a). Advanced Energy Settings. *Help Autodesk REVIT 2019.* Autodesk Revit 2019. Retrieved from http://help.autodesk.com/view/RVT/2019/ENU/?guid=GUID-24528ACB-E82C-410F-BEB7-24BDBA6D0769

Autodesk Inc. (2019b). Apply a Material by Category or Subcategory. *Help Autodesk REVIT 2019.* Autodesk Revit 2019. Retrieved from http://help.autodesk.com/view/RVT/2019/ENU/?guid=GUID-96B852C9-277F-4BAA-AA4D-58E8FB0175E6

Autodesk Inc. (2019c). Building information modeling software. *Autodesk Products. Features.* Autodesk Revit. Retrieved from https://www.autodesk.com/products/revit/features

Autodesk Inc. (2019d). Construction Type Characteristics. Autodesk Revit 2019. Retrieved from http://help.autodesk.com/view/RVT/2019/ENU/?guid=GUID-1C70EE2E-2DC5-4920-A056-9030B471E4CF

Autodesk Inc. (2019e). Door Type Properties. *Autodesk Knowledge Network.* Autodesk Revit 2019. Retrieved from https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-Model/files/GUID-29905EE0-3D7D-422E-A627-5A7A8AC34D7B-htm.html

Autodesk Inc. (2019f). Energy Analysis Using Building Elements-Quick Start. *Help Autodesk Building Performance Analysis.* Retrieved from http://help.autodesk.com/view/BUILDING_PERFORMANCE_ANALYSIS/ENU/?guid=GUID-F093F9BC-749D-4F48-B866-55045BEADA0E

Autodesk Inc. (2019g). Floor Type Properties. *Autodesk Knowledge Network.* Autodesk Revit 2019. Retrieved from https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-Model/files/GUID-AE45EE40-0B20-4638-A122-26A3E023CC27-htm.html

Autodesk Inc. (2019h). IFC Export Setup Options. Autodesk Revit 2019. Retrieved from http://help.autodesk.com/view/RVT/2019/ENU/?guid=GUID-E029E3AD-1639-4446-A935-C9796BC34C95

Autodesk Inc. (2019i). IFC for Revit (revit-ifc) (Version Beta4-v19.2.0): GitHub. Retrieved from https://github.com/Autodesk/revit-ifc

Autodesk Inc. (2019j). Material Element. Autodesk Revit 2019. Retrieved from http://help.autodesk.com/view/RVT/2019/ENU/?guid=GUID-B50FD220-593B-41CD-A196-8501FC20189A

Autodesk Inc. (2019k). Material Thermal Properties - Conceptual Types. *Help Autodesk REVIT 2019.* Autodesk Revit 2019. Retrieved from

http://help.autodesk.com/view/RVT/2019/ENU/?guid=GUID-004A470D-675B-4CB0-96AE-D4A6852BDDA3

Autodesk Inc. (2019l). Roof Type Properties. *Autodesk Knowledge Network.* Autodesk Revit 2019. Retrieved from https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-Model/files/GUID-0075FD89-34FB-464D-9523-6FAAC05AC3AE-htm.html

Autodesk Inc. (2019m). Window Type Properties. *Autodesk Knowledge Network.* Autodesk Revit 2019. Retrieved from https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-Model/files/GUID-1C03B7DF-89EE-48B1-B501-571745B1D513-htm.html

Beetz, J., Borrmann, A., & Weise, M. (2018). Process-Based Definition of Model Content. In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling: Technology Foundations and Industry Practice* (pp. 127-138): Springer International Publishing : Imprint: Springer, 2018.

Bergin, M. S. (2012). A Brief History of BIM. *ArchDaily*. Retrieved from Style of Design website: https://web.archive.org/web/20140302064642/http://www.styleofdesign.com/architecture/a-brief-history-of-bim-michael-s-bergin/

BIM Alliance Sweden. (2017). BIM i staten. https://www.bimalliance.se/utveckling-av-bim/initiativ-i-sektorn/bim-i-staten/

BIM Forum Argentina. (2017). Adopción de BIM en Argentina. *Resumen Ejecutivo.* Retrieved from http://biblioteca.camarco.org.ar/adopcion-de-bim-en-argentina-resumen-ejecutivo/

Borrmann, A., Beetz, J., Koch, C., Liebich, T., & Muhic, S. (2018). Industry Foundation Classes: A Standardized Data Model for the Vendor-Neutral Exchange of Digital Building Models. In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling: Technology Foundations and Industry Practice* (pp. 81-138): Springer International Publishing : Imprint: Springer, 2018.

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). Building Information Modeling: Why? What? How? In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling: Technology Foundations and Industry Practice* (pp. 1-24): Springer International Publishing : Imprint: Springer, 2018.

British Standards Institution, & UK Government, D. f. B., Energy & Industrial Strategy;. (2019). British Standards and Publicly Available Specifications (PAS) from BSI. Retrieved from https://bim-level2.org/en/standards/

Brumm, H., Crotty, S., Molloy, I., & Piechnick, P. (2018). What's new in Revit 2019? *REVIT BLOG*. https://blogs.autodesk.com/revit/2018/04/11/whats-new-in-revit-2019/

Brumm, H., Crotty, S., Molloy, I., & Piechnick, P. (2019). You've got to see what's new in Revit 2020. *REVIT BLOG*. https://blogs.autodesk.com/revit/2019/04/10/youve-got-to-see-whats-new-in-revit-2020/

buildingSMART Australasia. (2012). *National Building Information Modellin Initiative*. In. Retrieved from https://buildingsmart.org.au/wp-content/uploads/2014/03/NationalBIMIniativeReport_6June2012.pdf

BuildingSMART International Ltd. (2019). Summary of IFC Releases. Retrieved from http://www.buildingsmart-tech.org/specifications/ifc-releases/summary

Cabinet Office (Producer). (2011). Government Construction Strategy.

Cooperative Research Centre for Construction Innovation. (2007). *Adopting BIM for facilities management*. In *Solutions for managing the Sydney Opera House*. Retrieved from http://www.construction-innovation.info/images/CRC_Dig_Model_Book_20070402_v2.pdf

Cooperative Research Centre for Construction Innovation. (2009). *National Guidelines for Digital Modelling*. In (pp. 61). Retrieved from http://www.construction-innovation.info/images/pdfs/BIM_Guidelines_Book_191109_lores.pdf

Data Design System. (2017). DDS-CAD Viewer (Version x64 build 5/4-2017). Retrieved from https://www.dds-cad.net/

Datacomp Sp. Z o.o. (2018). BIM Vision (Version 2.19.10). Kraków, Poland. Retrieved from https://bimvision.eu/en/free-ifc-model-viewer/

Datacomp Sp. z o.o. (2019). BIM Vision: About. Retrieved from https://bimvision.eu/en/about/#

Dimyadi, J., Solihin, W., & Amor, R. (2018). *Using IFC to Support Enclosure Fire Dynamics Simulation.* Paper presented at the 25th EG-ICE International Workshop 2018, Lausanne, Switzerland.

Drysdale, D. (2011). *An introduction to fire dynamics.*: Oxford : Wiley-Blackwell, 2011. 3. ed.

Forero Ramírez, S. (Producer). (2018). Transformación digital del sector de la construcción. [slides] Retrieved from https://camacol.co/sites/default/files/presentaciones_eventos/Sandra%20Forero%20Ram%C3%ADrez.pdf

Forney, G. P. (2019). *Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data*. In Vol. User's Guide. Retrieved from https://pages.nist.gov/fds-smv/manuals.html

Grimm, D., List, C., Varis, K., Tucht, J., Gerundt, T., Sawanaki, T., . . . Skinner, A. (2014). What is WinMerge? (Version 2.16.0.0). Retrieved from http://winmerge.org/?lang=en

Ho, D. (2019). Notepad ++ (Version v. 7.5.9). Retrieved from https://notepad-plus-plus.org/

Hooper, M. (2015). *BIM anatomy II : standardisation needs & support systems*: Lund : Design Methodology, Department of Construction Sciences, Lund University, 2015.

Hurley, M. J., & Rosenbaum, E. R. (2015). *Performance-based fire safety design*: CRC Press.

International Organization for Standardization. (2017). Reaction to fire tests – Room corner test for wall and ceiling lining products – Part 1: Test method for a small room configuration. In (Vol. SS-ISO 9705-1:2017, pp. 56). Stockholm, Sweden: Swedish Standards Institute.

International Organization for Standardization. (2018). Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – information management using building information modelling – In *Part 1: Concepts and principles*: CEN, European Committee for Standardization

JetBrains s.r.o. (2019). PyCharm. Retrieved from https://www.jetbrains.com/pycharm/

Jung, W., & Lee, G. (2015). The status of BIM adoption on six continents. *International Journal of Civil, Structural, Construction and Architectural Engineering, 9*, 406-410.

Karwa, R. (2017). *Heat and Mass Transfer*. Singapore: Springer Science+Business Media.

Kreider, R., & Messner, J. (2013). The Uses of BIM: Classifying and Selecting BIM Uses. 22. https://www.bim.psu.edu/download/the_uses_of_bim.pdf

LUNARC. (2016, May 20). Aurora. Retrieved from http://www.lunarc.lu.se/resources/hardware/aurora/

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., & Vanella, M. (2019a, February 5). FDS Road Map. Retrieved from https://github.com/Autodesk/revit-ifc

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., & Vanella, M. (2019b). *Fire Dynamics Simulator User's Guide*. In. Retrieved from https://pages.nist.gov/fds-smv/manuals.html

McGraw Hill Construction. (2014). *The Business Value of BIM in Australia and New Zealand*. In H. Bernstein (Ed.), *How Building Information Modeling is Transforming the Design and Construction Industry*. Retrieved from http://www.consultaustralia.com.au/docs/default-source/bim/the-business-value-of-bim-in-australia-new-zealand.pdf

Mills, F. (2017). Delivering New Karolinska Solna Hospital with BIM. *The B1M*. https://www.theb1m.com/video/delivering-new-karolinska-solna-hospital-with-bim

National Institute of Building Sciences. (2019). WHAT IS A BIM? Retrieved from https://www.nationalbimstandard.org/faqs#faq1

NATSPEC Construction Information Systems Ltd. (Producer). (2019, April 13). AU BIM Standards. Retrieved from http://bim.natspec.org/documents/au-bim-standards

Parra Diettes, S. M., & Vecino Barbosa, C. A. (2014). *Utilización de Tecnologías BIM en el Modelado y Simulación del Proceso Constructivo de Edificaciones en Altura.* (Civil Engineering), Universidad Industrial de Santander, Bucaramanga, Colombia. Retrieved from http://tangara.uis.edu.co/biblioweb/tesis/2014/153881.pdf (C 28061)

Pitts, D. R., & Sissom, L. E. (1998). *Schaum's outline of theory and problems of heat transfer* (2nd ed.): New York : McGraw-Hill, cop. 1998.

PlanBIM. (2019). Qué es PlanBIM. Retrieved from https://planbim.cl/que-es-planbim/

Purser, D., & McAllister, J. (2016). Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In M. Hurley (Ed.), *SFPE Handbook of Fire Protection Engineering* (Vol. III): Springer Science+Business Media LLC.

Python Software Foundation. (2019). Python is powerful... and fast; plays well with others; runs everywhere; is friendly & easy to learn; is Open. Retrieved from https://www.python.org/about/

RIBA Enterprises Ltd. (2016). International BIM Report 2016. 24 pages. https://www.thenbs.com/knowledge/nbs-international-bim-report-2016

RIBA Enterprises Ltd. (2018). National BIM Report 2018. 27 pages. https://www.thenbs.com/knowledge/the-national-bim-report-2018

Scan2CAD. (2017, February 20). Autodesk – Everything You Need To Know. Retrieved from https://www.scan2cad.com/cad/autodesk/

Thunderhead Engineering Consultants Inc. (2018). PyroSim Manual (Version 2018.3.1210).

Trafikverket. (2017, June 16). Informationsmodellering BIM. Retrieved from https://www.trafikverket.se/for-dig-i-branschen/teknik/ny-teknik-i-transportsystemet/informationsmodellering-bim/

Verteeg, H. K., & Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics* (2nd ed.): Pearson Education Limited.
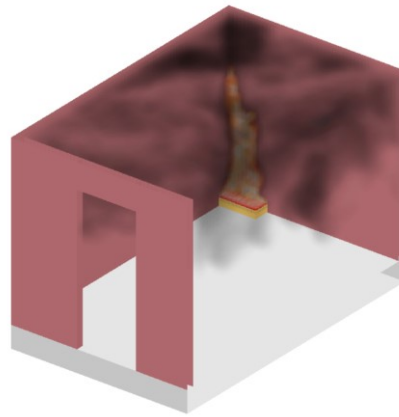
11 Appendices

11.1 3D figures of fire and smoke development in the Basic Building
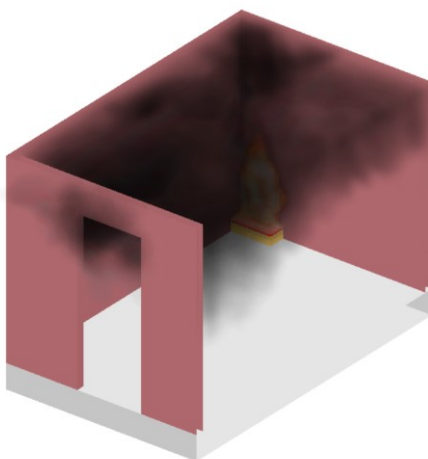
(Top and lateral elements clipped)
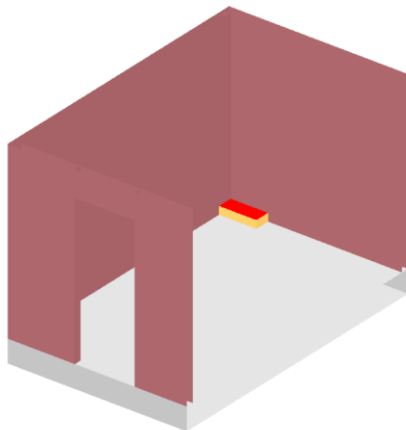
Time: 0.0 s

Time: 5.1 s

Time: 9.9 s

Time: 15 s

Time: 20.0 s

Time: 30.0 s

11.2 Contours of temperature and velocity vectors in the Basic Building

The hot layer stabilises at 1.4 meters after 30 s, and the conditions in the room stay constant during the remaining time of the simulation.

Temperature slice x=1.3 m:
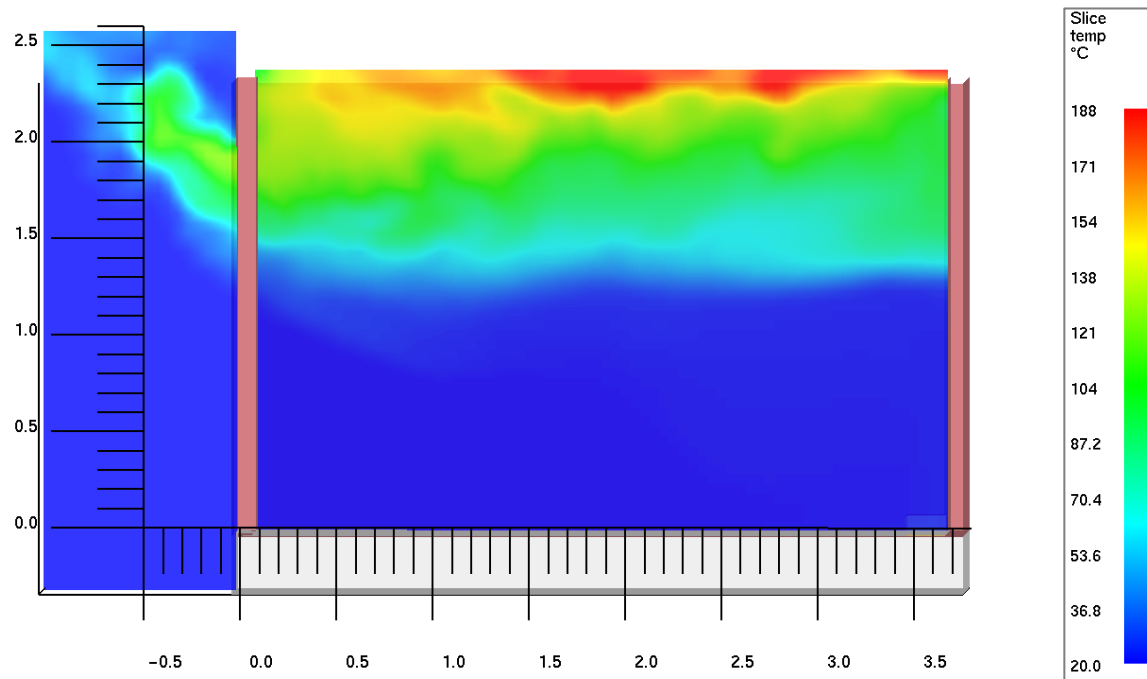
Velocity vectors, slice x=1.3 m:

11.3 3D figures of fire and smoke development in the Two-room Building
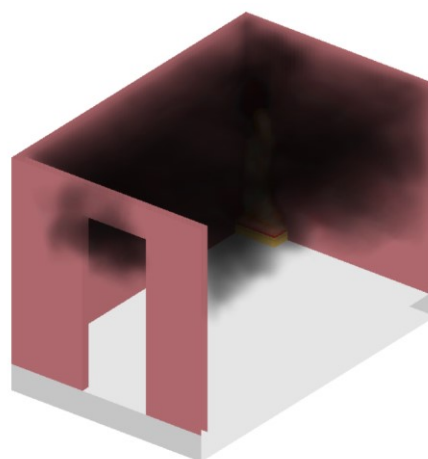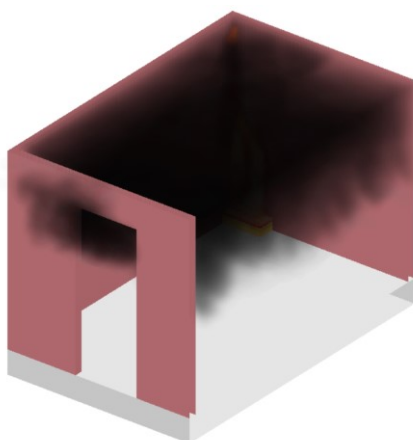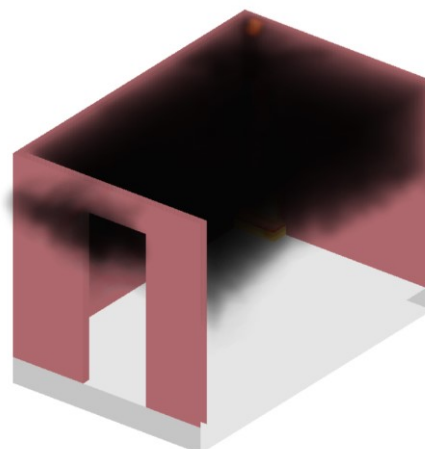
(Outline view)
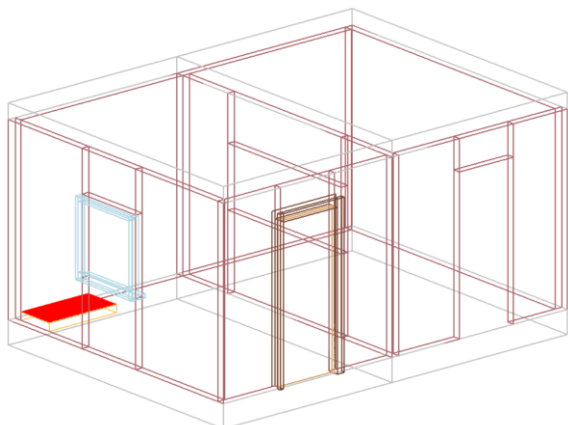
Time: 0.0 s

Time: 5.1 s

Time: 9.9 s

Time: 15 s
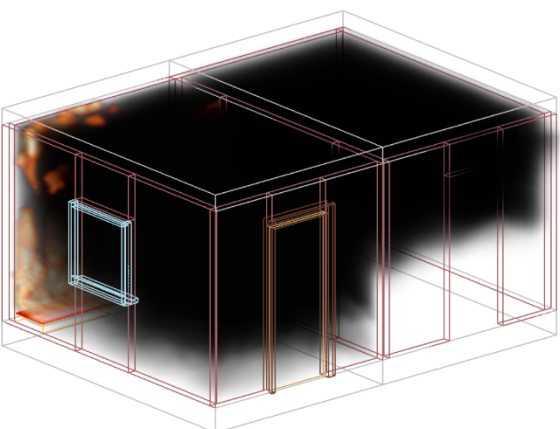
Time: 30.0 s
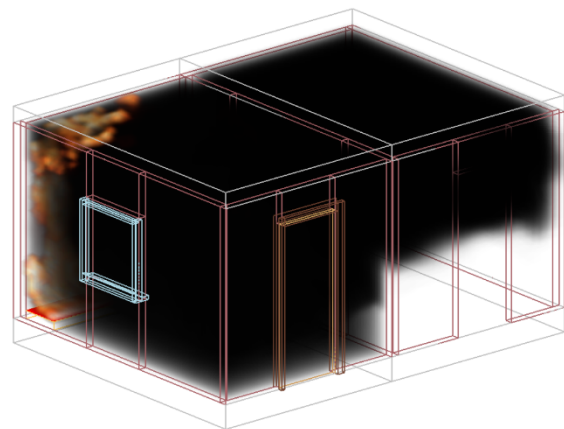
Time: 90.0 s

11.4 Contours of temperature and velocity vectors in the Two-room building

The hot layer stabilises at 1.0 meter height from the floor of room 1 (left) and around 1.5 meters in room 2 (right). After 90 s and the conditions in the room stay constant during the remaining time of the simulation.

Temperature slice Y=1.902 m:
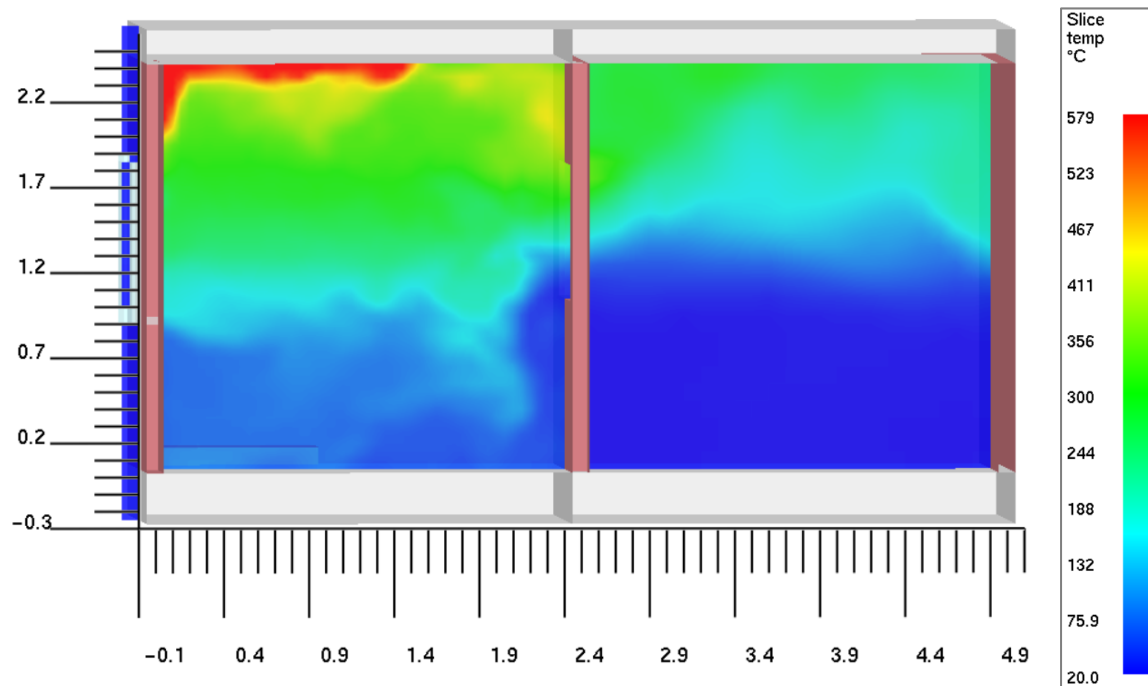
Velocity vectors, slice Y=1.902 m:

11.5 Contours of wall temperatures in the Health Center (Original model)

Wall temperatures in the atrium.
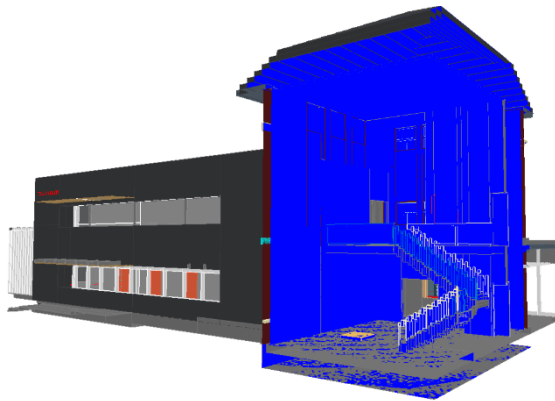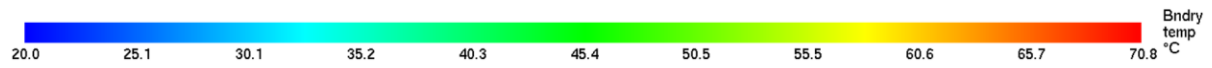
Time: 0.0 s
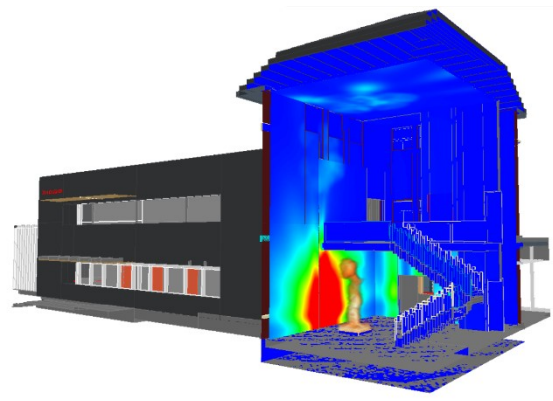
Time: 5.1 s
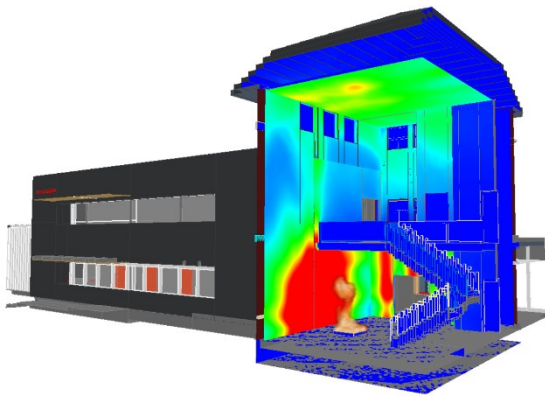
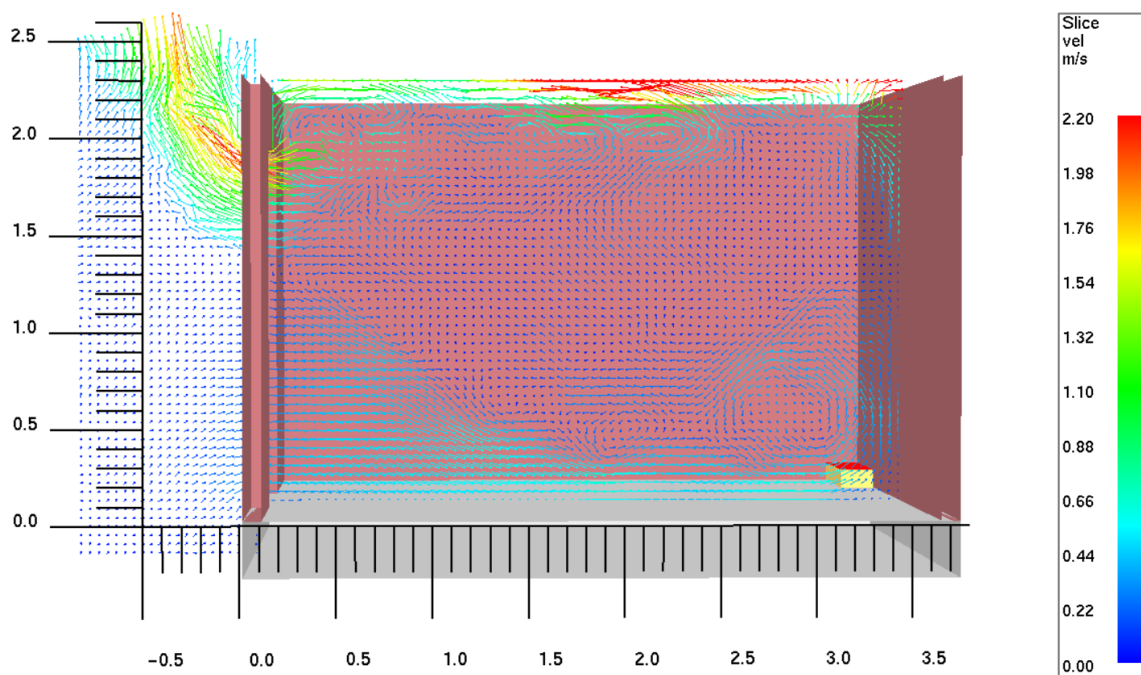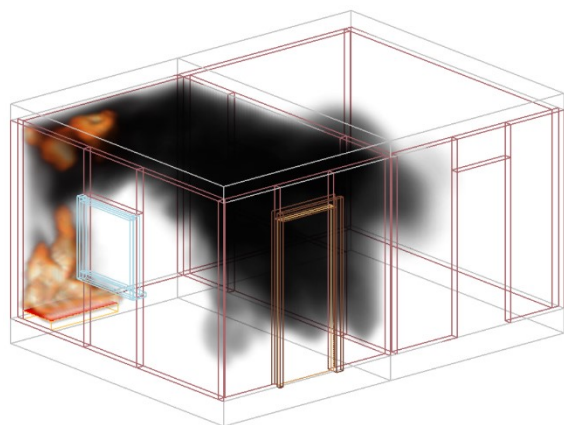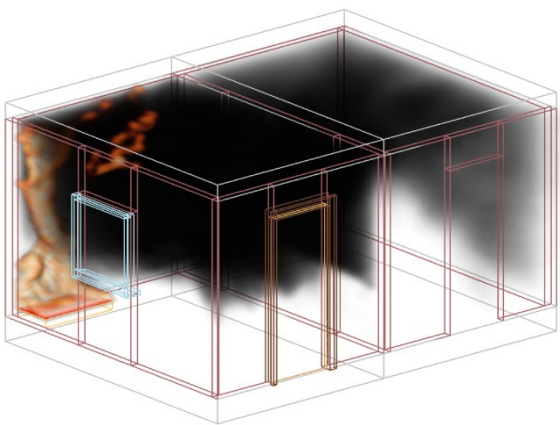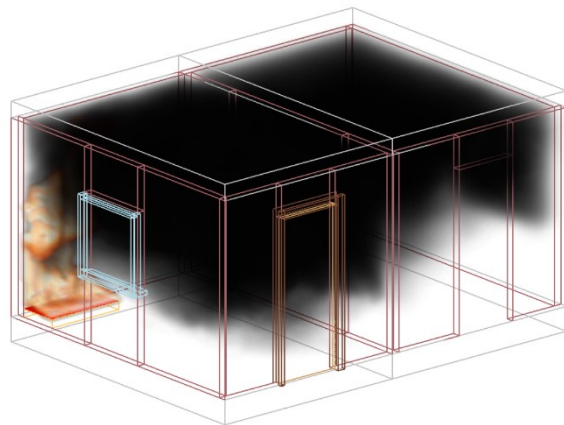Time: 30.0 s
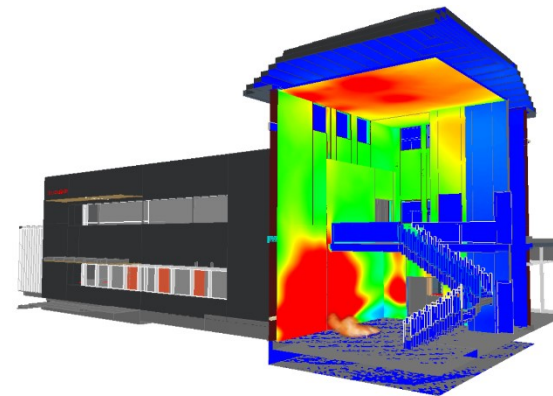
Time: 90.0 s
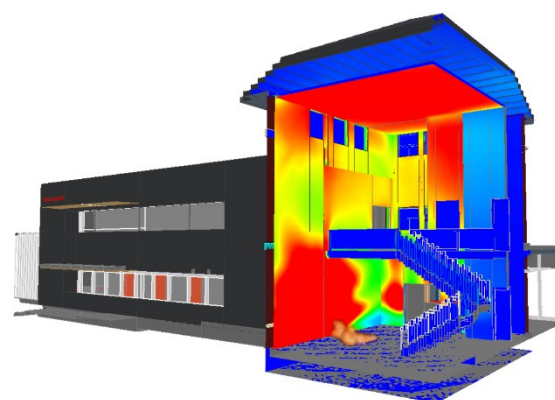
Time: 180.0 s
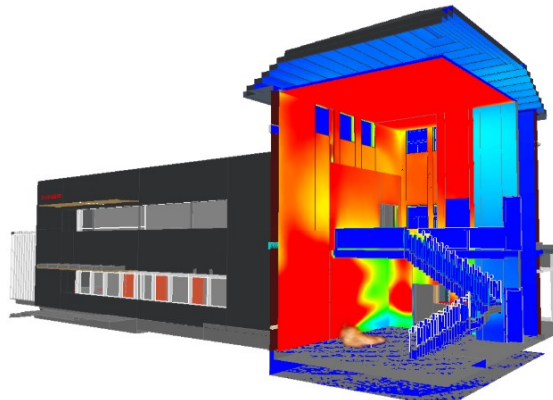
Time: 300.0 s

11.6 Python script for processing FDS input files

```python
import os
import errno


# Function. Open and read lines of a file
def read_file(file):
    f = open(file)
    file_data = f.readlines()
    f.close()
    return file_data


# Function. Returns predefined data (density)
def find_density(material_name):
    materials = ['Concrete, Cast In Situ', 'Brick, Common', 'Acoustic
Ceiling Tile 24 x 24', 'Porcelain , Ivory','Porcelain Linen', 'Concrete
Aerated', 'Concrete, Block pattern formwork', 'Concrete, Board Formed',
'Concrete, Broom Finish', 'Concrete, C12/15', 'Gypsum Wall Board', 'Metal
Stud Layer', 'Air', 'Air Infiltration Barrier', 'Plywood, Sheathing',
'Vapor Retarder', 'Aluminum', 'Aluminum Painted - Red', 'Asphalt Shingle',
'Cherry', 'Concrete Masonry Units', 'Concrete, Cast-in-Place', 'Concrete,
Precast', 'Copper', 'Earth', 'Glass', 'Iron, Ductile','Metal Deck',
'Roofing, EPDM Membrane', 'Standing Seam Metal Roof', 'Roofing, Slate',
'Concrete pavers', 'Metal Furring', 'Wall Texture, Stucco', 'Rigid
insulation', 'Structure, Steel Bar Joist Layer']
    material_density = [2300, 1550, 290, 3400, 3400, 580, 2300, 2300, 2300,
2300, 1100, 1.2, 1.2, 1090, 552, 1500, 2700, 2700, 1700, 630, 1800, 2300,
2300, 8920, 1300, 2480, 7150, 7850, 930, 1900, 2760, 2000, 7850, 1860, 23,
1.2]
    density_local = 200
    for mat in materials:
        if mat in material_name:
            material_index = materials.index(mat)
            density_local = material_density[material_index]
    return density_local


# Function. Prints the indices in which and specific text is found. IFC
file
def find_text_list(textl):
    indices_text = [zc for zc, s in enumerate(ifc_file_data) if textl in s]
    return indices_text


# Function. Prints the indices in which and specific text is found. IFC
file
def find_text_list2(text2):
    indices_text = [zb for zb, s in enumerate(ifc_file_data) if text2 in s]
    # print(indices_text)
    return indices_text[0]
```
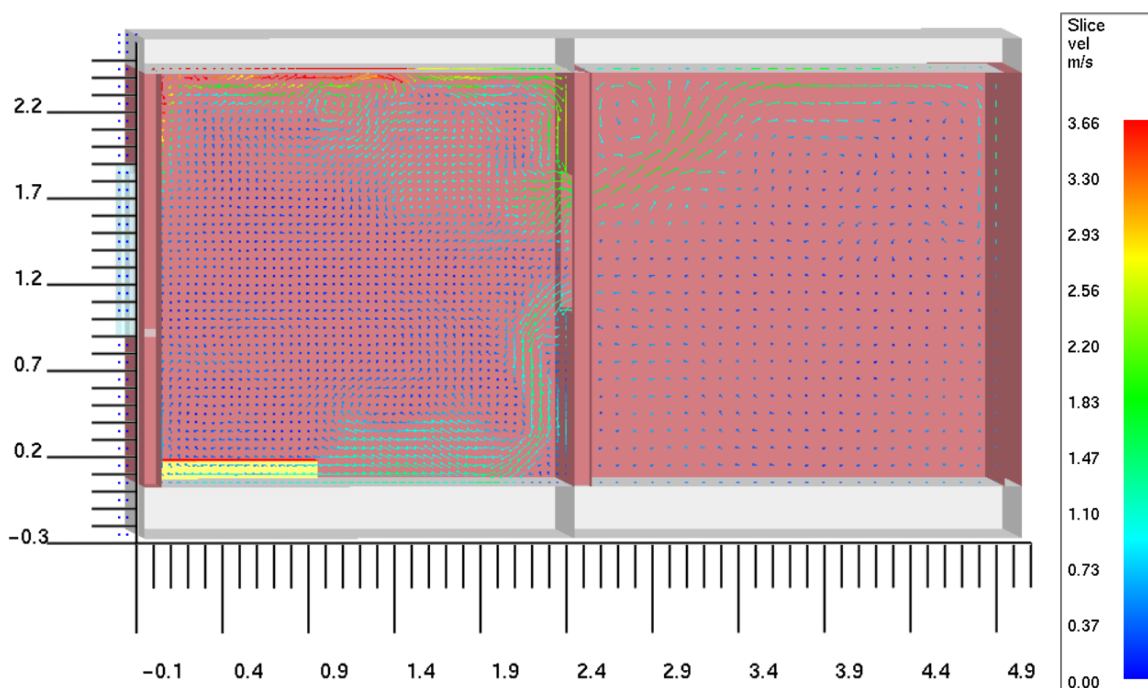
```python
# Function. Prints the indices in which and specific text is found. FDS
file
def find_text_list_fds(text3):
    indices_text = [v for v, s in enumerate(fds_file_data) if text3 in s]
    return indices_text



# Function. Gives the values of a desired group of properties
def thermal_property(valid_prop_name_local, valid_prop_value_local, prop):
    values2 = []
    a4 = 0
    while a4 < len(valid_prop_name_local):
        u_r_tm_index = [q for q, x in enumerate(valid_prop_name_local[a4])
if x == prop]
        values = [float(valid_prop_value_local[a4][q]) for q in
u_r_tm_index]
        values2.append(values[0])
        a4 = a4 + 1
    return values2



# Function. Finds indices of materials
def find_material_name(indices_ifc_mat):
    ifc_mat = []
    for l in indices_ifc_mat:
        for p in l:
            left_value1 = ifc_file_data[p].find("'") + 1
            right_value1 = ifc_file_data[p].rfind("$") - 2
            ifc_mat.append((ifc_file_data[p][left_value1:right_value1]))
    return ifc_mat



def find_material_layer_name(indices_mat_lay):
    mat_lay_name2 = []
    thick2 = []
    mat_hash2 = []
    for lst in indices_mat_lay:
        mat_lay_name = []
        thick = []
        mat_hash3 = []
        for num in lst:
            value_l = ifc_file_data[num].find("(") + 1
            value_r = ifc_file_data[num].find(",")
            mat_hash3.append((ifc_file_data[num][value_l:value_r]))
            left_value = ifc_file_data[num].find(",") + 1
            right_value = ifc_file_data[num].find("$") - 1

thick.append(float((ifc_file_data[num][left_value:right_value])))
            left = ifc_file_data[num].find(",'") + 2
            right = ifc_file_data[num].find("',")
            mat_lay_name.append((ifc_file_data[num][left:right]))
```

```python
            thick2.append(thick)
            mat_hash2.append(mat_hash3)
            mat_lay_name2.append(mat_lay_name)
        return mat_hash2, thick2, mat_lay_name2


def find_entities_hash(indices_entities):
    ent_hash = []
    for lst in indices_entities:
        for num in lst:
            fvalue = ifc_file_data[num].rfind("=")
            ent_hash.append((ifc_file_data[num][0:fvalue]))
    return ent_hash


def find_analytical_hash(ind_analytical):
    ent_hash = []
    for num in ind_analytical:
        fvalue = ifc_file_data[num].rfind("=")
        ent_hash.append((ifc_file_data[num][0:fvalue]))
    return ent_hash


def find_rel_mls(indices_asso, hashes):
    text_rel_asso = []
    for num in indices_asso:
        text_rel_asso.append(ifc_file_data[num])
    rel_text = [s for s in text_rel_asso if any(xs in s for xs in hashes)]
    return rel_text


def find_mls_hash(rel_text):
    a5 = 0
    mls_hash = []
    while a5 < len(rel_text):
        left_value = rel_text[a5].rfind("#")
        right_value = rel_text[a5].rfind(");")
        mls_hash.append(rel_text[a5][left_value:right_value])
        a5 = a5 + 1
    return mls_hash


def find_slab_hash(rel_text):
    a5 = 0
    mls_hash = []
    while a5 < len(rel_text):
        left_value = rel_text[a5].rfind("#")
        right_value = rel_text[a5].rfind("))")
        mls_hash.append(rel_text[a5][left_value:right_value])
        a5 = a5 + 1
    return mls_hash
```

```python
def find_covering_hash(rel_text):
    ag = 0
    mls_hash = []
    while ag < len(rel_text):
        left_value = rel_text[ag].find(",(") + 2
        right_value = rel_text[ag].rfind("),")
        mls_hash.append(rel_text[ag][left_value:right_value])
        ag = ag + 1
    return mls_hash


def find_prop_set_hash(indices_ty):
    prop_set_hash = []
    for lst in indices_ty:
        for num in lst:
            left_value = ifc_file_data[num].find("(#") + 1
            u = 0
            right_value = []
            while u != "OK":
                if ifc_file_data[num][left_value + u] == ",":
                    right_value = left_value + u
                    u = "OK"
                else:
                    u = u + 1

prop_set_hash.append((ifc_file_data[num][left_value:right_value]))
    return prop_set_hash


def find_indices(index_set):
    indices_set = []
    for n2 in index_set:
        indices_set.append(find_text_list(n2 + '='))
    return indices_set


def find_indices_list(hash_set):
    indices_set = []
    for n2 in hash_set:
        result = [find_text_list2(x + '=') for x in n2]
        indices_set.append(result)
    return indices_set


def find_text_set(indices_prop_set):
    text_prop_set = []
    for lst in indices_prop_set:
        for num in lst:
            text_prop_set.append(ifc_file_data[num])
    return text_prop_set


def find_hash_prop_val(text_property_set_local):
```

```python
        b = 0
        val_hash = []
        while b < len(text_property_set_local):
            left_value = text_property_set_local[b].find(",(") + 2
            right_value = text_property_set_local[b].rfind("));")
            val_hash.append(text_property_set_local[b][left_value:right_value])
            b = b + 1
        return val_hash


    def split_set_hashes(v_hash):
        c = 0
        hash_prop = []
        while c < len(v_hash):
            result = [x.strip() for x in v_hash[c].split(',')]
            hash_prop.append(result)
            c = c + 1
        return hash_prop


    def find_prop(indices_prop):
        prop_val2 = []
        prop_nam2 = []
        for lst in indices_prop:
            prop_val = []
            prop_nam = []
            for num in lst:
                if "IFCREAL" in ifc_file_data[num]:
                    left = ifc_file_data[num].find("IFCREAL") + 8
                    right = ifc_file_data[num].rfind("),")
                else:
                    left = ifc_file_data[num].find("IFCINTEGER") + 11
                    right = ifc_file_data[num].rfind("),")
                left_value = ifc_file_data[num].find("('") + 2
                right_value = ifc_file_data[num].find("',")
                prop_nam.append(ifc_file_data[num][left_value:right_value])
                prop_val.append(ifc_file_data[num][left:right])
            prop_val2.append(prop_val)
            prop_nam2.append(prop_nam)
        return prop_val2, prop_nam2


    def find_mat(mat_name):
        ind_mat = []
        for n3 in mat_name:
            ind_mat.append([za for za, s in enumerate(mat_name) if n3 in s])
        return ind_mat


    def replace_name(ind):
        left_v = fds_file_data[ind[0]].find("'") + 1
        right_v = fds_file_data[ind[0]].rfind("',") - 4
        old_name = fds_file_data[ind[0]][left_v:right_v]
```

```python
        dump_line = fds_file_data[ind[0]]
        dump_mod = dump_line.replace(old_name, new_name)
        return dump_mod


def find_hash_ml(txt_rel):
    b = 0
    val_hash = []
    while b < len(txt_rel):
        left_value = txt_rel[b].find("((") + 2
        right_value = txt_rel[b].find("),")
        val_hash.append(txt_rel[b][left_value:right_value])
        b = b + 1
    return val_hash


def find_hash_ml_set(txt_usage):
    b = 0
    val_hash = []
    while b < len(txt_usage):
        left_value = txt_usage[b].find("(#") + 1
        right_value = txt_usage[b].find(",")
        val_hash.append(txt_usage[b][left_value:right_value])
        b = b + 1
    return val_hash


def find_text_by_indices(indices_list, source_list):
    result_text = []
    for indx in indices_list:
        result_text.append(source_list[indx])
    return result_text


def element_to_value(element_type):
    indices_ifc_entities = [find_text_list(element_type)]
    ifc_entities_hash = find_entities_hash(indices_ifc_entities)
# Identifying material layer set hash
    property_set_hash = find_prop_set_hash(indices_ifc_entities)
# Identifying hash of property sets
    indices_property_set = find_indices(property_set_hash)
# Identifying indices of property sets
    text_property_set = find_text_set(indices_property_set)
# Identifying text of property sets
    prop_hash_set = find_hash_prop_val(text_property_set)
# Identifying set of hashes of property values
    hash_properties = split_set_hashes(prop_hash_set)
# splitting set of hashes of property values
    indices_properties = find_indices_list(hash_properties)
# Identifying indices of property values
    property_values, property_names = find_prop(indices_properties)
# Identifying name and values of properties
```

```python
    z = 0
    valid_prop_index = []
    while z < len(property_names):
        if "Heat Transfer Coefficient (U)" in property_names[z]:
            if "Thermal mass" in property_names[z]:
                valid_prop_index.append(z)
        z = z + 1

    valid_prop_name_local = find_text_by_indices(valid_prop_index,
property_names)
    valid_prop_value_local = find_text_by_indices(valid_prop_index,
property_values)
    valid_entity_hash_local = find_text_by_indices(valid_prop_index,
ifc_entities_hash)

    # Identifying U-value, Thermal mass from the list of properties
    u_found_local = thermal_property(valid_prop_name_local,
valid_prop_value_local, "Heat Transfer Coefficient (U)")
    tm_found_local = thermal_property(valid_prop_name_local,
valid_prop_value_local, "Thermal mass")

    return valid_entity_hash_local, u_found_local, tm_found_local


def get_prop_value(property_set_hash_local, ifc_entities_hash_local):
    indices_property_set = find_indices(property_set_hash_local)
# Identifying indices of property sets
    text_property_set = find_text_set(indices_property_set)
# Identifying text of property sets
    prop_hash_set = find_hash_prop_val(text_property_set)
# Identifying set of hashes of property values
    hash_properties = split_set_hashes(prop_hash_set)
# splitting set of hashes of property values
    indices_properties = find_indices_list(hash_properties)
# Identifying indices of property values
    property_values, property_names = find_prop(indices_properties)
# Identifying name and values of properties

    z = 0
    valid_prop_index = []
    while z < len(property_names):
        if "Heat Transfer Coefficient (U)" in property_names[z]:
            if "Thermal mass" in property_names[z]:
                valid_prop_index.append(z)
        z = z + 1

    valid_prop_name_local = find_text_by_indices(valid_prop_index,
property_names)
    valid_prop_value_local = find_text_by_indices(valid_prop_index,
property_values)
    valid_entity_hash_local = find_text_by_indices(valid_prop_index,
ifc_entities_hash_local)
```

```python
    # Identifying U-value, Thermal mass from the list of properties
    u_found_local = thermal_property(valid_prop_name_local,
valid_prop_value_local, "Heat Transfer Coefficient (U)")
    tm_found_local = thermal_property(valid_prop_name_local,
valid_prop_value_local, "Thermal mass")

    return valid_entity_hash_local, u_found_local, tm_found_local


def remove_duplicates(list_duplicates):
    ee = 0
    filtered = [list_duplicates[0]]
    while ee + 1 < len(list_duplicates):
        if list_duplicates[ee + 1] in filtered:
            ee = ee + 1
        else:
            filtered.append(list_duplicates[ee + 1])
            ee = ee + 1
    return filtered


def find_indices_text(texto):
    indices_set = []
    for n2 in texto:
        indices_set.extend(find_text_list(n2))
    return indices_set


def find_materials(hash_mlset_local, u_found_local, tm_found_local):
    mlset_hash_filtered = remove_duplicates(hash_mlset_local)
# removing duplicates of hashes of material layer sets

    indices_duplicates = []
    for text in mlset_hash_filtered:
# Identifying indices of material layer's duplicates
        indices_duplicates.extend(zc for zc, s in
enumerate(hash_mlset_local) if text in s)

    u_found_local_filtered = remove_duplicates([u_found_local[index] for
index in indices_duplicates])
    tm_found_local_filtered = remove_duplicates([tm_found_local[index] for
index in indices_duplicates])

    # similar
    indices_mls_local = find_indices(mlset_hash_filtered)
# Identifying indices of material layer sets
    text_mls_set_local = find_text_set(indices_mls_local)
# Identifying text of material layer sets
    hashes_ml_set_local = find_hash_ml(text_mls_set_local)
# Identifying set of hashes of material layers
    hash_material_layer_local = split_set_hashes(hashes_ml_set_local)
# splitting set of hashes of material layers
```

```python
    indices_material_layer_local =
find_indices_list(hash_material_layer_local)
# Identifying indices of material layer

    # Identifying material name and hash; and thickness
    material_hash_local, thick_local, material_layer_name_local =
find_material_layer_name(
        indices_material_layer_local)

    mat_hash_local = [item[0] for item in material_hash_local]
    indices_material_local = find_indices(mat_hash_local)
# Identifying indices of material
    ifc_materials_local = find_material_name(indices_material_local)
# Identifying material name

    return ifc_materials_local, u_found_local_filtered,
tm_found_local_filtered, material_layer_name_local, thick_local


# ########### Main:

# Input section:
ifc_file_data = read_file('Double_room_v4.ifc')
fds_file_data = read_file('Double_room_v4.fds')

# Process section:
# ********************For walls and slabs****************************
components_type = ['IFCWALLTYPE(', 'IFCSLABTYPE(']

valid_entity_hash = []
u_found_wl = []
tm_found_wl = []
for a in components_type:
    valid_entity_hash_r, u_found_r, tm_found_r = element_to_value(a)
    valid_entity_hash.extend(valid_entity_hash_r)
    u_found_wl.extend(u_found_r)
    tm_found_wl.extend(tm_found_r)

# Finding materials for walls and slabs:
indices_associates_material = find_text_list('IFCRELASSOCIATESMATERIAL(')
# Identify indices of Rel_Associates_material

rel_with_entity = find_rel_mls(indices_associates_material,
valid_entity_hash)
# Text of Rel_Associates... that contains hash entity

material_layer_set_hash = find_mls_hash(rel_with_entity)
# Identifying hash of material Layer set
indices_mls = find_indices(material_layer_set_hash)
# Identifying indices of material layer sets
text_mls_set = find_text_set(indices_mls)
# Identifying text of material layer sets
hashes_ml_set = find_hash_ml(text_mls_set)
```

```python
# Identifying set of hashes of material layers
hash_material_layer = split_set_hashes(hashes_ml_set)
# splitting set of hashes of material layers
indices_material_layer = find_indices_list(hash_material_layer)
# Identifying indices of material layer

# Identifying material name and hash; and thickness
material_hash_wl, thickness_wl, material_layer_name_wl =
find_material_layer_name(indices_material_layer)
mat_hash = [item[0] for item in material_hash_wl]
indices_material = find_indices(mat_hash)
# Identifying indices of material
ifc_Materials_wl = find_material_name(indices_material)
# Identifying material name

# **********************For ceilings********************************
components_type_cl = ['IFCCOVERINGTYPE(']
valid_entity_hash_cl = []
u_found_cl = []
tm_found_cl = []
for a in components_type_cl:
    valid_entity_hash_r, u_found_r, tm_found_r = element_to_value(a)
    valid_entity_hash_cl.extend(valid_entity_hash_r)
    u_found_cl.extend(u_found_r)
    tm_found_cl.extend(tm_found_r)

# Finding materials for ceilings:
indices_rel_def_type = find_text_list('IFCRELDEFINESBYTYPE(')
# Identify indices of Rel_Associates_material

rel_def_with_entity = find_rel_mls(indices_rel_def_type,
valid_entity_hash_cl)
# Text of Rel_defines... that contains hash entity for ceilings

ifccovering_hash = find_covering_hash(rel_def_with_entity)
# Identifying hash of IFCCOVERING

rel_with_entity_cl = find_rel_mls(indices_associates_material,
ifccovering_hash)
# Text of Rel_Associates... that contains ifccovering hash

material_layer_usage_hash = find_mls_hash(rel_with_entity_cl)
# Identifying hash of material Layer USAGE
indices_mlsu = find_indices(material_layer_usage_hash)
# Identifying indices of material layer set usage
text_mlsu_set = find_text_set(indices_mlsu)
# Identifying text of material layer usage
hash_mlset_cl = find_hash_ml_set(text_mlsu_set)
# Identifying hash of material layer sets

if len(hash_mlset_cl) == 0:
    print("No ceilings in this model")
    ifc_materials_cl = []
```

```
        u_found_cl_filtered = []
        tm_found_cl_filtered = []
        material_layer_name_cl = []
        thickness_cl = []
    else:
        ifc_materials_cl, u_found_cl_filtered, tm_found_cl_filtered,
material_layer_name_cl, thickness_cl = find_materials(
            hash_mlset_cl, u_found_cl, tm_found_cl)


    # ******************************For roofs:*******************************

    indices_roof_type = [find_text_list('IFCROOF(')]
    roof_hash = find_entities_hash(indices_roof_type)
    # Identifying roof hash
    indices_rel_def_property = find_text_list('IFCRELDEFINESBYPROPERTIES(')
    # Identify indices of Rel_Associates_material
    rel_def_with_entity = find_rel_mls(indices_rel_def_property, roof_hash)
    # Text of Rel_Associates... that contains hash entity

    indices_def_with_entity = find_indices_text(rel_def_with_entity)
    indices_analytical_prop = find_text_list('Analytical Properties(Type)')
    # Identify indices of Rel_Associates_material
    analytical_hash = find_analytical_hash(indices_analytical_prop)
    # Identifying hash of analytical properties
    rel_def_with_analytical = find_rel_mls(indices_def_with_entity,
    analytical_hash)
    # Text of Rel_Associates... that contains analytical hash

    prop_set_hash_rf = find_mls_hash(rel_def_with_analytical)
    # Identifying hash of IFC property set Analytical

    prop_set_hash_roofs = []
    for hash_num in roof_hash:
        for text_rel in rel_def_with_analytical:
            if hash_num in text_rel:

    prop_set_hash_roofs.append(prop_set_hash_rf[rel_def_with_analytical.index(t
    ext_rel)])

    valid_entity_hash_rf, u_found_rf, tm_found_rf =
    get_prop_value(prop_set_hash_roofs, roof_hash)

    # Finding materials for roofs:
    indices_rel_aggregates = find_text_list('IFCRELAGGREGATES(')
    # Identify indices of Rel_aggregates
    rel_agg_with_entity = find_rel_mls(indices_rel_aggregates,
    valid_entity_hash_rf)
    # Text of Rel_aggregates... that contains hash entity for roofs
    slab_hash = find_slab_hash(rel_agg_with_entity)
    # Identifying hash of ifcslab
    rel_with_slab = find_rel_mls(indices_associates_material, slab_hash)
    # Text of Rel_Associates... that contains slab hash
    hash_mlset_rf = find_mls_hash(rel_with_slab)
```

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```python
# Identifying hash of material Layer

if len(hash_mlset_rf) == 0:
    print("No roofs in this model")
    ifc_materials_rf = []
    u_found_rf_filtered = []
    tm_found_rf_filtered = []
    material_layer_name_rf = []
    thickness_rf = []
else:
    ifc_materials_rf, u_found_rf_filtered, tm_found_rf_filtered,
material_layer_name_rf, thickness_rf = find_materials(
        hash_mlset_rf, u_found_rf, tm_found_rf)


# _____


# Defining a density per material layer

material_layer_names = (material_layer_name_wl + material_layer_name_cl +
material_layer_name_rf)

density_found2 = []
for gr in material_layer_names:
    density_found = []
    for i in gr:
        density_found.append(find_density(i))
    density_found2.append(density_found)

thicknesses = (thickness_wl + thickness_cl + thickness_rf)

width = list(map(sum, thicknesses))

aa = 0
t_x_d = []
while aa < len(density_found2):
    thickness_x_density = [a * b for a, b in zip(thicknesses[aa],
density_found2[aa])]
    t_x_d.append(thickness_x_density)
    aa = aa + 1

sum_txd = list(map(sum, t_x_d))

weighted_average_density = [d / f for d, f in zip(sum_txd, width)]

u_found = (u_found_wl + u_found_cl_filtered + u_found_rf_filtered)
tm_found = (tm_found_wl + tm_found_cl_filtered + tm_found_rf_filtered)
IFC_Materials = (ifc_Materials_wl + ifc_materials_cl + ifc_materials_rf)

# Calculating Thermal Conductivity and Specific heat per material layer
thermal_conductivity = [a * b for a, b in zip(width, u_found)]
specific_heat = [a / (b * c * 1000) for a, b, c in zip(tm_found, width,
weighted_average_density)]
```

```
# ######## Output section

print("Material", '\t', "Cond", '\t', "Sp_h", '\t'"Thick", '\t'" Dens")  #
table column headings
print("--------", '\t', "----", '\t', "----", '\t', "----", '\t', "----")
t = 0
while t < (len(IFC_Materials)):
    print(IFC_Materials[t][0:10], '\t', "%.3f" % thermal_conductivity[t],
'\t', "%.3f" % specific_heat[t], '\t',
          "%.3f" % width[t], '\t', "%.3f" % weighted_average_density[t])
    t = t + 1

indices_surface = find_text_list_fds('&SURF ID=')
indices_reaction = find_text_list_fds('&REAC ID=')
index_end_line = find_text_list_fds('/')

end_line = ()
for g in index_end_line:
    if g < indices_surface[0]:
        if g > indices_reaction[0]:
            end_line = g + 1

indices_mat = find_mat(IFC_Materials)

cc = 0
while cc < len(IFC_Materials):
    fds_file_data.insert(end_line, "\n&MATL ID='" + IFC_Materials[cc] +
"',\n" "\tSPECIFIC_HEAT=" + str(
        specific_heat[cc]) + ",\n""\tCONDUCTIVITY=" +
str(thermal_conductivity[cc]) + ",\n""\tDENSITY=" + str(
        weighted_average_density[cc]) + "/\n")
    cc = cc + 1

indices_surface = find_text_list_fds('&SURF ID=')

j = 0
for n4 in indices_surface:
    h = 0
    while h < len(IFC_Materials):
        if "'" + IFC_Materials[h] + "'" in fds_file_data[n4 + j]:
            fds_file_data.insert(n4 + 1 + j,
"\tBACKING='VOID',\n\tMATL_ID(1,1)='" + IFC_Materials[
                h] + "',\n\tMATL_MASS_FRACTION(1,1)=1.0,\n\tTHICKNESS(1)="
+ str(width[h]) + ",\n")
            j = j + 1
        h = h + 1

new_name = 'two_room'
index_head = find_text_list_fds('&HEAD CHID=')
fds_file_data[index_head[0]] = "&HEAD CHID='" + new_name + "'/\n"
dump_index = find_text_list_fds('DUMP RENDER_FILE')
fds_file_data[dump_index[0]] = replace_name(dump_index)
```

```python
fds_file_data[0] = new_name + ".fds\n"

directory_local = './' + new_name
try:
    os.makedirs(directory_local)
except OSError as exception:
    if exception.errno != errno.EEXIST:
        raise
    else:
        print("\nBE CAREFUL! Directory %s already exists." %
directory_local)

fds_new_file = open(directory_local + "/" + new_name + ".fds", "w")
for lines in fds_file_data:
    fds_new_file.write(lines)

fds_new_file.close()
```

11.7 FDS input file for the Basic Building

(Text in blue colour was scripted with the tool created in the Python programming language)

```
iso_room.fds
Generated by PyroSim - Version 2018.3.1210
Apr 17, 2019 6:56:28 PM

&HEAD CHID='iso_room'/
&TIME T_END=300.0/
&DUMP RENDER_FILE='iso_room.ge1', COLUMN_DUMP_LIMIT=.TRUE.,
DT_RESTART=300.0, DT_SL3D=0.25/

&MESH ID='MESH', IJK=52,96,58, XB=0.0,2.6,-1.0,3.8,-0.3,2.6/

&REAC ID='PMMA',
      FYI='SFPE Handbook, 3rd Edition',
      FUEL='REAC_FUEL',
      C=1.0,
      H=1.6,
      O=0.4,
      CO_YIELD=0.01,
      SOOT_YIELD=0.022/

&MATL ID='Concrete, Cast In Situ',
      SPECIFIC_HEAT=0.657,
      CONDUCTIVITY=1.046,
      DENSITY=2300.0/
&MATL ID='Concrete, Cast In Situ(1)',
      SPECIFIC_HEAT=0.657,
      CONDUCTIVITY=1.046000000000001,
      DENSITY=2300.0/
&MATL ID='Brick, Common',
      SPECIFIC_HEAT=0.84,
      CONDUCTIVITY=0.54,
      DENSITY=1550.0/

&SURF ID='Concrete, Cast In Situ(1)',
      BACKING='VOID',
      MATL_ID(1,1)='Concrete, Cast In Situ(1)',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.3,
      COLOR='SILVER'/
&SURF ID='Brick, Common',
      BACKING='VOID',
      MATL_ID(1,1)='Brick, Common',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.1,
      RGB=170,100,105/
&SURF ID='Concrete, Cast In Situ',
      BACKING='VOID',
      MATL_ID(1,1)='Concrete, Cast In Situ',
      MATL_MASS_FRACTION(1,1)=1.0,
```

```
        THICKNESS(1)=0.2,
      COLOR='SILVER'/
&SURF ID='Fire',
      COLOR='RED',
      HRRPUA=1000.0,
      TMP_FRONT=300.0/

&OBST ID='Obstruction', XB=0.1,0.6,3.5,3.7,0.0,0.1, SURF_ID='INERT'/
&OBST ID='Floor:Concrete_floor_0.3m:294747', XB=0.0,2.6,2.914335E-16,3.8,-
0.3,-4.163336E-17, COLOR='SILVER', SURF_ID='Concrete, Cast In Situ(1)'/
&OBST ID='Basic Wall:Brick_Wall_0.1m:293994', XB=0.0,2.5,3.7,3.8,-
4.163336E-17,2.4, RGB=170,100,105, SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.1m:293995', XB=0.0,0.1,2.914335E-16,3.7,-
4.163336E-17,2.4, RGB=170,100,105, SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.1m:293996', XB=0.1,0.9,2.914335E-16,0.1,-
4.163336E-17,2.4, RGB=170,100,105, SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.1m:293996', XB=0.9,1.7,2.914335E-
16,0.1,2.0,2.4, RGB=170,100,105, SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.1m:293996', XB=1.7,2.6,2.914335E-16,0.1,-
4.163336E-17,2.4, RGB=170,100,105, SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.1m:293997', XB=2.5,2.6,0.1,3.8,-
4.163336E-17,2.4, RGB=170,100,105, SURF_ID='Brick, Common'/
&OBST ID='Floor:Concrete_floor_0.2m:294779', XB=0.0,2.6,2.914335E-
16,3.8,2.4,2.6, COLOR='SILVER', SURF_ID='Concrete, Cast In Situ'/

&VENT ID='Mesh Vent: MESH [XMAX]', SURF_ID='OPEN', XB=2.6,2.6,-1.0,3.8,-
0.3,2.6/
&VENT ID='Mesh Vent: MESH [XMIN]', SURF_ID='OPEN', XB=0.0,0.0,-1.0,3.8,-
0.3,2.6/
&VENT ID='Mesh Vent: MESH [YMAX]', SURF_ID='OPEN', XB=0.0,2.6,3.8,3.8,-
0.3,2.6/
&VENT ID='Mesh Vent: MESH [YMIN]', SURF_ID='OPEN', XB=0.0,2.6,-1.0,-1.0,-
0.3,2.6/
&VENT ID='Mesh Vent: MESH [ZMAX]', SURF_ID='OPEN', XB=0.0,2.6,-
1.0,3.8,2.6,2.6/
&VENT ID='Mesh Vent: MESH [ZMIN]', SURF_ID='OPEN', XB=0.0,2.6,-1.0,3.8,-
0.3,-0.3/
&VENT ID='Fire', SURF_ID='Fire', XB=0.1,0.6,3.5,3.7,0.1,0.1/

&BNDF QUANTITY='WALL TEMPERATURE'/
&SLCF QUANTITY='TEMPERATURE', PBZ=2.0/
&SLCF QUANTITY='TEMPERATURE', PBY=1.9/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBZ=2.0/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=1.9/
&SLCF QUANTITY='TEMPERATURE', PBX=1.3/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBX=1.3/
&SLCF QUANTITY='TEMPERATURE', PBY=3.6/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=3.6/
&SLCF QUANTITY='VISIBILITY', PBZ=2.0/
&SLCF QUANTITY='VISIBILITY', PBY=1.9/
&SLCF QUANTITY='VISIBILITY', PBX=1.3/
&SLCF QUANTITY='VISIBILITY', PBY=3.6/
&TAIL /
```

11.8 FDS input file for the Two-room Building

(Text in blue colour was scripted with the tool created in the Python programming language)

```
two_room.fds
Generated by PyroSim - Version 2018.3.1210
Apr 17, 2019 7:03:32 PM

&HEAD CHID='two_room'/
&TIME T_END=300.0/
&DUMP RENDER_FILE='two_room.ge1', COLUMN_DUMP_LIMIT=.TRUE.,
DT_RESTART=300.0, DT_SL3D=0.25/

&MESH ID='MESH', IJK=52,96,58, XB=-0.098,2.502,-0.998,3.802,-0.3,2.6/
&MESH ID='MESH01', IJK=26,48,29, XB=2.502,5.102,-0.998,3.802,-0.3,2.6/

&REAC ID='PMMA',
      FYI='SFPE Handbook, 3rd Edition',
      FUEL='REAC_FUEL',
      C=1.0,
      H=1.6,
      O=0.4,
      CO_YIELD=0.01,
      SOOT_YIELD=0.022/

&MATL ID='Concrete, Cast In Situ',
      SPECIFIC_HEAT=0.657,
      CONDUCTIVITY=1.046,
      DENSITY=2300.0/

&MATL ID='Concrete, Cast In Situ(1)',
      SPECIFIC_HEAT=0.657,
      CONDUCTIVITY=1.046000000000001,
      DENSITY=2300.0/

&MATL ID='Brick, Common',
      SPECIFIC_HEAT=0.84,
      CONDUCTIVITY=0.539999999999996,
      DENSITY=1550.0/

&SURF ID='Door - Frame',
      RGB=118,70,51/
&SURF ID='Door - Panel',
      RGB=210,159,95/
&SURF ID='Concrete, Cast In Situ(1)',
      BACKING='VOID',
      MATL_ID(1,1)='Concrete, Cast In Situ(1)',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.3,
      COLOR='SILVER'/
&SURF ID='Brick, Common',
      BACKING='VOID',
      MATL_ID(1,1)='Brick, Common',
```

```
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.102,
      RGB=170,100,105/
&SURF ID='IfcWindow',
      RGB=173,216,229,
      TRANSPARENCY=0.501961/
&SURF ID='Concrete, Cast In Situ',
      BACKING='VOID',
      MATL_ID(1,1)='Concrete, Cast In Situ',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.2,
      COLOR='SILVER'/
&SURF ID='Fire',
      COLOR='RED',
      HRRPUA=1000.0,
      TMP_FRONT=300.0/

&OBST ID='Obstruction', XB=0.102,1.102,3.202,3.702,0.0,0.1,
SURF_ID='INERT'/
&OBST ID='M_Single-Flush:800 x 2000:298428', XB=0.802,0.852,-0.048,2.0E-3,-
4.163336E-17,2.1, RGB=118,70,51, SURF_ID='Door - Frame'/
&OBST ID='M_Single-Flush:800 x 2000:298428', XB=0.852,1.652,2.0E-3,0.052,-
4.163336E-17,2.0, RGB=210,159,95, SURF_ID='Door - Panel'/
&OBST ID='M_Single-Flush:800 x 2000:298428', XB=0.852,1.652,-0.048,2.0E-
3,2.0,2.1, RGB=118,70,51, SURF_ID='Door - Frame'/
&OBST ID='M_Single-Flush:800 x 2000:298428', XB=1.652,1.752,-0.048,2.0E-3,-
4.163336E-17,2.1, RGB=118,70,51, SURF_ID='Door - Frame'/
&OBST ID='M_Single-Flush:800 x 2000:298428', XB=0.802,0.852,0.102,0.102,-
4.163336E-17,2.1, RGB=118,70,51, SURF_ID='Door - Frame'/
&OBST ID='M_Single-Flush:800 x 2000:298428',
XB=0.852,1.652,0.102,0.102,2.0,2.1, RGB=118,70,51, SURF_ID='Door - Frame'/
&OBST ID='M_Single-Flush:800 x 2000:298428', XB=1.652,1.752,0.102,0.102,-
4.163336E-17,2.1, RGB=118,70,51, SURF_ID='Door - Frame'/
&OBST ID='Floor:Concrete_floor_0.3m:294747', XB=2.0E-3,2.502,2.0E-3,3.802,-
0.3,-4.163336E-17, COLOR='SILVER', SURF_ID='Concrete, Cast In Situ(1)'/
&OBST ID='Floor:Concrete_floor_0.3m:294747', XB=2.502,5.102,2.0E-3,3.802,-
0.3,-2.775558E-17, COLOR='SILVER', SURF_ID='Concrete, Cast In Situ(1)'/
&OBST ID='Basic Wall:Brick_Wall_0.102m:293994',
XB=2.502,5.002,3.702,3.802,-2.775558E-17,2.4, RGB=170,100,105,
SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.102m:293995',
XB=2.502,2.602,0.902,2.902,-2.775558E-17,1.0, RGB=170,100,105,
SURF_ID='Brick, Common'/
&OBST ID='Basic Wall:Brick_Wall_0.102m:293995', XB=2.502,2.602,2.0E-
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Common'/
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Common'/
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Common'/
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SURF_ID='IfcWindow'/
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SURF_ID='IfcWindow'/
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SURF_ID='IfcWindow'/
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0.998,3.802,-0.3,-0.3/
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