Integrating Fire Evacuation into the Building Information Modelling Workflow

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Abstract
Building Information Modelling (BIM) is arising gradually as a useful methodology in the AEC field. One of the many benefits of BIM is coordination between stakeholders from multiple disciplines. However, the field of Fire Safety Engineering (FSE) is relatively lagging by its lack of integration into this digital workflow (Chevin, 2020). This lack of integration increases the efforts needed to evaluate the designs and hinders possible collaboration of parties undertaking projects. It also causes a fragmentation of the design and review processes which may result in data loss, inconsistent documentation and ambiguity in roles and responsibilities, and ultimately lead to life safety issues and property damage.

In order to address these gaps, this thesis proposes to develop a framework for smoothly integrating FSE into BIM-authoring tools, with a specific focus on evacuation. Through this framework, the potential for exchange and collaboration is leveraged by embedding prescriptive requirements and evacuation simulation data into a shared BIM model. This will enable professionals and authorities to review building design models coupled with analysis results and perform more efficient and comprehensive assessments.

Ultimately, this will result in the creation of a full data loop linking BIM platforms and evacuation assessment tools and the implementation of a digital record, referred to as the "golden thread of information".

In this report, a number of developments by the author are discussed, which include establishing a technical framework and associated data exchange formats from an FSE perspective. Additionally, the benefits of two-way data flow between BIM and fire evacuation assessment tools are demonstrated by implementing a prototype system for coupling Revit, a popular BIM platform, and Pathfinder, a widely used evacuation simulator.

The work presented in this paper provides a practical demonstration for the integration of fire evacuation into BIM and will contribute to the ongoing efforts of the community in support for FSE and occupant movement data exchange.

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Abstract

Building Information Modelling (BIM) is arising gradually as a useful methodology in the AEC field. One of the many benefits of BIM is coordination between stakeholders from multiple disciplines. However, the field of Fire Safety Engineering (FSE) is relatively lagging by its lack of integration into this digital workflow (Chevin, 2020). This lack of integration increases the efforts needed to evaluate the designs and hinders possible collaboration of parties undertaking projects. It also causes a fragmentation of the design and review processes which may result in data loss, inconsistent documentation and ambiguity in roles and responsibilities, and ultimately lead to life safety issues and property damage.

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الملخص

تظهر نمذجة معلومات البناء (BIM) تدريجياً كمنهجية مفيدة في مجال الهندسة المعمارية و من فوائدها التنسيق بين المتخصصين. ومع ذلك ، فإن مجال هندسة السلامة من الحرائق متأخر نسبيًا بسبب عدم تكامله مع هذه المنهجية الرقمية. وهذا يزيد من الجهود اللازمة لتقييم التصاميم يعيق إمكانية التعاون بين الأطراف التي تقوم بتنفيذ المشاريع. وقد يتسبب أيضًا في تجزئة عمليات التصميم والمراجعة مما يؤدي إلى فقدان البيانات وعدم اتساق التوثيق والغموض في الأدوار والمسؤوليات.

من أجل معالجة هذه الثغرات ، تقترح هذه الأطروحة تطوير إطار عمل لدمج أدوات تأليف BIM مع هندسة السلامة من الحرائق ، مع التركيز بشكل خاص على الإخلاء من الحرائق. في هذا الإطار ، يتم تعزيز إمكانية التبادل والتعاون من خلال تضمين المتطلبات الإلزامية وبيانات محاكاة الإخلاء في نموذج BIM مشترك. سيمكن ذلك المهنيين والسلطات من مراجعة نماذج تصميم المباني المقترنة بنتائج التحليل وإجراء تقييمات أكثر كفاءة وشمولية.
في النهاية ، سينتج عن ذلك إنشاء حلقة بيانات متكاملة تربط بين منصات BIM وأدوات تقييم الإخلاء و كذا إنشاء سجل رقمي ، يشار إليه بالخيط الذهبي للمعلومات.

تمت مناقشة عدد من التطورات من قبل المؤلف ، والتي تشمل إنشاء إطار تقني وتنسيق تبادل البيانات المرتبطة بها من منظور هندسة السلامة من الحرائق.
بالإضافة إلى ذلك ، يتم إبراز فوائد تدفق البيانات ثنائي الاتجاه بين BIM وأدوات تقييم الإخلاء من خلال تصميم نموذج أولي لربط Revit (منصة BIM شائعة) و Pathfinder ، وهو منصة محاكاة إخلاء مستخدم على نطاق واسع.

يقدم هذا العمل عرضًا عمليًا لدمج الإخلاء من الحرائق في BIM ويساهم في مشروع buildingSMART الذي يهدف لتعزيز تكامل السلامة من الحرائق في BIM.

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
API	Application Programming Interface
ASET	Available Safe Escape Time
BIM	Building Information Modelling
CAD	Computer-Aided Design
FSE	Fire Safety Engineering
IDE	Integrated Development Environment
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
RSET	Required Safe Escape Time
SI	International System of Units
UI	User Interface

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1. INTRODUCTION

1.1 Background and motivation

Building Information Modeling (BIM) is arising gradually as a useful methodology in the AEC field and is seeing a rapid expansion in uptake across the globe. In fact, it is replacing CAD and becoming a mandated requirement for government-funded projects in many countries (Paul, 2018).

One of the many benefits of BIM is coordination between stakeholders from multiple disciplines. However, the field of Fire Safety Engineering is relatively lagging by its lack of integration into this digital workflow (Chevin, 2020). This lack of integration increases the efforts needed to evaluate the designs, which causes those evaluations to be delayed up to when it can potentially be expensive and difficult to perform adjustments. It also hinders possible collaboration of parties undertaking projects and causes a fragmentation of the design and review processes which may result in inconsistent documentation and ambiguity in roles and responsibilities. This can ultimately lead to safety issues.

Recently, the International Fire Safety Standards (IFSS), a worldwide coalition of over 80 fire safety organizations, has launched a 'Decade of Action for Fire Safety 2022-2032', which aims to ensure a global approach to the fire safety of buildings and infrastructures, in line with the UN Sustainable Development Goals (IFSS, 2021). In this plan, the IFSS calls for "a framework to support audits, compliance checks and global standards" and suggests to "Improve the quality of fire safety data collected" and "promote the use of effective code-checking and inspection systems and technology" as keys actions supporting fire safety in buildings (IFSS, 2021).

Moreover, the Hackitt report (Hackitt, 2018), in response to the Grenfell Tower fire, established the need for a "Golden Thread of Information" as a mean to prevent life and property loss by keeping track of design and maintenance data of a building throughout its life cycle.

However, this is yet to be achieved. A recent paper (A. A. Siddiqui et al., 2021) highlights limitations in the current BIM workflow which can obstruct the implementation of the "golden thread of information" for fire safety engineering. These include the inability to capture, display and store data generated by FSE assessment tools (such as fire or evacuation simulations). Furthermore, data exchange protocols lack the support for FSE discipline, and this can be a source of conflicts, data loss and frustration among stakeholders.

For instance, an architect and a fire consultant may use different formats (nomenclature, units, etc.) to store and process FSE related data in their undertaking (such as evacuation component dimensions, simulation output, etc.) which could impede their cooperation.

Furthermore, an asset manager overseeing multiple building projects will have difficulties consolidating data if it is not stored in a standard format. This is especially true for government authorities managing public buildings at the level of a town, region, or even a whole country.

In order to address these limitations, this thesis aims to develop a framework for smoothly integrating FSE into BIM-authoring tools, with a specific focus on evacuation. A prototype will be implemented, coupling Revit, a BIM software platform (Autodesk, 2022c), to Pathfinder (Thunderhead Engineering, 2022), an evacuation modelling tool. This research will also enhance the workflow of FSE by allowing designers to evaluate compliance of building designs with prescriptive requirements.

The potential for exchange and collaboration between stakeholders is leveraged by embedding prescriptive requirements and evacuation simulation data into a shared BIM model. This will enable professionals and authorities to review building design models coupled with analysis results allowing them to perform more efficient and comprehensive assessments.

Ultimately, this will result in the creation of a full data loop between the BIM platform (Revit) and evacuation assessment tools allowing to pass input parameter and calculation results between them and achieving the “golden thread of information”.

The prototype tools developed in the context of this thesis will be open-source and accessible for the FSE community and will contribute to the international project initiated by buildingSMART (The BIM standard organization) to support FSE and occupant movement data exchange (buildingSMART, 2020).

1.2 Objectives

In the previous section, the need for a framework that enhances the FSE workflow and improves its integration with BIM was highlighted. This thesis will focus essentially on the occupant evacuation aspect of Fire Safety Engineering in order to maintain the project scope in line with the thesis timeframe. The main research question is: "**For fire safety engineers, how can we solve the current disconnect between BIM and evacuation assessment tools in order to join up a workflow and achieve a "Golden Thread of Information"?**

In order to answer this question, a set of objectives was determined. These objectives aim to address both the prescriptive and performance-based workflows (described in Chapter 2).

1. Identify, evaluate, and select key properties related to evacuation from a Revit BIM model that are required for prescriptive checks of acceptable quality (e.g., door widths, travel paths, etc.). This will be based on a set of prescriptive rules selected from the International Building Code (International Code Council, 2018).

2. Identify key inputs and outputs that are imported to/from evacuation simulation tools.

3. Draft a proposal for a data schema that enables exchange and sharing of evacuation safety information identified in steps 1 and 2. This schema will provide a standard format (i.e properties names, units, etc.) to ensure synergy between the different tools.

4. Prototype an add-in package for Revit, which will implement the coupling of the BIM model in Revit with fire evacuation assessment tools. Data exchanged between these tools will be structured according to the data schema proposed in step 3.

5. Evaluate the tool to ensure the integrity of assessment data that is being transferred.

The proposed Revit add-in will also include a prototype of automated prescriptive code reviewer, based on the IBC code, in order to generate data related to prescriptive checks. This will showcase data exchange and processing between BIM and prescriptive assessment tools.

1.3 Methodology

In order to tackle the objectives of this study, a methodology consisting of 4 main steps was implemented. These steps are covered in Chapters 2 to 5 of this report, and can be broken down as follows:

- Literature review
First, in Chapter 2, a literature review was carried out to gather information on BIM and FSE workflows. At the highest level, the points of data loss in the current workflow were investigated as the latest tools do not yet support comprehensive data exchange between BIM and evacuation assessment tools. This led to the identification of suitable data points and parameters required for prescriptive and performance fire evacuation assessment as well as outputs from such assessments.

- Establishing a technical framework
Next, a framework was proposed in Chapter 3 to establish a data loop, linking between Revit BIM and assessment tools. In this framework, input properties will be transferred from the BIM model to the assessment tool and the results will be captured and sent back to the model.

The Industry Foundation Class (IFC) (buildingSMART, 2022a) was retained as a vendor-neutral format for data exchange between these nodes. For this purpose, a data schema was drafted in line with the specifications of IFC to store the data points previously identified in Chapter 2 in a proper format. This will help preserve data integrity, ensure proper coordination, and avoid any conflicts or data loss.

This data framework was based on rough pre-existing draft definitions (Abualdenien et al., 2021; A. A. Siddiqui, 2019) that were extended in collaboration with these authors.

- Prototyping the technical framework
To implement the proposed framework and subsequent IFC data schema, an add-in was developed using the Revit Application Programming Interface (Autodesk, 2022b) to extract data automatically from any BIM model (e.g., Door / staircase widths, corridor length, occupancy…), add user input, and store output from evacuation assessment tools.

The add-in also enables the possibility to visualize assessment results within the Revit interface (through graphs, schedules, and annotations). This allows for a quick reassessment and tracking of code compliance and evacuation performance as the design evolves from early to later stages.

- Evaluation and discussion
Finally in Chapter 4, the add-in was tested to ensure the integrity of exchanged data and the correctness of the prescriptive checks that are performed. The discussion is presented in Chapter 5.

1.4 Scope and limitations

This study focuses on the occupant evacuation aspect of fire safety engineering. Both performance and prescriptive approaches are considered as they are well established and widely used (Kirchen, 2018).

For the prescriptive approach, design rules for evacuation are considered, such as the geometric form and limitations to egress components (maximum length of routes, component width, flow capacities, number of exits, etc.). Therefore, specifications related to fire protection (active and passive), or structural integrity are not included.

Regarding the performance-based approach which typically involves running simulations, the various evacuation simulation packages in the market generate outputs in different formats, which makes it difficult to develop a generic prototype that natively supports all of these tools. This study focuses on processing the data produced by Pathfinder, an agent based simulator (Thunderhead Engineering, 2022). It can be adapted in the future to support additional packages.

Selected software and standards

In the beginning of this research, the choice was made to narrow down the scope of the project into using specific tools and standards given the limited timeframe of the thesis.

First, Revit was chosen as a BIM platform. This is because it is widely used according to surveys (NBS Enterprises, 2022) but also because it offers the possibility for developers to extend its capabilities and add more features by developing add-in applications through a dedicated Application Programming Interface (API) (Autodesk, 2022b). This API will be employed to prototype the add-in package described in the objectives.

Regarding fire evacuation assessment tools, Pathfinder was chosen as a “model” evacuation simulator because it is one of the most used solutions in the market (Lovreglio et al., 2020) and offers comprehensive documentation online (Thunderhead Engineering, 2022).

Finally, the IBC code was selected to implement the prescriptive reviews because it is well documented, and the full text is available in English and openly accessible online (International Code Council, 2022a). It is widely adopted in the USA where it serves as a reference for several local codes (International Code Council, 2022b).

2. LITTERATURE REVIEW

In this chapter, a literature review is carried out to gather information on the BIM and FSE workflows. In order to set the context of this research, key concepts are developed highlighting the limitations of current workflow and areas of improvement. Moreover, data points required in evacuation assessments are analyzed and presented, covering both input and output parameters.

2.1 The “Golden thread of information”

The Grenfell Tower fire that occurred on June 2017 in London, resulting in 72 deaths, sparked a large debate regarding the established construction practices (‘Grenfell Tower Fire’, 2022).

The Hackitt Report (Hackitt, 2018) was commissioned by the UK Government and unveiled a series of failings of the construction sector. In particular, the fire safety compliance assessment process was described as "weak and complex” and characterized by “poor record keeping and change control" (Hackitt, 2018).

Therefore, the authors of the report recommend the implementation of a “golden thread of information” embedded throughout the entire building lifecycle, to serve as a digital record. This was upheld by the IFSS coalition in its "Decade of Action" where it called for this principle to be enacted (IFSS, 2021).

The goal of this digital record is to store information about a building, from the initial design intent to the final built state, including decisions and modifications meant to improve the safety of the building (Li et al., 2020). According to the Hackitt report (Hackitt, 2018), this digital record helps ensure the owner documents the fire strategy for the building and why the safety precautions have been considered in the first place. This is because the development of a building project is often a collective effort between specialists from different disciplines. So the ability to deliver the required information, on request, and in the right format can be crucial to the success of the construction project (Li et al., 2020).

The implementation of the golden thread of information can help enforce regulations, and prevent a fragmentation of processes and systems resulting in safety issues, inconsistent documentation and ambiguity in roles and responsibilities (Li et al., 2020). Moreover, Jylhä and Suvanto state that “if the information is poor, the actions that are based on (this) information are also wrong”, and this can have a negative impact on the construction and maintenance processes (Jylhä & Suvanto, 2015).

2.2 Building Information Modelling (BIM)

Building Information Modelling can be described as a process of creating a virtual model of a building by combining physical objects and information (A. A. Siddiqui, 2019). It enables the collaboration of architects, engineers and contractors who exchange data on the design, construction, maintenance, and management of the building. In fact, BIM is formally defined in the standard ISO 19650-1 as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes" (ISO, 2018a)

2.2.1 Adoption

There is a disparity in the adoption of BIM across the world. Some pioneering countries went as far as imposing mandates to use BIM for certain types of projects such as Germany (for new transportation projects), states in the USA as well as France, UK and Scandinavian countries who have published standards (Lorek, 2018). In 2015, a survey (Jung & Lee, 2015) reported that the usage of BIM was quite established in Europe, Asia and North America while the Middle East/Africa and South America have just started adopting it.

While BIM is becoming popular in the architecture and construction industry, some engineering disciplines, particularly fire safety, are still lagging. A study (McAlinden, 2019) pointed at a few sources of error in AEC projects, including the lack of input from other disciplines, in addition to issues when exchanging information across disciplines and between software systems. These limitations apply to fire evacuation assessment tools such as evacuation simulators.

2.2.2 Benefits and issues

A list of benefits of BIM was compiled by (A. A. Siddiqui, 2019) and is reported in this section.

Firstly, a BIM model combines the geometry and information regarding materials and several aspects. Thus, it can centralize all knowledge about a building throughout its life cycle. This makes it a good fit to support the idea of an embedded "golden thread" of information recommended by the Hackitt Report (Hackitt, 2018).

BIM also facilitates the collaboration between stakeholders who can work on a shared 3D model to report their findings.

Moreover, BIM can be used to manage the entire lifecycle of a building. Through customized enhancements, BIM processes are able to include and maintain the data for all core aspects of an end-to-end AEC design workflow. This particular feature will be leveraged in this research to embed properties related to the fire evacuation in the BIM model.

Finally, employing BIM in a construction project can result in reduced waste and lower costs, thanks to advanced scheduling, careful planning, and clash detection capabilities. In this regard, a study in the USA indicated net savings up to 5% of construction costs (DBIS, 2011). Consequently, the UK Government's Construction Vision (Cabinet Office, 2011) aims to achieve lower costs, faster delivery and lower emissions thanks to the adoption of BIM.

Therefore, by improving the integration of FSE into the BIM workflow, this discipline could also benefit from these advantages and increased productivity.

On the other hand, several limitations have been reported such as increased development costs, high expertise required from staff members and model ownership.

2.2.3 Evolution of BIM

In 2008, Bew and Richards introduced a "roadmap of BIM evolution", which sets out the goals for the future development of BIM (Bew & Richards, 2008). They divide the evolution of BIM into 4 successive stages. The initial stage (Level 0) relates to 2D CAD while Level 1 saw the early adoption of BIM (a combination of 3D and 2D CAD). In Level 2, stakeholders collaborate on a project by sharing common resources. Currently, the AEC industry is generally acknowledged to be moving towards Level 2 (A. A. Siddiqui et al., 2021). In the future, moving into Level 3 will be achieved by sharing a fully integrated single BIM model held on a centralized cloud repository.

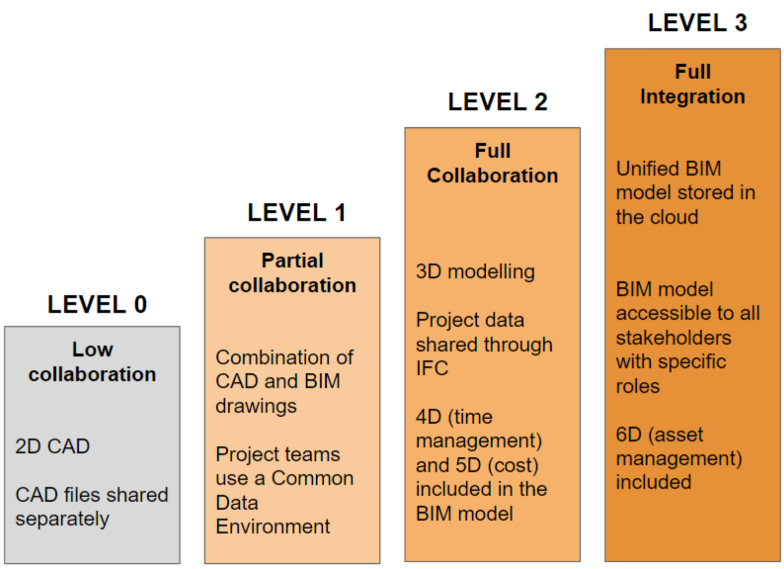


Figure 1 – BIM Maturity Levels
Adapted from (ACCAsoftware, 2019)

This project aims to put FSE in line with the efforts aiming to progress BIM into higher levels of integration by integrating fire evacuation into this digital workflow.

2.2.4 Autodesk Revit

Autodesk Revit is a Building Information Modelling software platform developed by Autodesk (Autodesk, 2022c). It is used to plan, design, and manage buildings and infrastructure. Currently, it is one of the most used BIM solution in the AEC industry (NBS Enterprises, 2022).

Revit offers useful capabilities for professionals since it facilitates tasks such as 3D drawing and rendering, detecting clashes, establishing quantity take-offs, cost estimation, and generating construction schedules (Autodesk, 2022c).

In this research, Autodesk Revit 2022 will be employed as the main BIM platform for prototyping FSE evacuation data exchange.

Revit API

A.P.I. is the acronym for "application programming interface". It is used by software developers to interact with an existing piece of software and access functionalities and stored data.

Autodesk Revit provides a powerful API which can be used in automating repetitive tasks, extending the core functionalities of Revit as well as reading and writing information related to objects in the model (such as doors, stairs, rooms, etc.).

In this research, the Revit API will enable the prototyping of an add-in and help implement a technical framework to extract data required by assessment tools and store assessment results.

2.3 FSE Workflow and Data Exchange

2.3.1 Fire Safety Engineering

Fire Safety Engineering is a safety support discipline. It is formally defined as "an application of scientific and engineering principles to the protection of people, property and the environment from fire" (BSI, 2002).

FSE requires a wide range of building-specific data from other disciplines and utilizes fire, evacuation, and structural modelling tools to perform assessments. Moreover, results of such assessments need to be communicated to architects, owners, and authorities to have the design approved (A. A. Siddiqui et al., 2021).

In their undertaking, FSE engineers can choose between two fire safety design approaches, namely performance and prescriptive based design (ISO, 2018b).

The prescriptive method relies on a set of rules, typically stated in a standard or a regulation, and looks at two essential aspects: evacuation design rules (the geometric form, sizing of escape routes, maximum length of routes, width and number of exits), and fire protection rules (compartmentalization, fire rating of elements, detection, firefighting…) (ISO, 2018b). This involves a comprehensive building plan checking process which can be inefficient and time-consuming (Abualdenien et al., 2019).

In contrast, the performance-based approach applies an engineering methodology to achieve fire safety objectives. For life safety considerations, this approach relies on modelling and simulations to establish whether the Available Safe Egress Time (ASET) is greater than the Required Safe Egress Time (RSET) plus a safety margin. The ASET is driven by the fire development and often determined by a fire simulation model while RSET is driven by human behavior and can be determined by an evacuation simulation model (Hurley et al., 2016).

According to (A. A. Siddiqui, 2019), evacuation modelling "is the development and application of predictive tools to describe the movement and behavior of a population (…) subjected to emergency conditions". In the context of a performance-based life safety study, evacuation modelling helps determine the Required Safe Egress Time (RSET). Contrary to rule-based compliance check, evacuation models simulate the movement of agents in a building model. With the help of these simulations, architects and engineers can uncover shortfalls in their designs which can hinder crowd movements(Abualdenien et al., 2019).

2.3.2 Pathfinder

Pathfinder is an agent-based evacuation simulation package developed by Thunderhead Engineering (Thunderhead Engineering, 2022). It implements a combination of steering behaviors and physical constraints to simulate evacuation of buildings based on the movement of individual agents.

The software supports extraction of geometrical data from BIM models (through IFC files). Also, simulation results can be exported to CSV format, and include detailed information on movement of agents, door and room usage, evacuation times, etc.

In this study, the 2022 version of Pathfinder is used.

2.3.3 Data exchange between BIM and Evacuation Modelling Software

In practice, FSE engineers require a minimum set of information from the architect in order to perform their assessments. The need for smooth digital information sharing between stakeholders during all phases of a project led to the creation of an open data exchange standard known as the Industry Foundation Classes (IFC) (A. A. Siddiqui, 2019).

Industry Foundation Classes (IFC) is a data model and an industry standard for describing building data that ensures BIM information can be accessed by all stakeholders regardless of the software they are using. The buildingSMART consortium is responsible for developing and maintaining IFC (buildingSMART, 2022a). The current major version is IFC4 which was released in 2013 and registered under the ISO 16739:2013 Standard (ISO, 2013). The open data structure and the neutrality of the format have convinced a large sector of the design and engineering professions to use IFC (Borrmann et al., 2018).

In this project, IFC will serve as the enabling mechanism in the data pipeline linking the BIM tool (Revit) and evacuation assessment tools - supporting the transmission of semantic information between them but also storing data in a standard format, thus achieving the golden thread of information.

An important aspect of IFC is that the information is separated in two parts, namely geometry (vertices and coordinates) and semantic information (object properties such as materials, function, fire rating, etc.) (buildingSMART, 2022a). IFC establishes an object-oriented data schema based on inheritance. It comprises several classes for capturing and sharing general and discipline-specific building data. The detailed structure of IFC is described extensively in the literature (Borrmann et al., 2018; A. A. Siddiqui, 2019).

A key concept in IFC is Model View Definitions. A Model View Definition (MVD) helps determine which information is necessary and which is optional for a particular application or discipline (e.g., FSE).

For instance, an FSE engineer may be interested in the RSET of a space or usage of an exit, but not a structural engineer or a building energy analyst. In this regard, the MVD specifies what parts of the overall BIM model is filtered out and also which data is required for a specific purpose (Borrmann et al., 2018).

The buildingSMART consortium develops and maintains a set of MVDs for various disciplines (buildingSMART International, 2022b). However, the MVD related to Fire Safety Engineering is lagging behind (buildingSMART, 2022b).

Model View Definition	IFC version introduced	Model transfer intention
Reference View	4	**BIM model to viewing package**
Design Transfer View	4	**BIM model to generate analysis**
Space Boundary Add-on	2x3	**BIM model for energy analysis**
Structural Analysis View	2x3	**Structural design (structural analysis)**
Basic FM Handover View	2x3	**BIM model to facilities management**
Occupant Movement Analysis	Under development Est. 2023	**BIM model to Evacuation & Circulation Analysis**
Fire Safety Engineering *(fire, smoke, structure)*	Still seeking funding	**BIM model to Fire Safety Engineering**

Figure 2 – Development status of various MVDs
Redrawn based on (A. Siddiqui & Ronchi, 2022)

One of the objectives of this research is drafting a data schema that enables exchange and sharing of evacuation safety data. This is achieved by analyzing data requirements for fire evacuation assessment which in turn are converted into IFC specifications. The proposed IFC specifications will contribute to the development of the MVD for Fire Safety Engineering by buildingSMART (buildingSMART, 2020).

2.3.4 BIM-FSE integration limits

A review of BIM's Industry Foundation Classes (IFC) performed by (A. A. Siddiqui, 2019) highlighted some challenges and limitations which hinder the smooth integration of FSE in BIM and the achievement of the "golden thread of fire safety information":

The data sharing between BIM and FSE using fire and evacuation tools is described as "relatively poor" and it is not possible to capture and write data back to BIM from FSE assessment tools. This means the data flow is essentially "one-way" since the output is not directly fed back into the BIM model.

Moreover, within the BIM Industry Foundation Classes (IFC) Model, critical data requirements for FSE assessments are not natively supported making data extraction and manipulation difficult. In other words, there are currently no built-in parameters in the IFC standard for storing these data requirements and map them with pre-defined property names and units.

Lastly, the nature and type of outputs from FSE assessment tools (such as evacuation modelling tools), varies from one software to another, and is not supported by a broad definition within BIM.

This thesis proposes to tackle some of these issues by proposing a prototype framework, described in Chapter 3.

2.4 Usage of BIM in fire evacuation

This section presents an overview on past research related to the usage of BIM in fire evacuation.

A recent paper by (Davidson & Gales, 2021) presented trends, methodologies and limitations of BIM adoption in FSE. Even though FSE is lagging compared to other disciplines, the authors noticed a surge in the literature published about the topic between 2019 and 2021. This indicates that the community has identified the gap and is working to resolve it. It is also stated that most studies focused on providing 3D geometric data to setup evacuation simulations.

This was demonstrated in an early research (Spearpoint, 2007) which reviewed entities in the IFC model and examined how they can be mapped to the input requirements of various modelling solutions employed in FSE. For reference, a list of evacuation modelling software supporting IFC import was compiled from literature (A. A. Siddiqui, 2019) and is reported Table 1.

Table 1 – Evacuation tools supporting IFC import

Evacuation modelling package	Reference
Pathfinder	(Thunderhead Engineering, 2022)
buildingEXODUS	(FSEG, 2022)
MassMotion	(Arup, 2022)
STEPS	(Mott MacDonald, 2022)
LEGION	(Bentley, 2022)
Pedestrian Dynamics	(Pmcorp, 2022)

Relevant publications were reviewed by the author. They are summarized in Table 2 below.

Table 2 – Summary of publications related to BIM usage in FSE

Reference	Summary
(Al-Sadoon & Scherer, 2021)	The paper presented research aiming to achieve real-time data exchange between fire and evacuation simulations and building models. The authors proposed an extension of the IFC schema to enhance building elements with properties that have multiple dynamic values, to capture their status at the simulation running time. The extended properties are represented by links to separate files. The combination of IFC file (including geometry) and the property set model constitutes a multimodal container stored on the cloud.
(Wehbe & Shahrour, 2021)	In this project, BIM was used to prototype an emergency management system which locates and tracks occupants inside a building in fire, generates evacuation paths in real time and guides occupants using mobile applications. When a fire source is detected, the system automatically generates an optimal evacuation solution by analysing a database of fire and evacuation simulations performed on the building. The fire and evacuation simulation outputs are stored and visualized in the BIM environment. The proposed system highlights the optimal evacuation paths for occupants and provides the necessary information such as the RSET, the distance needed, and the suggested exit door.
(Mirahadi et al., 2019)	In this research, a framework was developed for evaluating the evacuation safety performance of buildings based on multi-criteria risk indices and with the integration of agent-based modelling, fire simulation tools, and building information models. Two risk indices, Route Risk Index (RRI) and Compartment Risk Index (CRI), were defined by the authors to quantify the safety of the egress routes and building compartments. In this context, BIM was mainly used to setup fire and evacuation simulations.
(A. A. Siddiqui, 2019)	This research presented a conceptual strategy for enhanced data sharing between FSE and BIM, covering both fire modelling and occupant evacuation. An initial draft MVD comprising data requirements for FSE was produced. Additionally, a first attempt was made by the author to enable two-way data communication by developing a prototype system together with a preliminary FSE based database in which results from fire and evacuation simulations can be stored along with geometry data extracted from an IFC file.
(Abualdenien et al., 2019)	The authors analysed a German regulation and data requirements for pedestrian simulation in order to propose an IFC data schema that improves parsing of building models by pedestrian simulators.
(Wang et al., 2015)	This work presented a model that applies Revit capabilities for 3D visualization and data storage to support fire safety management. The model can evaluate ASET and RSET times, obtained in separate fire and evacuation calculations. An escape route planning module can determine whether the distance of an escape route is acceptable with the help of Revit's commands for dimension measurements. Acceptable escape routes can be indicated in the 3D model. The architectural model is transferred to simulation packages via 2D DWG files
(Abolghasemzadeh, 2013)	The author proposed a method for simulating building egress, which considers the response of occupants in case of a fire. The method was implemented in Revit BIM. An algorithm is responsible for reading the properties of the building and associated parameters, generate an evacuation model, then capture and render the movement of agents.

From analysing the literature, several recurring gaps were identified.

Often, the data exchange is one-way (from BIM to evacuation assessment tools) and the results from fire evacuation assessments are not captured in the BIM model. In many instances, the architectural model is transferred to simulation packages via 2D drawing files (such as DWG format), which limits the extent of information that can be transferred.

Regarding two-way data transfer, an attempt was made (Al-Sadoon & Scherer, 2021) to capture some output from fire and evacuation simulations in real time and send it back to the Revit BIM model. They also proposed an extension of the IFC schema to store this data. However, only a limited number of data points were covered and the data exchange process itself was not integrated in the BIM workflow since a separate software package had to be used for the coupling of Revit and simulation software. This adds an extra layer of complexity and may result in data loss and miscoordination. Moreover, the properties were spread over multiple files: the main IFC file included the definition and a link to external files which stored the time-dependent values.

A PhD thesis (A. A. Siddiqui, 2019) presented a conceptual strategy for enhanced data sharing between FSE and BIM, covering both fire modelling and occupant evacuation. In this research, an initial draft MVD comprising data requirements for FSE was produced. A first attempt was also made by the author to enable two-way data communication by developing a prototype system together with a preliminary FSE based database in which results from fire and evacuation simulations can be stored on a server along with geometry data extracted from an IFC file. However, the IFC schema was not fully implemented nor prototyped (i.e, the semantic data related to simulation input and results was not exported into IFC files), and the research does not consider the prescriptive approach to fire evacuation assessment.

It is worth mentioning that buildingSMART, the international authority for maintaining BIM and IFC, has initiated projects (buildingSMART, 2022b) to incorporate fire and life safety definitions into the BIM workflow connecting the 3D model, calculation results and review. At the date of this thesis, these projects remain at an initial phase.

Regarding automated code checks, developers have successfully been able to automatically check BIM models for code compliance. For many applications, there is an increasing reliance on automated code-checking which improves the efficiency of prescriptive reviews with up to 80% less time required compared to manual methods (Beltrani et al., 2018). However, most of the tools are released as commercial packages. A list of evaluation tools supporting BIM is presented in Table 3.

Table 3 – Examples of FSE automated code checking tools supporting BIM

Name	Reference
Verifi3D	(Verifi3d, 2022)
Bimfire Tools	(bimfiretools, 2022)
UpCodes AI	(Upcode, 2022)
SMARTreview	(SMARTreview, 2022)

In the end, previous research did not develop a comprehensive solution for the integration of fire evacuation into BIM. More effort is needed to extract parameters from BIM, capture assessment results and improve synergy with assessment tools. It also important to define a standard exchange format (by updating the IFC schema) and integrate the data sharing process into BIM platforms. This is because the external integration process, often seen in past projects, involves many time-consuming steps, is prone to errors and contradicts the current trend of evolving BIM into higher levels of centralization.

2.4.1 Added value and contribution

This research builds-up on the outcome and findings of past projects and proposes to fill the gaps that were identified as follows:

- Creating a data loop enabling two-way data exchange from a BIM platform (Revit) to fire evacuation assessment tools.
- Storing data in a standard format for seamless data transfer.
- Implementing an updated IFC data schema which includes semantic data related to fire evacuation.
- Extending Revit and assessment tools to support the import/export of IFC files featuring this new schema.
- Integration into Revit BIM by developing an add-in. This removes the need for external software packages or databases.
- Visual feedback and animation of time-dependent properties in Revit's interface for better understanding of evacuation performance and informed decision making.
- Collaboration with software vendors (Thunderhead Engineering) to enhance assessment tools and enable support of the two-way data exchange.
- Releasing the prototyped tools as open source for transparency and to enable the community to carry out further development.

2.5 Analysis of data requirements for prescriptive fire evacuation review

In this section, the data requirements for a prescriptive review of occupant evacuation in the context of FSE is analyzed. For this purpose, a review of the International Building Code (International Code Council, 2018) is performed by the author in order to identify the requirements related to occupant evacuation. The main focus is evacuation design, i.e., design rules in the geometric form, and limitations of escape routes such as maximum length of routes, the width, flow capacities and number of exits. Therefore, specifications related to fire protection (active and passive), or structural integrity are not included.

A set of prescriptions is selected to implement an automated code reviewer. Then, the input and output data for each prescription is identified.

As a reminder, the main reason for implementing a code reviewer is to generate data related to prescriptive checks and showcase data transfer between BIM and assessment tools in an open-source process, which is transparent to authorities, and is intended to assist in the development of new data standards.

2.5.1 The International Building Code

The International Building Code (IBC) is a building code developed by the International Code Council (ICC) (International Code Council, 2022a). It has been adopted by several states in the USA, many of which use it as a model and release specific implementations in their jurisdiction. The code provisions are intended to “protect public health and safety while avoiding both unnecessary costs and preferential treatment…” (International Code Council, 2015). In this study, the 2018 version of the IBC code is considered.

2.5.2 Selected prescriptions from the IBC

The author performed an extensive review of the IBC code. Tables 4 and 5 present a short summary of the prescriptions that were retained. Most of these are included in Chapter 10, “Means of Evacuation” (International Code Council, 2018).

A typical fire evacuation prescription review with the IBC code is conducted over three imbricated levels: space, storey, and building. A space is located on a storey, and all storeys are part of a building. At the level of a storey, the combined number of occupants of all the spaces is considered for the sizing of egress components. At the highest level (Building), the evacuation design of the entrance (or “final evacuation” discharge level - usually the ground floor) is reviewed to ensure it can service all the occupants.

Besides checking the evacuation capacity of spaces, storeys, and building, it is important to ensure that the number of occupants in a space does not exceed the maximum allowed and that travel distance from any rooms does not exceed a specified limit.

Table 4 – Evacuation design presciptions for spaces in the IBC code*

Level	No.	Prescription	Observation
Spaces	§1010.1.1	Exit doors have the required minimum size	813 mm x 2032 mm
	§1006.2.1 §1006.2.2	The number of exit doors is sufficient.	Depending on the number of occupants and travel distance : 1-4 exits.
	§1005.3.2	The combined width of all doors (evacuation capacity) servicing a space is sufficient	3.8 or 5.1 mm per occupant depending on building class and presence of sprinkler + voice alarm
	§1005.5	The evacuation capacity is well balanced	If one door is lost (blocked by fire) the remaining capacity should not drop below 50% of the initial capacity.
	§1007.1.1 §1007.1.2	Distance between exits is sufficient	Doors are separated by a distance superior to half the room diagonal. If there are sprinklers + alarms, only a third is required.

Table 5 – Evacuation design presciptions for storeys in the IBC code*

Level	No.	Prescription	Observation
Storey	§1006.3.2	The number of exit doors is sufficient.	Depending on the number of occupants : 2-4 exits.
	§1005.3.2	The combined width of all doors (evacuation capacity) for that storey is sufficient	3.8 or 5.1 mm per occupant depending on building class and presence of sprinkler + voice alarm
	§1005.5	The evacuation capacity is well balanced	If one door is lost (blocked by fire) the remaining capacity does not drop below 50% of the initial capacity
	§1006.3.2	Stairs are in sufficient number	Depending on the number of occupants and travel distance : 1-4.
	§1005.3 §1011.2	The combined width of all stairs is sufficient with regards to the number of occupants served.	5.1 or 7.6 mm per occupant depending on building class and presence of sprinkler + voice alarm The minimum width is 914 or 1118 mm depending on the number of occupants.
	§1011.5.2	Stairs are well constructed	102mm < Riser height < 178mm Tread depth > 279mm
	§1005.4	The stair capacity is maintained over storeys.	Same width at each storey to avoid bottlenecks.
	§1005.5	The stair capacity is well balanced	If one stair is lost (blocked by fire) the remaining capacity should not drop below 50% of the initial capacity.

* Extracted from (International Code Council, 2018)

2.5.3 Selected data points for IBC prescriptive review

After analyzing the prescriptions listed in the previous section, a list of relevant input and output data properties was established by the author. It is shown in Tables 6 and 7.

Table 6 – Identified input parameters for prescriptive reviews

Property name	Description
Occupancy Type	Occupancy type for this building. It is defined according to the IBC code § 302.1
Emergency Communication	Indication whether the building is equipped with an emergency communication system
Sprinkler Protection	Indication whether the building is sprinkler protected
Category	Category of space usage or utilization of the area
Occupant Count	Actual number of occupants in a space/storey/building
Occupant Count Limit	Maximum number of occupants allowed in a space
Occupant Load	Maximum density of occupants for the space [m^2/pers]
Actual Evacuation Capacity	Actual combined width of exits serving a space or a storey [mm]
Actual Exit Count	Actual number of exits serving a space or a storey
Travel Distance	Actual distance from a room/space to an exit [mm]
Travel Distance Limit	Maximum allowed distance from any space to an exit [mm]
Stair Capacity Per Occupant	Required stair width per occupant [mm/pers]
Evacuation Capacity Per Occupant	Required exit width per occupant [mm/pers]
Actual Stair Count	Actual number of stairs serving a storey
Actual Stair Capacity	Actual combined width of stairs serving a storey

Table 7 – Identified output parameters from prescriptive review

Property name	Description
Required Evac. Capacity	Exit width required by IBC code for a space or a storey [mm]
Required Exit Count	Number of exits required by IBC code for a space or storey
Evac. Capacity Adequate	Indication whether the combined width of exits serving a space or storey is sufficient compared to the number of occupants
Exit Count Adequate	Indication whether the number of exits serving a space/storey is sufficient compared to the number of occupants
Evac. Capacity Balance	Indication whether the evacuation capacity is well distributed over the available exits
Travel Distance Excess	Indication whether the maximum allowed travel distance is exceeded
Occupant Count Excess	Indication whether the number of occupants exceeds the limit
Components Placement	Indication whether the exits are spaced correctly according to IBC code
Stair Continuity	Indication whether the number/capacity of stairs used for evacuation is maintained at each storey
Sprinkler Requirement	Indication whether a sprinkler system is required by the IBC code
Dimension Adequate	Indication whether a door has adequate dimensions
Required Stair Count	Required number of stairs for the storey
Required Stair Capacity	Required stair capacity for the storey according [mm]
Stair Count Adequate	Indication whether the number of stairs serving the storey is sufficient compared to the number of occupants
Stair Capacity Adequate	Indication whether the combined width of stairs serving the storey is sufficient compared to the number of occupants
Stair Capacity Balance	Indication whether the evacuation capacity is well distributed over the available stairs on the storey
Riser / Tread Adequate	Indication whether the stair has an adequate riser height / tread length

2.6 Analysis of data requirements for performance-based fire evacuation studies

In this section, the data requirement for performance-based studies of occupant evacuation is analyzed. This relates to the input properties for evacuation modelling tools and the output results they generate. For this purpose, the author compiled a list of data properties from multiple sources.

First is Pathfinder's user manual which lists properties defining the evacuation model to be simulated as well as output results.

Additional properties were gathered from literature and used to cross-check the properties extracted from Pathfinder's documentation. The research conducted by (A. A. Siddiqui, 2019) presented the type and level of information captured by various evacuation modelling tools. This includes Pathfinder (Thunderhead Engineering, 2022), buildingEXODUS (FSEG, 2022), MassMotion(Arup, 2022) and STEPS (Mott MacDonald, 2022). Another instructive reference was (Abualdenien et al., 2021) who identified the performance-based evacuation analysis workflow and the current support for data exchange, its limitations, and areas for improvement.

2.6.1 Selected data points for performance fire evacuation studies

The list of relevant input and output data properties established by the author from the sources mentioned previously is shown in Tables 8 and 9.

Table 8 – Identified input parameters for evacuation simulation

Property name	Description
Alarm time	Time to Detection + Notification
Pre evacuation time	Delay between the time evacuation is notified and the time agents start moving
Number of occupants	Desired number of agents in a space/room
Occupant load	Desired density of agents for a space/room [m^2/pers]
Peak number of occupants	Maximum number of occupants allowed in a space
Building occupancy day/night	Evolution of occupancy number over the day
Component status	State of a component (open/closed)
Required door flow rate	Required flow rate through a door component [pers/sec]
Occupant profiles	A set of profiles describing the characteristics of agents : speed, diameter, and impairment.
Admitted profiles	List of agent profiles that are allowed to pass through a component

Table 9 – Identified output parameters from evacuation simulation

Property name	Description
Evacuation Model Info	Name/version/vendor of the evacuation model used for the simulation
Simulation Brief	Description of the simulation
Initial Occupant Number	Initial number of agents assigned to each space at simulation start
Evacuation Time	Time from start of simulation until agents exit a space/room (RSET)
Overall Evacuation Time	Time from start of simulation until all agents exit the building
Occupant History	The evolution of agent count in a space, building or stairway over time
Travel distances	Total distance travelled by any agent (min, max and average)
First occupant in	Time to first agent crossing a component
Last occupant out	Time to last agent crossing a component
Total use	Total number of agents crossing a component
Door Flow rate History	The evolution of flow rate through a door over time
Average occ. flow rate	Average flow rate though a door [pers/seconds]

3. IMPLEMENTATION

3.1 Proposed framework for the integration of Fire Evacuation and BIM

The literature review presented in Chapter 2 highlighted the need for a better integration of FSE in the BIM workflow as well as and the key challenges that hinder this integration. At the current stage, data is essentially exchanged in one way, i.e., from BIM packages to evacuation assessment tools, and consists mainly of geometrical data, while the user has to provide any additional input that may be required by these assessment tools.

The focus of this study is to establish a full data loop, linking BIM software to evacuation assessment tools and resulting in an effective two-way data exchange comprising not only geometry but also semantic information required for these assessments. Then, the results will be captured and stored in the BIM model. This data loop is illustrated in Figure 3 below.

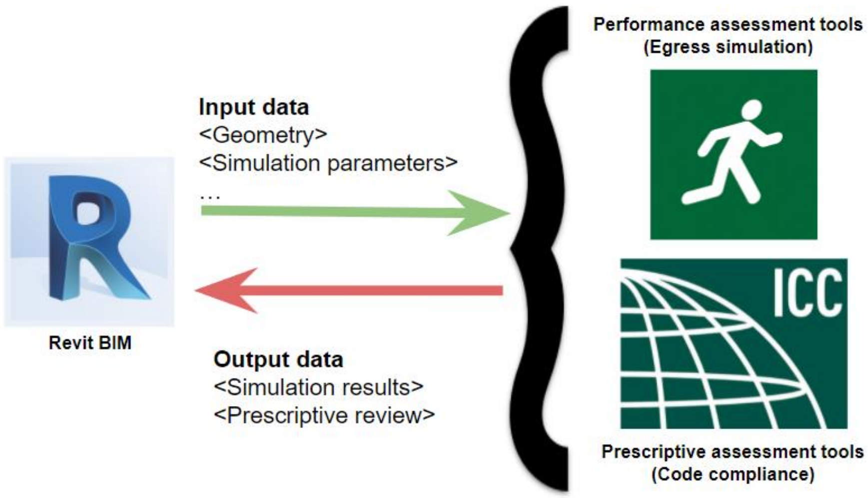


Figure 3 – Data loop linking Revit to assessment tools

In this framework, IFC will serve as a vector for transferring data in a standard format. It is therefore essential that the IFC Model is enhanced to support the required semantic information (input/output data). Those data points (input and output parameters) were identified in the literature review (from Chapter 2) but will need be converted into IFC Specifications.

The development effort in support of this framework is described in this chapter. It comprises three essential steps. It is important to emphasize that these steps implement the strategy proposed by (A. A. Siddiqui et al., 2021) in their “Strategy for data sharing”.

Step 1: Implement enhanced IFC Model Specification

The data requirements for fire evacuation assessment were previously identified in Chapter 2 and presented in Tables 6,7,8 and 9.

The selected properties will be compared to existing IFC Specifications so that new entities can be defined and incorporated. This will result in the development of an expanded IFC schema covering the data requirements for fire evacuation and supporting the current efforts for the implementation of the FSE MVD led by buildingSMART.

Note that (A. A. Siddiqui et al., 2021) already introduced an initial set of new IFC specifications (mainly targeting simulation software). In this research, the author extended this list, to cover additional properties, and also refined it by mapping them into property sets and proposing a nomenclature with property names and units.

Step 2: Enhance BIM tools to support the framework

As stated previously, Revit was selected for the prototyping of the proposed framework.
Therefore, an add-in will be developed in order to extend the current capabilities of Revit and support importing, exporting, storing, and processing data requirements for fire evacuation (through IFC) and enable interoperability between the BIM package and independent engineering analysis software. This will reinforce Revit as a centralized platform bringing together stakeholders from various disciplines (architects, consultants, authorities) and will enable the achievement of the golden thread of information by storing fire evacuation assessment data in the BIM model.

Step 3: Enhance evacuation assessment tools to support BIM

Evacuation assessment tools are an essential component of the proposed data loop. These tools require input data to perform their analysis and generate output data that needs to be stored in the BIM model.

This research covers both prescriptive and performance approaches. For prescriptive approach, an automated code reviewer will be implemented in Revit, based on the IBC code, in order to prototype importing and capturing data from prescriptive reviews.

Regarding the performance approach, Pathfinder was selected as an evacuation simulator. Thanks to a collaboration between the author and Thunderhead Engineering (the developers of Pathfinder), a demo version of the software was implemented with the capability of reading and processing the newly proposed IFC schema, which includes not only the geometrical information but also input data to the simulation.

On the other hand, the add-in described in Step 2 above can capture, process, display and then store simulation results from Pathfinder in the Revit/BIM model.

3.2 Benefits of the proposed framework

In this section, the author presents the main benefits from using this framework.

First, the fire evacuation information is embedded in the model so it can be shared with all stakeholders for informed decision making. Information can also be accessed and visualized within Revit throughout the project life cycle. Moreover, the stored evacuation assessment data serves as a golden thread for asset management, auditing, and even forensics - post accident assessment. Completing the data loop for the "golden thread of information" for evacuation modelling means that designers and engineers will be able to consider alternative design scenarios as a consequence of removing data loss in the workflow. This in turn enables generative processes to optimize different designs, review results from alternate schemes, and hence maximize life safety in the future.

Additionally, by embedding the FSE evacuation information into the BIM model, this project is in line with the efforts aiming to progress BIM into a high level of integration, described by Bew and Richards as Level 2 of BIM Maturity (Bew & Richards, 2008).

On the other hand, coupling models and engineering tools via a vendor-neutral format (IFC) (buildingSMART, 2022a) establishes a fully open and inspectable data loop between the components of the FSE workflow. And the proposed IFC specifications are in line with the current draft MVD for FSE in development (buildingSMART, 2020) and will offer an opportunity to add a fire evacuation analysis layer to the architectural model.

With all this, the framework implements key actions stated by IFSS's "Decade of Action for Fire Safety 2022-2032" (IFSS, 2021). Precisely, it provides a framework that effectively "supports audits, compliance checks and global standards" and improves to "the quality of fire safety data collected".

Also, the built-in prescriptive reviewer facilitates the compliance check of design as it evolves and over the life cycle of the building and allows for quick and automated re-evaluation of modifications.

Finally, the prototyped tools will be made available to the FSE community and any interested parties free and open source. This makes it transparent and allow for future development by the community.

A recent publication (buildingSMART, 2022b) summarized the benefits of a better FSE integration in BIM for different categories of stakeholders involved in a typical FSE project. This is shown in Table 10.

Table 10 – Perceived benefits of FSE integration in BIM by FSE stakeholders
From (buildingSMART, 2022b)

	Regulators	FSE Eng.	Owner	Contractor	Consultants
Digital audit trail	x		x		x
Compliance checking	x	x	x	x	x
Informed decision making	x	x	x	x	x
Automation*		x	x	x	x
Safety**			x	x	x

* Automation of compliance checking and processing of simulation results

** Understanding the FSE strategy and its implementation

3.3 Proposed IFC data schema in support of Fire Evacuation

In the previous section, it was stated that IFC will serve as a vector for transferring data between the nodes of the data loop. However, the Industry Foundation Classes (IFC) model does not yet support the data requirements for FSE evacuation assessments which makes data extraction and transfer difficult. There are currently no built-in parameters in the IFC standard for storing these data requirements and map them with pre-defined property names and units. In this section, the development work aiming to propose a new IFC data schema in support of fire evacuation is presented.

In Chapter 2, an analysis of data requirements was performed which helped identify data points and parameters included in typical fire evacuation assessments, in the case of a prescriptive or a performance-based design.

After listing these properties, the next step is to map them into the IFC model. In order to achieve this, the properties should be given a valid name (for identification), and a type (which relates to the type of data carried by this parameter: area, length, time…). Properties sharing the same purpose (such as output from a prescriptive review, input for evacuation simulation) or targeting a similar object (such as building, space….) can be grouped into property sets. An example is given in Table 11.

Table 11 – Example of a property converted into IFC property

Property	Description	Proposed IFC name	Proposed IFC type	Proposed Property set
Evacuation Time	Time from start of simulation until agents exit a space/room	EvacuationTime	IfcTimeMeasure	Pset_SpaceEvacuationPerformanceInformation
Required Exit Count	Number of exits required by IBC code for a space or storey	ExitCountRequirement	IfcCountMeasure	Pset_SpaceOccupancyPrescriptionsReview

The names of IFC properties were chosen based on a careful analysis of the nomenclature related to fire evacuation from relevant standards such as the ISO 13943:2017 on Fire safety Vocabulary (ISO, 2017), the ISO 20414:2020 on Fire safety engineering - Verification and Validation protocol for building fire evacuation models and documents (ISO, 2020) as well as documents such as (Gwynne, 2010). Similarly, the property types are selected from a set of pre-defined measure types included in the IFC standard (buildingSMART International, 2022a). The units are expressed in the International System (SI).

Following this methodology, the author analyzed all the selected parameters and established a complete list of IFC properties. These properties were also grouped into property sets, summarized in Table 12. In total, 87 properties were defined, spread over 18 property sets (of which 7 already exists in IFC specifications and were expanded with additional parameters, while the rest was newly implemented). The complete list of IFC properties is presented in Appendix A: List of Property Sets for the proposed IFC schema.

Table 12 – Summary of proposed property sets
(Perf. = Performance (simulations), Presc. = Prescriptive reviews)

Proposed Property Set Name	Object	Application		Role
		Perf	Presc	
Pset_SimulationID	Project	X		Capture information on the evacuation simulation (model used, version…)
Pset_BuildingCommon	Building	X	X	Specify input on common building properties such as available protection systems, occupancy type and distribution
Pset_BuildingOccupancyPrescriptionsReview	Building		X	Capture results from prescriptive review at building level
Pset_BuildingFireSafetyPrescriptionsReview	Building		X	
Pset_BuildingEvacuationPerformanceInformation	Building	X		Capture simulation results at building level (e.g overall RSET…)
Pset_BuildingOccupancyRequirements	Building	X		Specify input to simulation on occupant profiles and pre-movement times
Pset_BuildingStoreyCommon	Storey	X	X	Specify input to prescriptive review of storeys
Pset_BuildingStoreyOccupancyPrescriptionsReview	Storey		X	Capture results from prescriptive review at storey level
Pset_DoorCommon	Door	X	X	Specify input on door properties such as required flow rate or accessibility
Pset_DoorEvacuationPerformanceInformation	Door	X		Capture simulation results for door components
Pset_SpaceCommon	Space	X	X	Specify input on space properties
Pset_SpaceOccupancyPrescriptionsReview	Space		X	Capture results from prescriptive review at space level
Pset_SpaceFireSafetyRequirements	Space	X		Specify input to simulation on fire protection for space (e.g alarm time)
Pset_SpaceEvacuationPerformanceInformation	Space	X		Capture simulation results at storey level
Pset_SpaceOccupancyRequirements	Space	X		Specify input to simulation on occupant load for space
Pset_StairPrescriptionsReview	Stair		X	Capture results from prescriptive review for stair components
Pset_StairEvacuationPerformanceInformation	Stair	X		Capture simulation results for stair components
Pset_StairCommon	Stair	X	X	Specify input on stair properties

3.4 Implementation of the prototype Revit add-in

In this section, the development work for the proposed Revit add-in is presented.

In principle, the proposed add-in acts as a program that will be “transplanted” into the Revit environment in order to extend its current functionalities with additional commands. These additional commands will fulfill the objectives stated previously, for which Revit does not offer support yet.

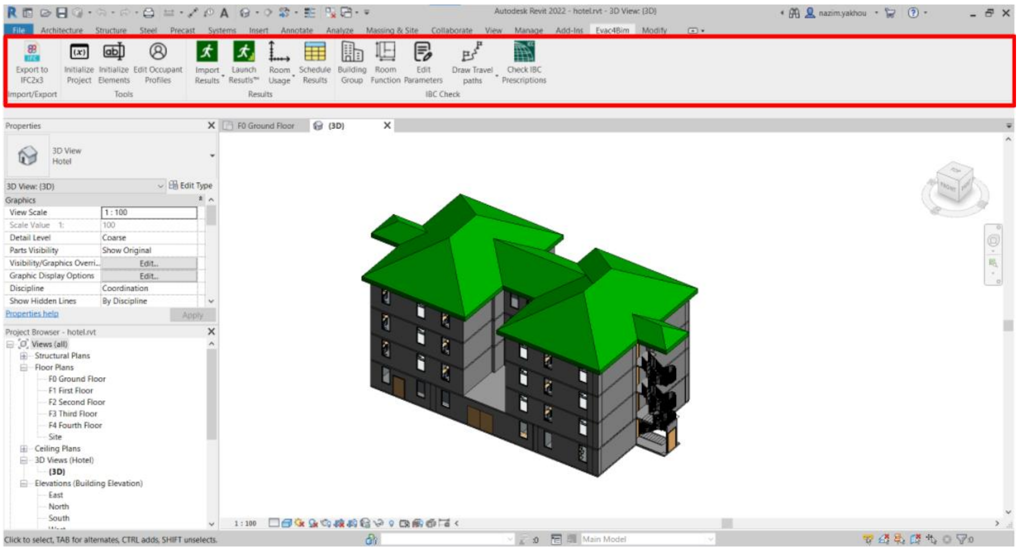


Figure 4 – Illustration of the add-in integration in Revit’s main interface.

The add-in program will run within the Revit environment and therefore, it can access, read, display, edit and save any information available in the Revit model, as shown in Figure 5.

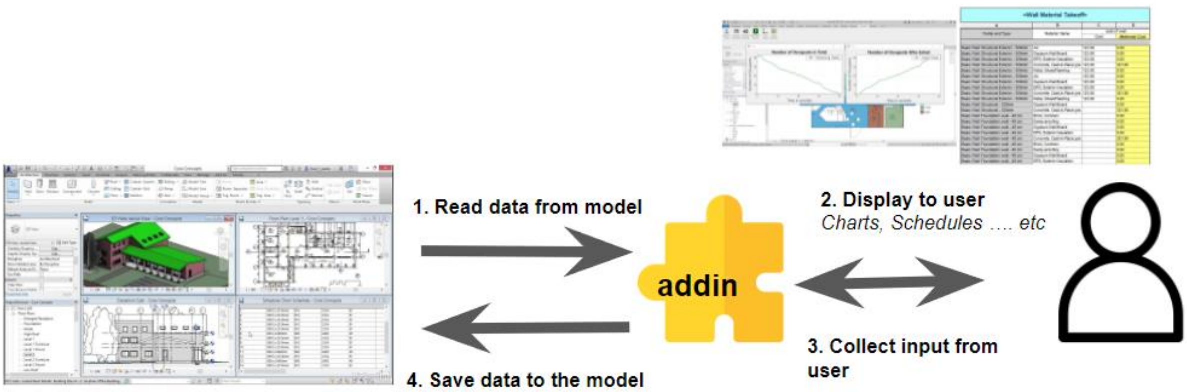


Figure 5 – Illustration of add-in primary functionality

The add-in was developed using the Revit Application Programming Interface (API) (Autodesk, 2022b). The API acts as a "messenger", allowing two applications to "talk" to each other, in this case, the Revit software and the add-in. The add-in consists of a dynamically linked library, placed in the add-ins folder, and loaded at Revit initialization. The resources and methods in the add-in are accessed by Revit to add buttons and dialogs to the Revit interface. In addition, this structure, via the API also allows the add-in to access and add to the data stored in the BIM model. The code was written in the C# language using Microsoft's Visual Studio development environment (IDE) (Microsoft, 2022).

The Revit open source IFC export (Autodesk, 2022a) allows to export Revit geometry into IFC, and its code was made publicly available by Autodesk. In this research, the source code for this export tool was upgraded by the author to add support for the proposed IFC specifications (which are not natively handled by Revit).

Note

A detailed overview of the logical implementation of the codified methods is given in Appendix D: Code reference. This appendix includes schematic diagrams of data flow and logical connections, which highlight the implementation methodology applied. These are not included in the body of the text so that the thesis can be read without a background in computer coding.

Overview of the add-in

In this section, an overview of the add-in is presented. Table 13 summarizes the commands that can be accessed in the add-in from the main Revit interface, also shown in Figure 6.

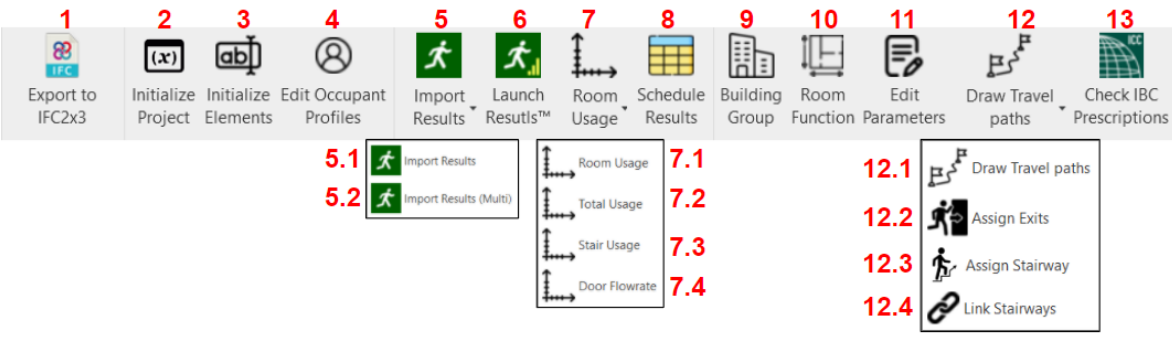


Figure 6 – Available commands in the Revit add-in

Table 13 – Summary of commands available in the Revit add-in

Command n°	Role
1	Export model into IFC (including specifications related to fire evacuation)
2	Initialize project (initialize project settings)
3	Initialize element properties
4	Edit occupant profiles (speed, shape…)
5.1	Import simulation results from pathfinder (single run)
5.2	Import simulation results from pathfinder (multiple run simulation)
6	Launch the pathfinder result viewer
7.1	Display room usage graph (number of occupants vs time)
7.2	Display total usage graph (number of occupants in building vs time)
7.3	Display stair usage graph (number of occupants in a stair vs time)
7.4	Display door flow rate graph (door flow rate vs time)
8	Display simulation results in schedules
9	Edit building category (for a prescriptive review)
10	Edit room function (for a prescriptive review)
11	Edit room, storey, door and stair properties required for prescriptive review
12.1	Automatically draw paths of travel from room/spaces to exits
12.2	Assign an exit to room/space for evacuation
12.3	Assign a stairway to a room/space for evacuation
12.4	Connect multi-storey stairways to compute vertical travel distance
13	Execute an automated prescription check

Figure 7 summarizes the working sequence of the add-in.

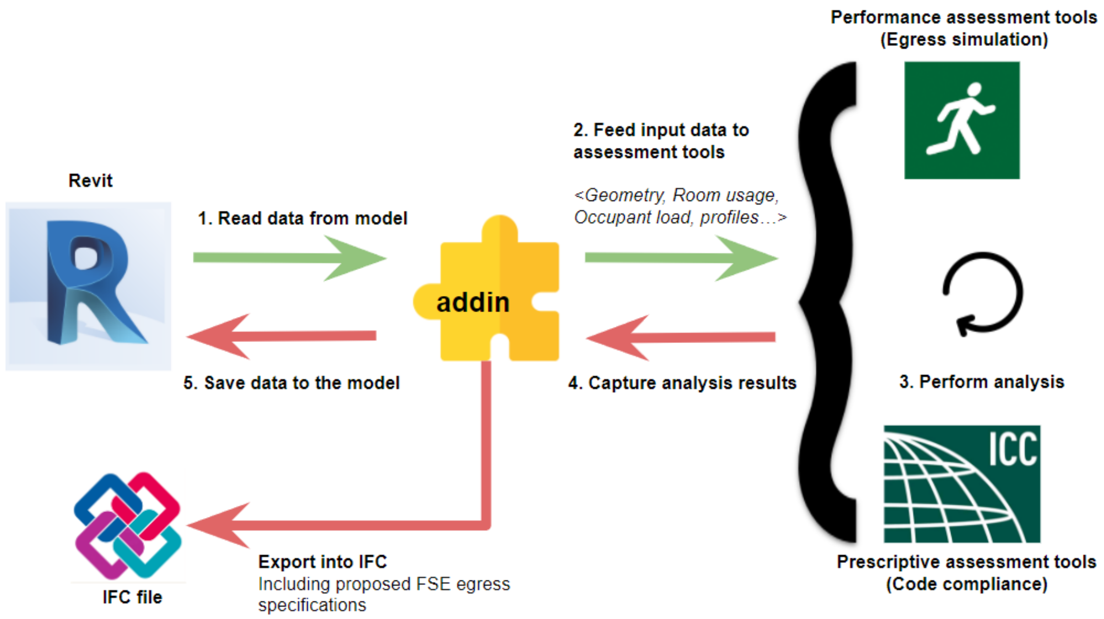


Figure 7 – Illustration of the data loop implemented by the add-in

The working sequence of the add-in can be described as follows:

1. Extract information required to perform assessments (e.g number of exits serving a space, width of stairways serving a storey). The user can also edit/include additional information (for instance, occupant profiles – needed when performing evacuation simulations, number of occupants, room function/usage, etc.).

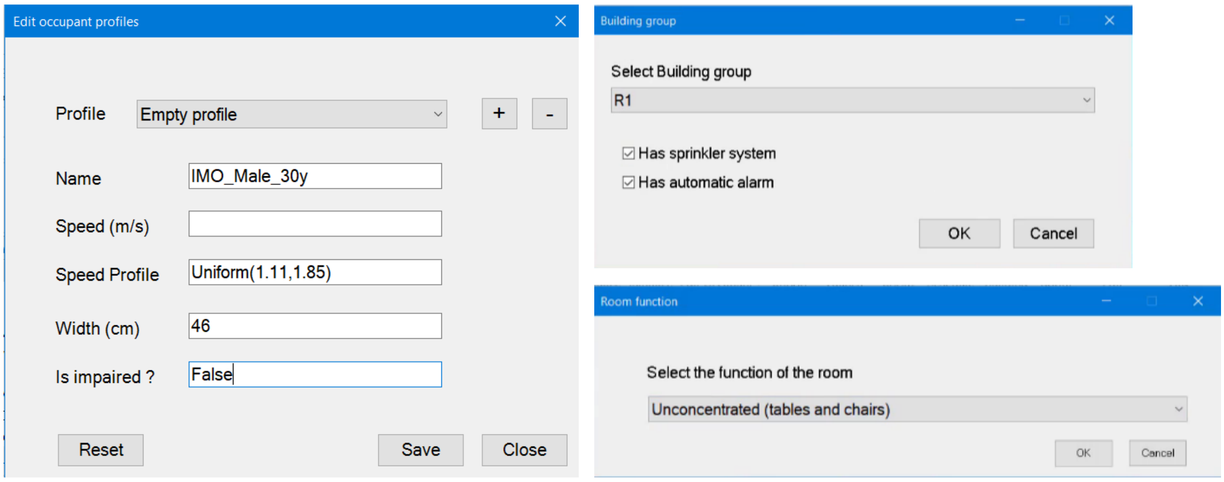


Figure 8 – User input for evacuation assessment tools in the add-in

2. Feed the extracted information to the evacuation assessment tools (by exporting into an IFC file that can be parsed by the assessment tool).

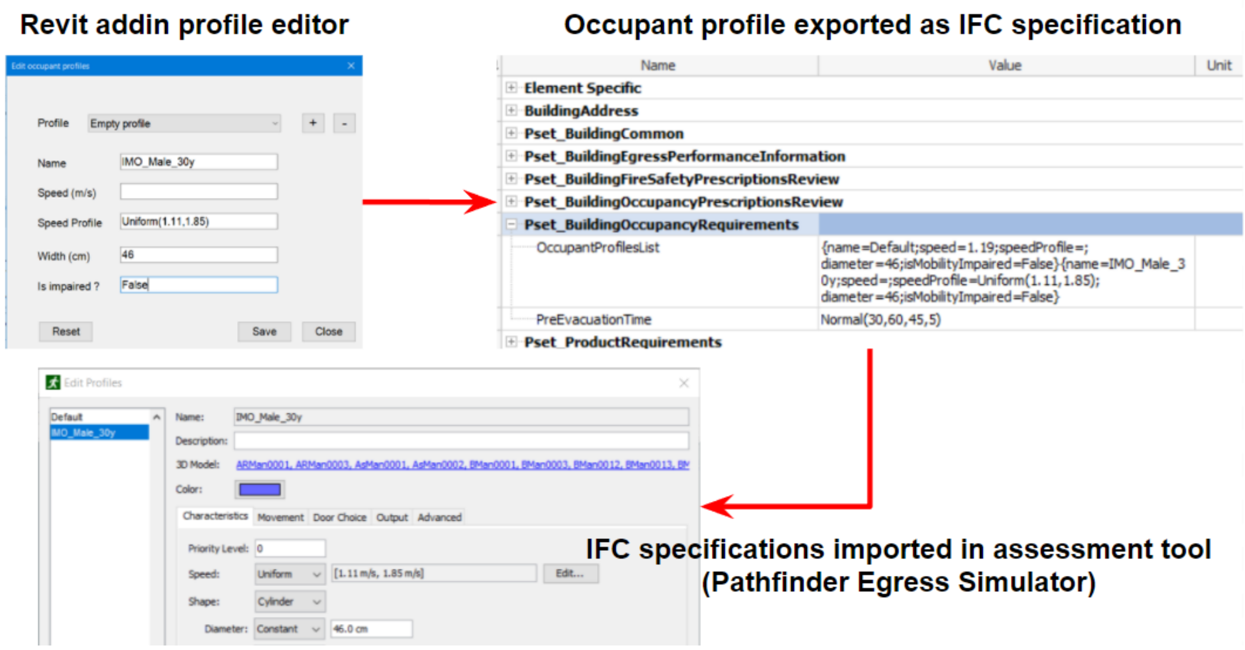


Figure 9 – Exporting input for evacuation assessment

3. Perform an assessment (either an evacuation simulation or a prescriptive review).

4. Capture the results from evacuation assessment.

5. Save data back into the Revit model and display assessment results to the user in the interface.

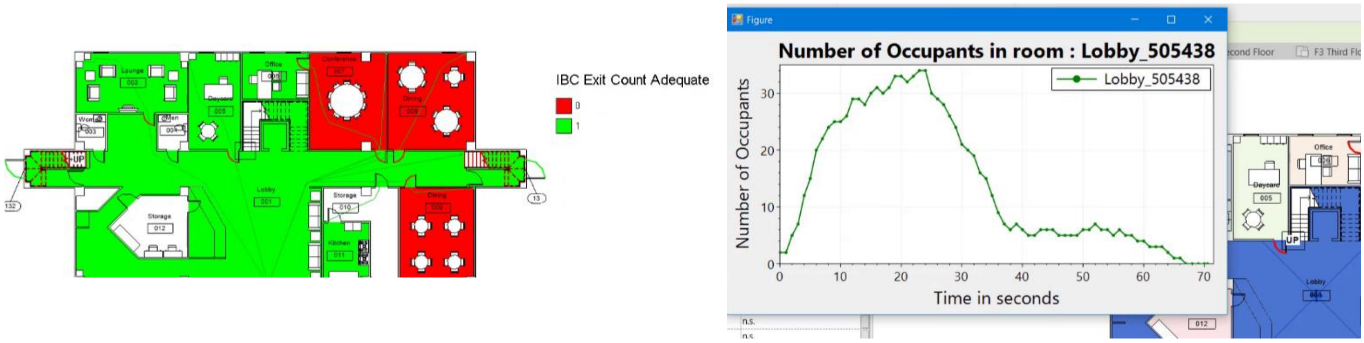


Figure 10 – Evacuation assessment results displayed in Revit by the add-in
Left: Results from the prescriptive assessment – Right: Simulation results

Additionally, the add-in can animate some of the fire evacuation results which are stored as time distributions, as shown in Figure 11.

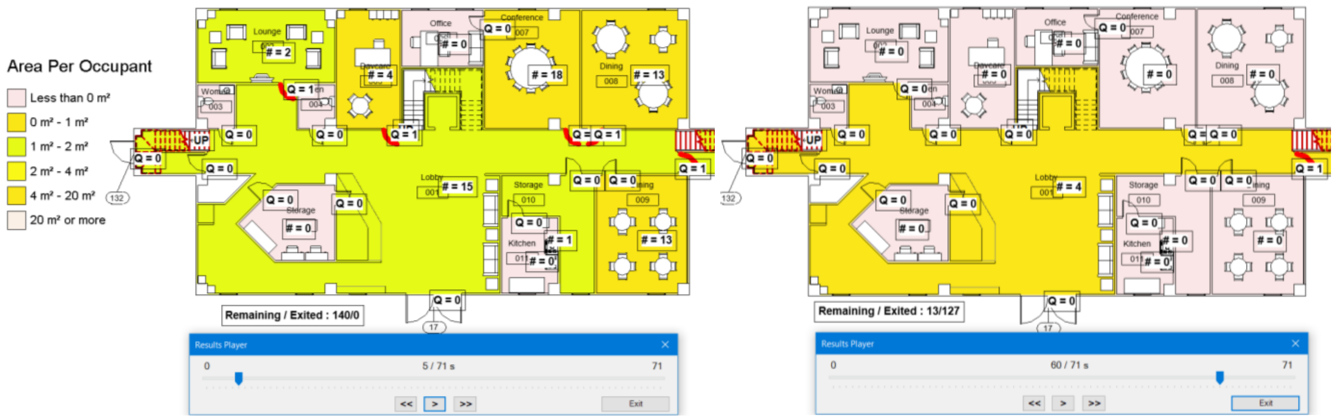


Figure 11 – Illustration of results animation in the prototype add-in

The properties that are displayed include, at various time steps: door flow rate, number of occupants remaining in a room and the density of a room (shown as a color scheme).

This timed feedback helps stakeholders visualize and grasp the level of performance achieved by the building design in terms of fire evacuation for informed decision making. Additionally, this partially eliminates the need for sharing and storing large contour files (generated by Pathfinder) and fragmenting assessment results, since the data necessary for these animations is captured by Revit and stored in the BIM model as lightweight text input. Moreover, stakeholders who need to evaluate fire evacuation performance but are not familiar with simulation software can access this useful information from the main Revit/BIM model.

6. The add-in can generate IFC files that are enriched with IFC specifications presented in the previous sections, enabling support for fire evacuation data requirements.

Name	Value	Unit
Element Specific		
BuildingAddress		
Pset_BuildingCommon		
EmergencyCommunication	Yes	
OccupancyDistributionDayNight	n.s.	
OccupancyType	R1	
SprinklerProtection	Yes	
Pset_BuildingEgressPerformanceInformation		
AverageEvacuationTime	34.36	
AverageTravelDistance	26.29	
EvacuationTimeOverall	70.28	
MaxTravelDistance	55.04	
MinEvacuationTime	5.62	
MinTravelDistance	5.99	
OccupancyHistoryOverall	0,140,0;1,140,0;2,140,0;3,140,0;4,140,0;5,140,0;6,139,1;7,139,1;8,139,1;9,137,3;10,134,6;11,132,8;12,129,11;13,127,13;14,124,16;15,121,19;16,118,22;17,115,25;18,114,26;19,111,29;20,108,32;21,106,34;22,103,37;23,101,39;24,99,41;25,94,46;26,91,49;27,89,51;28,84,56;29,80,60;30,78,62;31,74,66;32,72,68;33,68,72;34,64,76;35,60,80;36,57,83;37,53,87;38,50,90;39,48,92;40,47,93;41,46,94;42,44,96;43,42,98;44,40,100;45,39,101;46,37,103;47,36,104;48,34,106;49,32,108;50,30,110;51,28,112;52,26,114;53,25,115;54,23,117;55,22,118;56,20,120;57,18,122;58,16,124;59,14,126;60,13,127;61,11,129;62,10,130;63,8,132;64,6,134;65,5,135;66,4,136;67,3,137;68,2,138;69,2,138;70,1,139;70.53,0,140	
Pset_BuildingFireSafetyPrescriptionsReview		
SprinklerProtectionLacking	No	
SprinklerProtectionRequirement	No	
Pset_BuildingOccupancyPrescriptionsReview		
EgressCapacityPerOccupant	0.0038	m
EgressPathTravelDistanceLimit	76.25	m
EgressPathTravelDistanceLimitHighOccupancy	22.875	m
EgressPathTravelDistanceLimitLowOccupancy	22.875	m
OccupancyNumberBuilding	140	
OccupancyNumberLimitSingleExitSpace	10	
StairCapacityContinuity	Yes	
StairCapacityPerOccupant	0.0051	m
StairCountContinuity	Yes	

Figure 12 – Illustration of the IFC file generated by the add-in
(Including the proposed IFC specifications)

7. The add-in also comprises an automated code reviewer based on the IBC code. This is meant to showcase and prototype importing and capturing data from prescriptive reviews. The selected prescriptive checks that the add-in can perform are presented in Tables 4 and 5. The following limitations should be considered regarding the prototype code reviewer due to constraints in this project's timeline:
   - Only the starting number of occupants is considered for evacuation capacity check (i.e., rooms discharging to other rooms are not considered)
   - Path of travel: only one per room. Alternative paths are not considered.
   - There can only be one discharge level in a multistorey building. At the discharge level, discharge exits are sized for all occupants from all other storeys (including the discharge level itself).
   - Spiral stairways are not considered.
   - The stair landing path is computed following the Predtechenskii and Milinskii method.
   - Refuge areas are not considered.
   - Project units should be set in SI units.
   - For spaces, only gross floor area is considered.
   - High rise buildings are not considered.

- Prescriptions related to corridors are not checked.
- Doors must be oriented outwards.
- Paths of travel are generated as direct line-of-sight, and for illustration only. IBC-compliant pathways should be L-shaped.

Finally, configuration files (described in the code reference) are provided allowing the user to edit, customize or update key properties and default values, for instance, those related to IBC requirements (like maximum distance to exit, or occupant load factors depending on room usage/function). This allows more flexibility but also to keep pace with possible future changes of code prescriptions.

Pathfinder IFC import

In a previous section, it was mentioned that data exchange from BIM to fire evacuation simulation software was limited to geometry import since there is no provision in the IFC schema for natively transferring data points that may serve as input to evacuation simulations (A. A. Siddiqui, 2019).

An attempt was made to address this limitation and it is now possible to generate IFC files comprising input properties for evacuation simulators, thanks to the IFC schema proposed earlier. Moreover, the prototype add-in makes it possible to edit these properties from the Revit interface, as shown in Figure 8.

However, it was necessary to update Pathfinder so that it could actually parse and interpret these new properties.

Thanks to a collaboration with Thunderhead Engineering (the developers of Pathfinder), an experimental version of the software (version number 2022-1-0404) was implemented, and which can read and process the newly proposed IFC schema. This enables the passing of input parameters, required to setup the evacuation simulation, into Pathfinder, which can in turn read those properties and include them into the evacuation model.

For this prototype version, a selection of IFC properties was extracted from the IFC schema introduced earlier (and presented in Appendix A: List of Property Sets for the proposed IFC schema). The selected properties were mapped to corresponding Pathfinder properties as presented in Table 14.

Table 14 – List of selected IFC properties for implementation in Pathfinder

IFC Property	Description	Pathfinder property
OccupancyNumber	Required number of agents to populate a space/room [pers]	Populate space with occupants
AreaPerOccupant	Required density of agents for a space/room [m^2/pers]	
OccupancyNumberPeak	Maximum number of agents allowed in the space/room	Room Capacity
ifcName	Name of the space/room/door element	Room Name
isAccessible	Door state (open/closed)	Door State
RequiredDoorFlowrate	Required flow rate through component [pers/sec]	Door Flowrate
PreEvacuationTime	Delay between the time evacuation is notified and the time agents start moving [seconds]	Behaviors - Initial delay
OccupantProfilesList	A set of profiles describing the desired characteristics for agents: speed, width...	Create new profiles

Figure 13 was extracted from the IFC file imported into Pathfinder. It shows the some of the IFC specifications intended to be included in the evacuation simulation model.

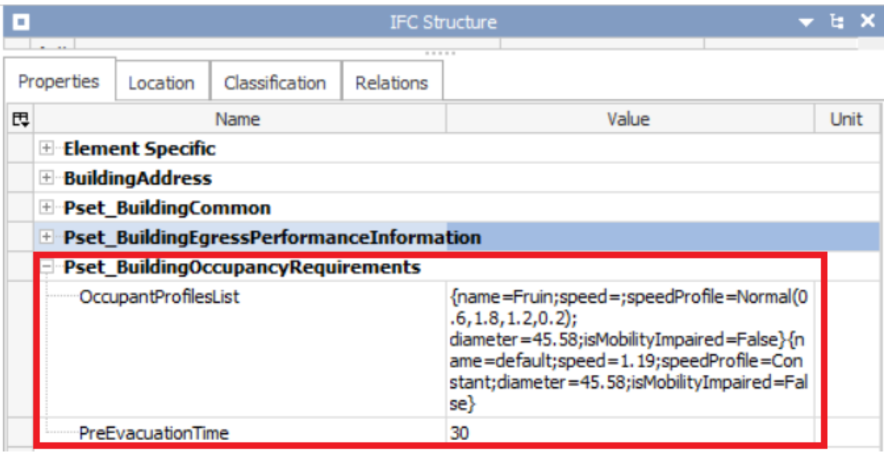


Figure 13 – Illustration of IFC file including input parameters for the Pathfinder simulation

As a result, Pathfinder is now capable of importing spaces from the BIM model as rooms and populate them with agents based on the specified number of occupants or occupant density (m^2/pers), as shown in Figure 14.

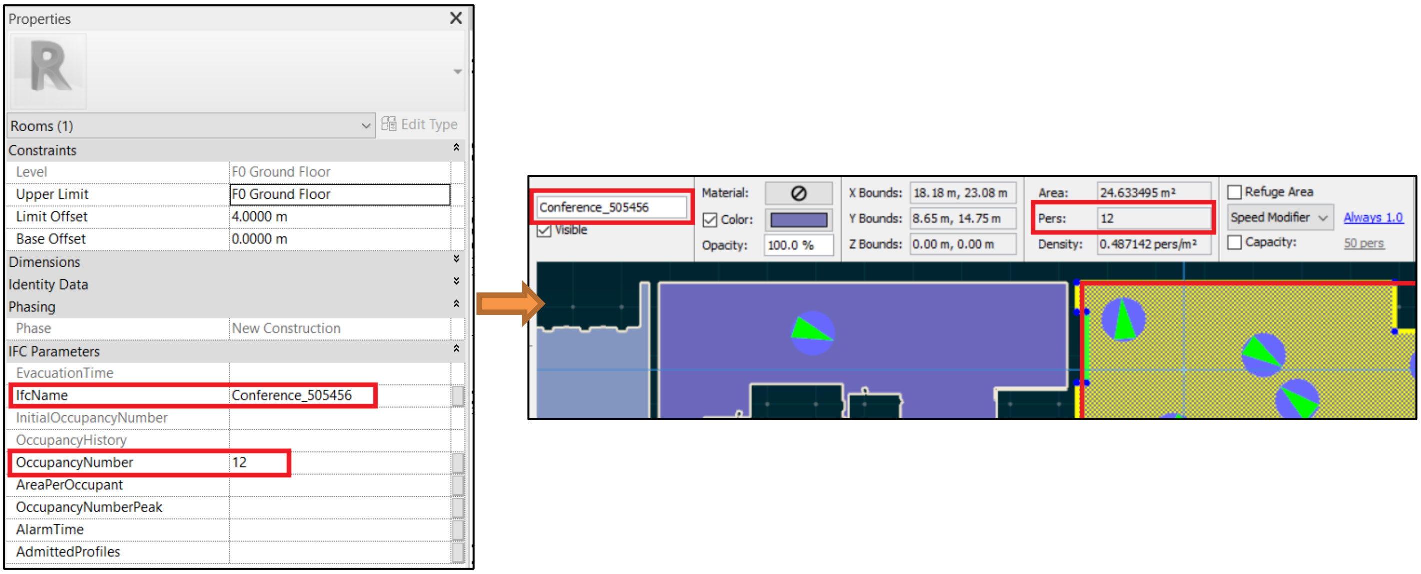


Figure 14 – Passing rooms and number of occupants to Pathfinder
Left: original room model in Revit - Right: Imported room model in Pathfinder

Similarly, door properties such as state (open/closed) and flow rate (pers/sec) can be passed into the evacuation simulator, as shown in Figure 15.

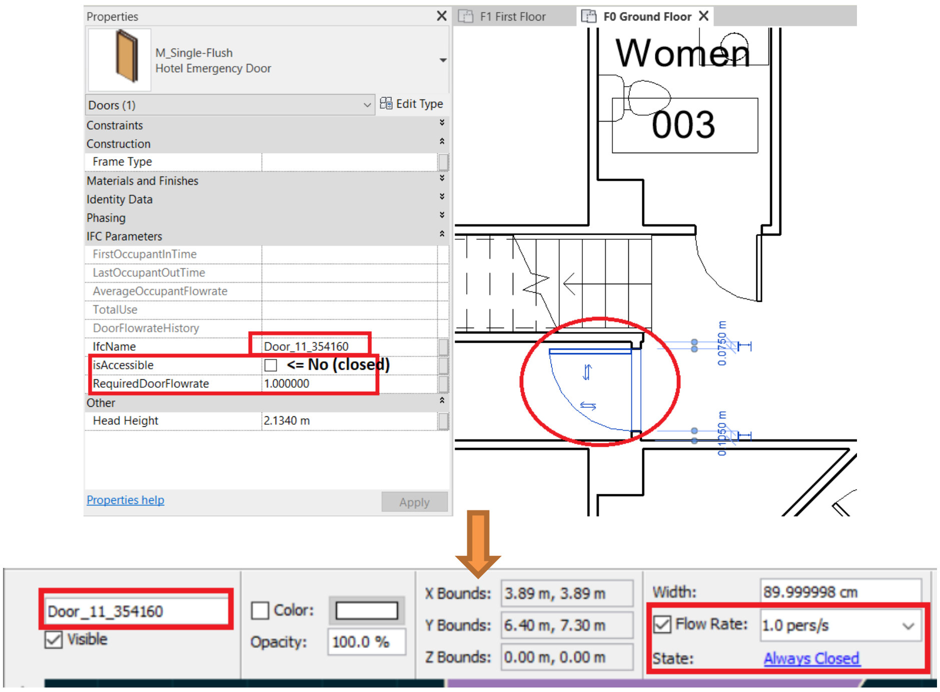


Figure 15 – Passing door properties to Pathfinder
Top: Door model in Revit - Bottom: Imported door model in Pathfinder

Additionally, occupant profiles and behavior (pre-movement time) can also be fed into the Pathfinder simulation, as shown in Figure 16.

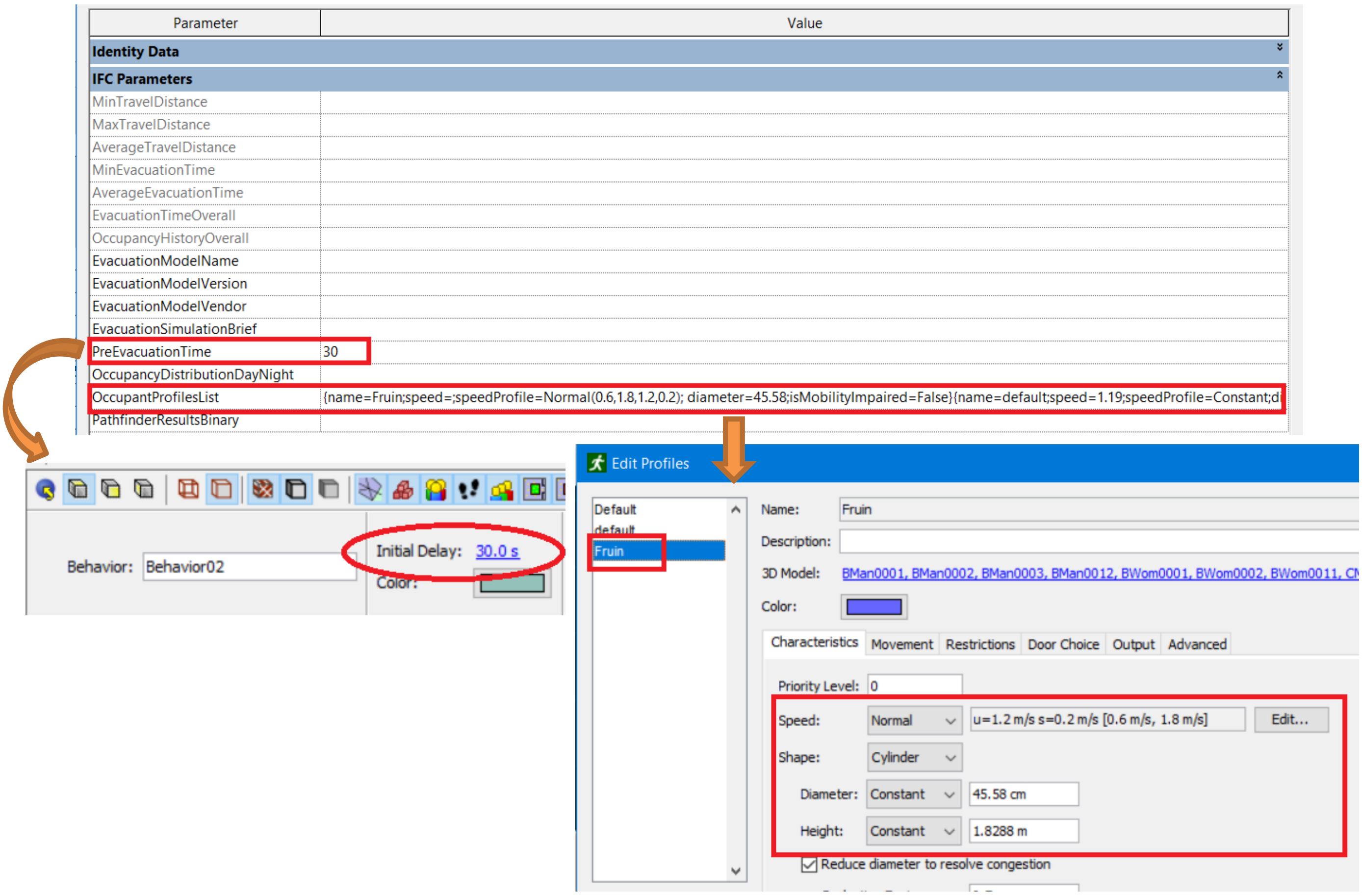


Figure 16 - Passing occupant profiles and behaviour into Pathfinder
Top: Revit model - Bottom: Imported properties in Pathfinder

4. TESTING AND CASE STUDIES

4.1 Workflow for testing

In this section, the add-in presented in the previous chapter is tested on two case studies. The sequence for testing the add-in is intended to cover all its features, as follows:

1. Initialize the case study model (import all required parameters etc.) using the built-in commands.
2. Perform necessary modifications to prepare the model (e.g., switch door directions outward, name rooms, assign room functions…etc.)
3. Perform a code review with the built-in reviewer to generate data on prescriptive assessment and demonstrate data exchange.
4. Export the Revit model into an IFC file combining geometry and input parameters for the Pathfinder simulation. After that, the evacuation simulation is executed.
5. Import Pathfinder simulation results.
6. Export into a final IFC model which combines geometry and assessment results.

This sequence will be applied for each case study. The outcome of each step will be checked to ensure the correctness of the results. The validation criteria for both case studies are shown in Table 15.

Table 15 – Validation criteria for testing the add-in

Function	Criterion	Expected outcome
Prescriptive assessment	Prescriptions are implemented correctly	Generate data related to prescriptive assessments
	Required input data is passed to the assessment tool	Effective 2-way data exchange between Revit and assessment tool
	Output data is captured by the BIM model	
Performance assessment	Required input data is passed to the assessment tool (Pathfinder)	Effective 2-way data exchange between Revit and assessment tool
	Output data is captured in the BIM model	
IFC export	Values and units are preserved	Data integrity is preserved during the exchange process Effective coupling of Revit and assessment tools
	Parameters are exported with the correct name	
	Parameters are mapped correctly in the IFC schema	
Data access	Required data points for FSE evacuation are stored correctly in the Revit BIM model	Golden thread of information Integration of fire evacuation in the BIM workflow Collaboration between stakeholders for informed decision making
	The data points can be accessed and displayed to the user dynamically in the Revit interface	

For the IBC Code review, it is necessary to ensure that the add-in applies the prescriptions correctly. The results from the automated review will be cross-checked with a manual review performed by the author according to the checklist in Table 16, and ensure they match.

Table 16 - Checklist for the IBC prescriptive review validation

Category	Criterion	Comment	Result Pass/Fail
Building properties	Evac. capacity allocation per occupant according to (§1005.3.2) *		
	Stair allocation per occupant according to (§1005.3.1) *		
	Evacuation travel distance limit according to (§1017.2) *		
	Total number of occupants extracted correctly (for of all rooms)		
Room/space properties	Area per occupant matches the space function (Table 1004.5) * for each room		
	Occupancy number limit is computed correctly (Area of the room / Area per occupant)		
	The required evacuation capacity for each room estimated correctly based on IBC (§1005.3.2) *		
	The available evacuation capacity retrieved correctly		
	The required number of exits for each room estimated correctly based on IBC (§1006.3.2) *		
	The number of exits for each room retrieved correctly		
	Prescriptions evaluated correctly (i.e Adequate exit count and Adequate evacuation capacity)		
Storey	Total number of occupants estimated correctly (Sum of all the rooms in the storey)		
	The required evacuation capacity for each storey estimated correctly based on IBC (§1005.3.2) *		
	The available evacuation capacity retrieved correctly		
	The required number of discharge exits for each storey estimated correctly based on IBC (§1006.3.2) *		
	The available number of discharge exits for each storey retrieved correctly		
	Prescriptions evaluated correctly (i.e Adequate exit count and Adequate evacuation capacity)		
	The required stair capacity for each storey estimated correctly based on IBC (§1005.3) *		
	The available stair capacity retrieved correctly		
	The required number of stairs for each storey estimated correctly based on IBC (§1006.3.2) *		
	The number of stairs for each storey retrieved correctly		

*(International Code Council, 2018)

Regarding IFC export, it is necessary to ensure that the integrity of data points is preserved with regards to:

- Units (for numerical properties)
- Values (i.e the values were not altered during the export process)
- Mapping to IFC schema (i.e each property was exported under the right category / property set and with the correct name).

The first two criteria are assessed manually, by cross-checking the exported IFC file with the values written in the Revit model. The third criterion is checked using a software called Solibri.

Solibri is a BIM quality assurance software solution that analyzes BIM models for validation, compliance control, design process coordination, design review, analysis, code checking and clash detection (Solibri, 2021). One interesting feature of Solibri is the validation of IFC files to ensure they follow the correct structure specified in a ruleset (Solibri, 2022).

The ruleset defines a list of IFC properties, along with their name, unit, object they apply to, and the category/property set they fall under. The list of IFC specification in "Appendix A: List of Property Sets for the proposed IFC schema" is used by the author to generate the ruleset. Next, the IFC files generated by Revit and comprising the additional properties will be loaded into Solibri and checked against it.

Property Set	Property	Value Exists	Value Conditions
Pset_SpaceOccupancyPrescriptionsReview	OccupancyNumberSpace	Optional	
Pset_SpaceOccupancyPrescriptionsReview	OccupancyNumberLimit	Optional	
Pset_SpaceOccupancyPrescriptionsReview	AreaPerOccupantSpace	Optional	
Pset_SpaceOccupancyPrescriptionsReview	EgressCapacity	Optional	
Pset_SpaceOccupancyPrescriptionsReview	EgressCapacityRequirement	Optional	
Pset_SpaceOccupancyPrescriptionsReview	ExitCount	Optional	
Pset_SpaceOccupancyPrescriptionsReview	ExitCountRequirement	Optional	
Pset_SpaceOccupancyPrescriptionsReview	EgressPathTravelDistance	Optional	
Pset_SpaceOccupancyPrescriptionsReview	EgressCapacityAdequate	Optional	X = True or False
Pset_SpaceOccupancyPrescriptionsReview	ExitCountAdequate	Optional	X = True or False
Pset_SpaceOccupancyPrescriptionsReview	EgressCapacityBalance	Optional	X = True or False
Pset_SpaceOccupancyPrescriptionsReview	EgressPathTravelDistanceExcess	Optional	X = True or False
Pset_SpaceOccupancyPrescriptionsReview	OccupancyNumberExcess	Optional	X = True or False
Pset_SpaceOccupancyPrescriptionsReview	EgressPathTravelXYZ	Optional	X = *
Pset_SpaceOccupancyPrescriptionsReview	EgressComponentsPlacement	Optional	X = True or False

Figure 17 – Illustration of Solibri's ruleset manager

Lastly, the simulation results that were imported into Revit are checked to ensure they were not altered. Here again, the assessment is performed manually by comparing results stored in Revit to those produced by Pathfinder at the end of the simulation (Pathfinder can export simulation results into a csv file).

4.2 Case studies

In order to test the prototype add-in introduced in the previous section and demonstrate the two-way data sharing between BIM and assessment tools, two test case studies were selected. The floor plans are presented in the "Appendix B: Floor plans from the case studies". The first model (school building) is a sample project provided by the developers of Revit. The second model (hotel building) is a courtesy of Dr Enrico Ronchi. Both of them were chosen because they fall under the scope of the IBC code for the perspective review and can easily be transferred into Pathfinder to setup evacuation simulations.

Case study 1: School building:
This is a fictitious school, consisting of 3 storeys (2 levels above ground). It has two main exits, and an additional two fire exits. The storeys are connected by 5 stairways, but only 3 of them are used for emergency evacuation. The building includes educational facilities (classrooms, computer labs, a library), two cafeterias, a kitchen as well as offices and multiple conference rooms. The building is assumed to be equipped with a sprinkler system and automatic detection and alarm.

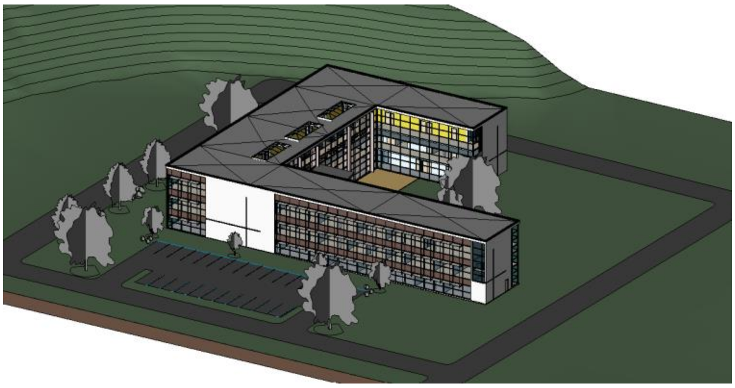


Figure 18 – Overview of the School building

Case study 2: Hotel building
The second case study investigates a fictitious hotel building which consists of 4 storeys (3 levels above ground). The storeys are connected via a central staircase which opens out onto the main lobby. In addition, there are two emergency stairways on each side of the building discharging the upper storeys outside of the hotel. The upper floors mainly consist of sleeping rooms whereas the ground floor comprises facilities such as a kitchen, dining rooms, a day care, a lounge, and a conference room, in addition to the main reception at the lobby. The building is assumed to be equipped with a sprinkler system and automatic detection and alarm

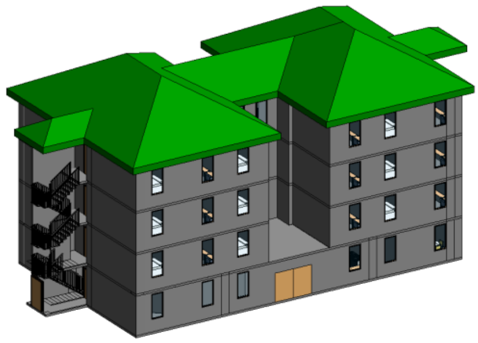


Figure 19 – Overview of the Hotel building

4.3 Testing and evaluation

In this section an overview of the results of the two case studies are presented and discussed. The main steps of the testing sequence, introduced in the previous section are applied for each case.

Case study 1: School building

Step 1: Initialize the model

The model is initialized using the commands available in the add-in. These commands load required shared parameters into the Revit environment and initialize them with default values.

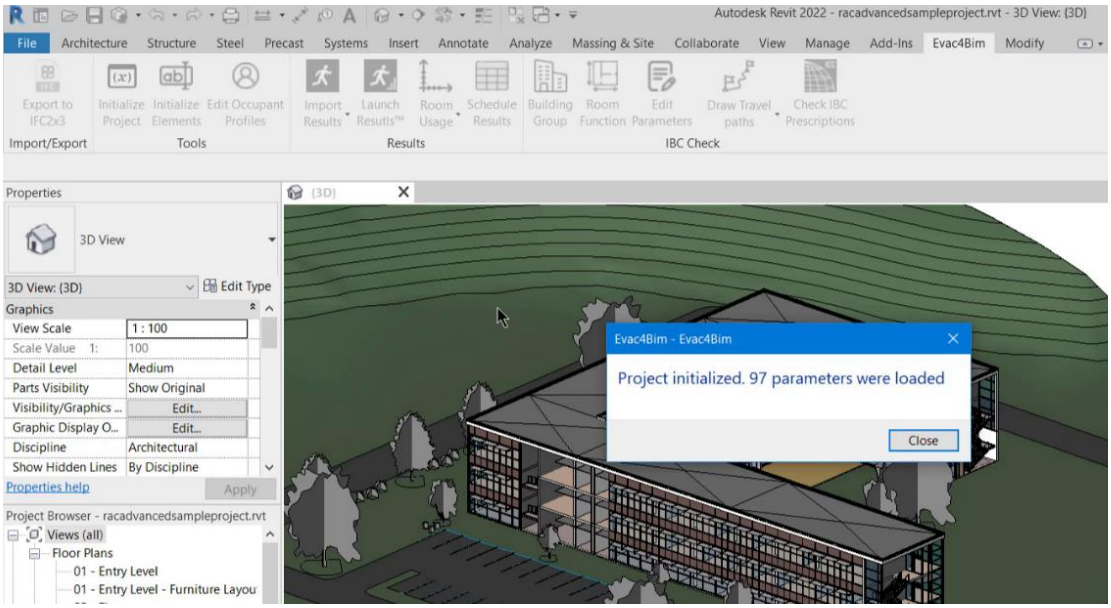


Figure 20 – Model initialization in the Revit add-in (case study 1)

Step 2: Prepare the model for the automated prescriptive review

For this purpose, a set of commands are available in the add-in to help streamline the process.

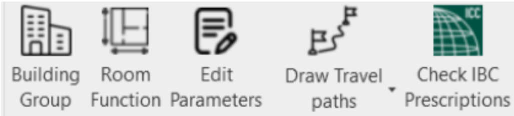


Figure 21 – Add-in commands for automated code review

The first step is the specification of the building group, as shown in Figure 22. According to the IBC code, a school falls under the category E (Educational institutions).

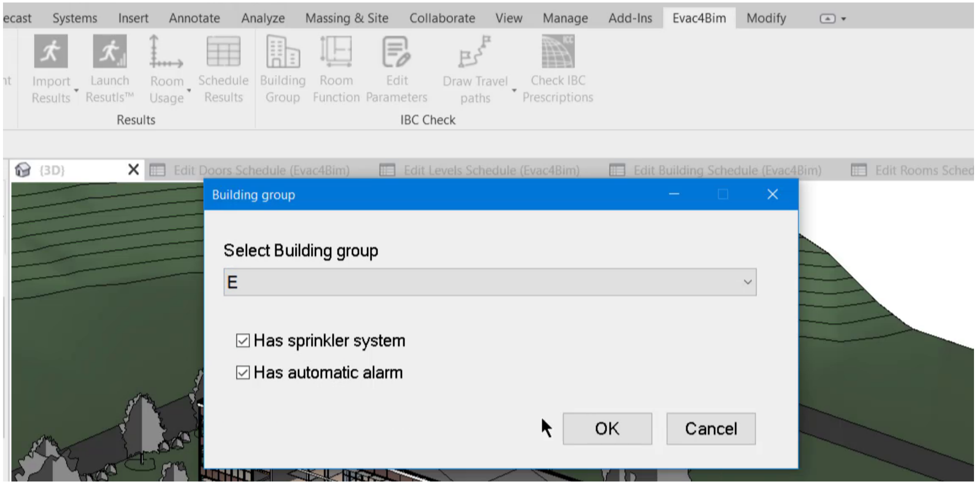


Figure 22 – Specification of building group in the Revit add-in (case study 1)

Next, room functions are specified as shown in Figure 23. The IBC code defines a set of room functions and associated occupant load factors [m²/person]. This helps determine the maximum occupant load that is allowed, obtained by dividing the area by a load factor.

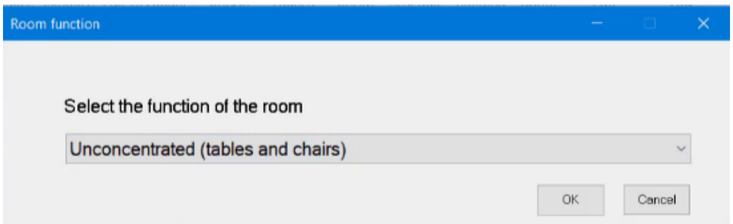


Figure 23 – Add-in command for assigning room functions

It also necessary to identify exit doors and discharge exits. For each space, the doors used for evacuation need to be specified (to distinguish from internal doors, e.g, bathroom door). Similarly, the discharge exits serving a storey need to be specified. This is done by selecting a door in the floor plan and ticking a checkbox included in the parameters of the object, as shown in Figure 24.

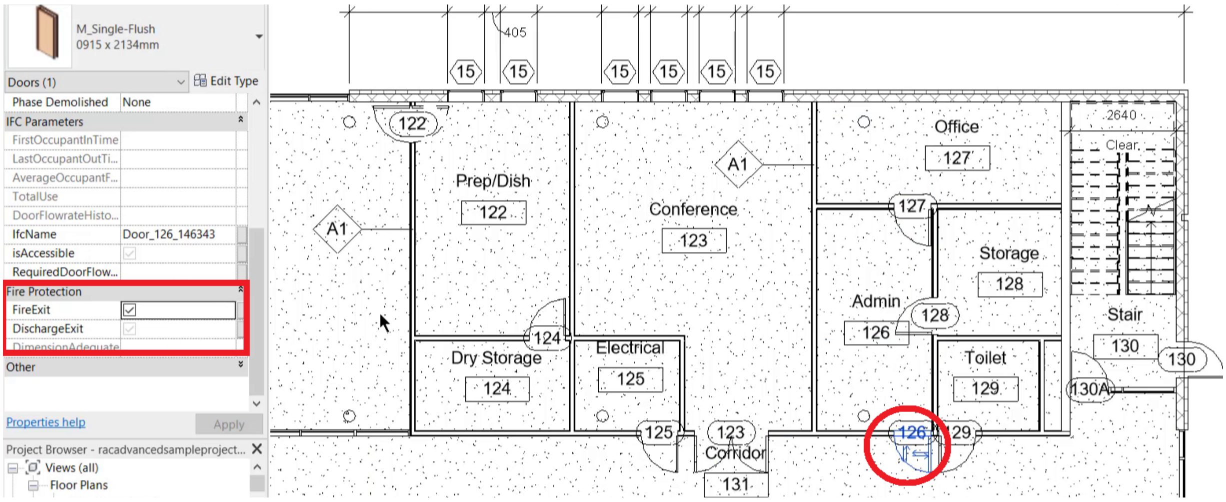


Figure 24 – Fire exit specification in the Revit add-in

Moreover, emergency stairways are specified for the evacuation of upper floors, as shown in Figure 25.

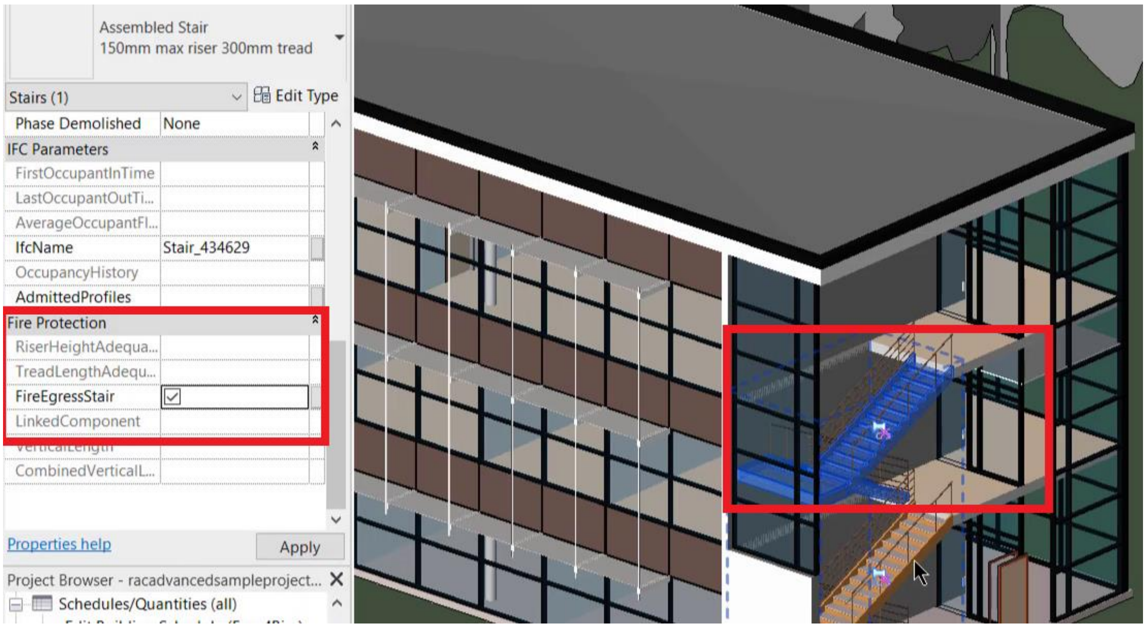


Figure 25 – Evacuation stairway specification in the Revit add-in

With regards to travel paths, a specific command in the add-in can automatically draw them from the furthest point in each room to a specific exit and compute the total travel distance (sum of horizontal distance and vertical distance if a stairway is specified). But first, exit doors and stairways must be assigned to each room, as shown in Figures 26 and 27.

Figure 26 – Add-in commands for Path of Travel generation

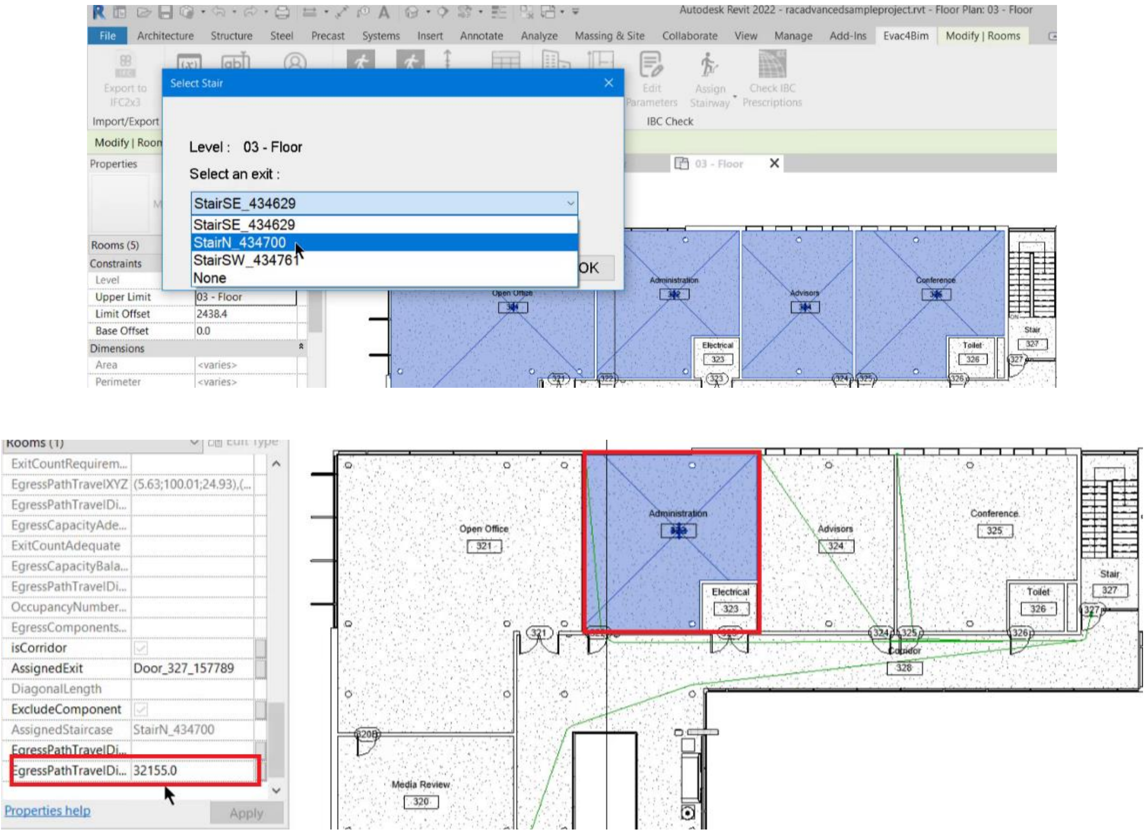


Figure 27 – Exit choice and travel path generation in the Revit add-in

Step 3 Perform a code review with the built-in reviewer to generate data on prescriptive assessment.

Once the model was prepared, the automatic prescription reviewer can be executed, Figure 28.

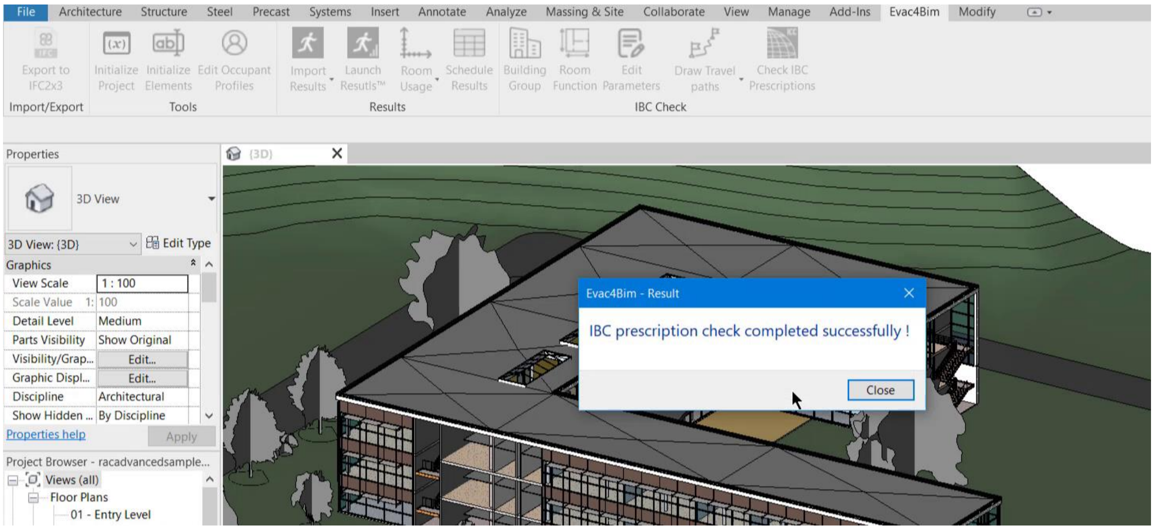


Figure 28 – Prescriptive review execution in the Revit add-in (case study 1)

The results from the automated prescription review are stored in the Revit model, according to the specifications introduced in Section 3.3. The results are also displayed in the main Revit interface in the form of color schemes, schedules, and annotations, Figure 29.

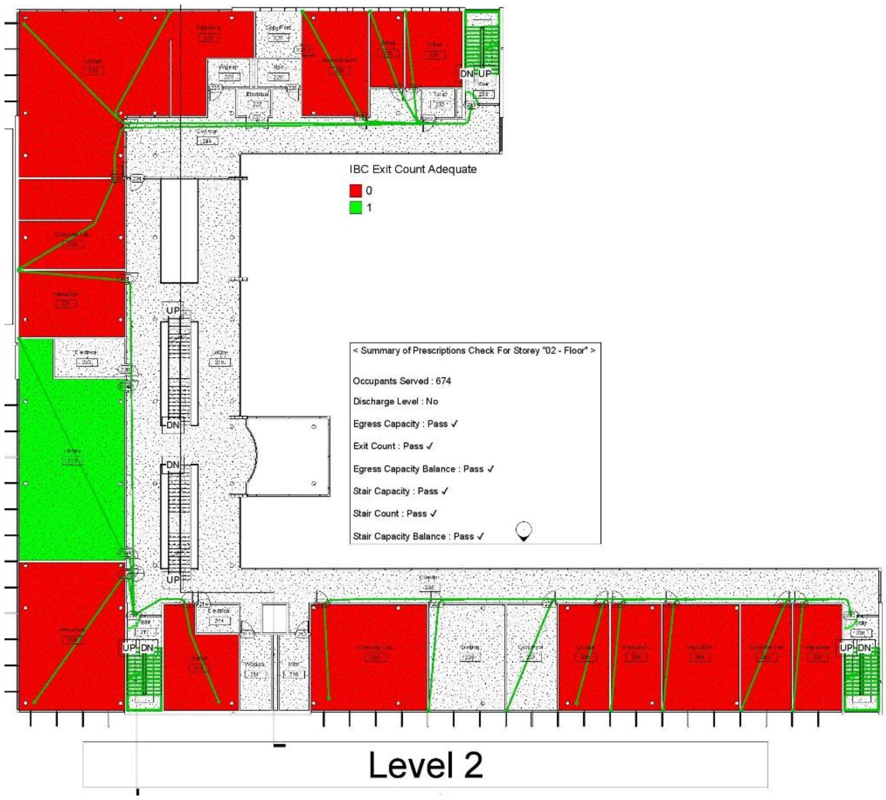


Figure 29 – Prescription review results (case study 1)
Rooms are colored based on the outcome: Green: Pass – Red: Fail

The complete results are presented in the "Appendix C: Prescriptive review results".

It can be noticed that some prescribed rules are not fulfilled (highlighted in red), notably with regards to the number of exits required for each space. Because the review process is automated and streamlined, it is possible to modify the model, in order to comply with the requirements, then re-execute the assessment. Therefore: additional exits were added in order to comply with the requirements related to evacuation count. After running the prescriptive review again, the error was resolved, Figure 30.

Figure 30 – Exit count check prior and after modification of the model (case study 1)

After this, the results from this automated review are assessed manually by the author to ensure the prescriptions are well implemented by the add-in. The validation checklist was used, and the results are shown in Table 17.

Table 17 – Prescriptive review validation checklist for case study 1

Criterion	Comment	Result
Evac. capacity allocation per occupant according to (§1005.3.2) *	Building is sprinklered + occupancy type E ➔ 3.8 mm / occ	**Pass**
Stair allocation per occupant according to (§1005.3.1) *	Building is sprinklered + occupancy type E ➔ 5.1 mm / occ	**Pass**
Evacuation travel distance limit according to (§1017.2) *	Type E + Sprinklered ➔ 250 ft = 76.2 m	**Pass**
Total number of occupants extracted correctly (for of all rooms)		**Pass**
Area per occupant matches the space function (Table 1004.5) * for each room		**Pass**
Occupancy number limit is computed correctly (Area of the room / Area per occupant)		**Pass**
The required evacuation capacity for each room estimated correctly based on IBC (§1005.3.2) *	3.8 mm * number of occupants with a minimum of 813 mm	**Pass**
The available evacuation capacity retrieved correctly		**Pass**
The required number of exits for each room estimated correctly based on IBC (§1006.3.2) *	At least 2 exits if the number of occupants exceeds 49 or the travel distance exceeds 22.87 m (Table 1006.2.1) Building is sprinklered + occupancy type E	**Pass**
The number of exits for each room retrieved correctly		**Pass**
Prescription evaluated correctly (i.e Adequate exit count and Adequate evacuation capacity)		**Pass**
Total number of occupants estimated correctly (Sum of all the rooms in the storey)		**Pass**
The required evacuation capacity for each storey estimated correctly based on IBC (§1005.3.2) *	Building is sprinklered + occupancy type E ➔ 3.8 mm / occ	**Pass**
The available evacuation capacity retrieved correctly		**Pass**
The required number of discharge exits for each storey estimated correctly based on IBC (§1006.3.2) *		**Pass**
The available number of discharge exits for each storey retrieved correctly		**Pass**
Prescription evaluated correctly (i.e Adequate exit count and Adequate evacuation capacity)		**Pass**
The required stair capacity for each storey estimated correctly based on IBC (§1005.3) *	5.1 * number of occupants with a minimum of 1118 mm (more than 50 occupants per storey)	**Pass**
The available stair capacity retrieved correctly		**Pass**
The required number of stairs for each storey estimated correctly based on IBC (§1006.3.2) *		**Pass**
The number of stairs for each storey retrieved correctly		**Pass**

*(International Code Council, 2018)

Thus, the add-in succeeded in enabling a two-way communication with the prescriptive assessment tool by passing the necessary data to perform the analysis, capturing the results in the BIM model, and displaying them to the user. Moreover, the automated code reviewer successfully implemented the selected prescriptions from IBC code, which helped showcase the data exchange between Revit and prescriptive assessment tools.

In the following steps, the data exchange between Revit and a performance-based assessment tool (Pathfinder) will be evaluated.

Step 4: Export to IFC and generate a Pathfinder model

In this section, the data loop linking Revit and Pathfinder (shown in Figure 7) and will be examined.

First, input data is passed from the Revit model to Pathfinder via IFC. The IFC file comprises, in addition to the geometry, additional specifications introduced previously in Table 8, such as occupant profiles, pre movement times, state of doors …etc. It is possible to edit those specifications from within Revit thanks to the dedicated commands.

The IFC file is then imported in Pathfinder, which parses the geometry as well as the additional input parameters. This makes use of the experimental feature described in Section 3.4 Implementation of the prototype Revit add-in

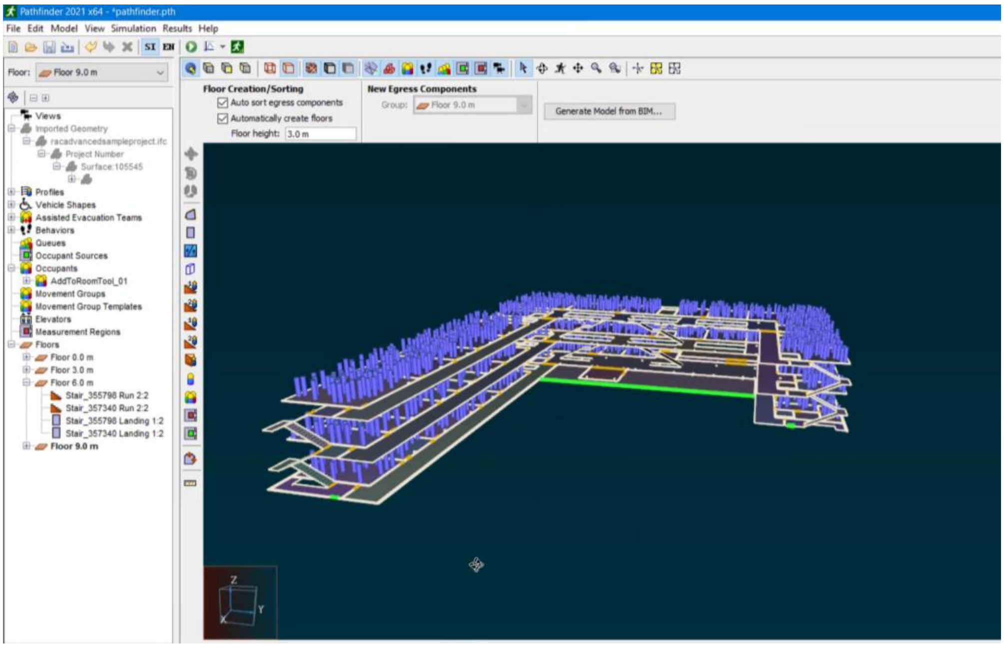


Figure 31 – Preview of the model imported in Pathfinder (case study 1)

A simulation is performed on this Pathfinder model. The exact input data is not reported because the objective is only to demonstrate the working principle of the add-in.

Step 5: Import Pathfinder simulation results

After running the simulation, the results are imported back into the Revit model to close the data loop. A dedicated command is available in the add-in.

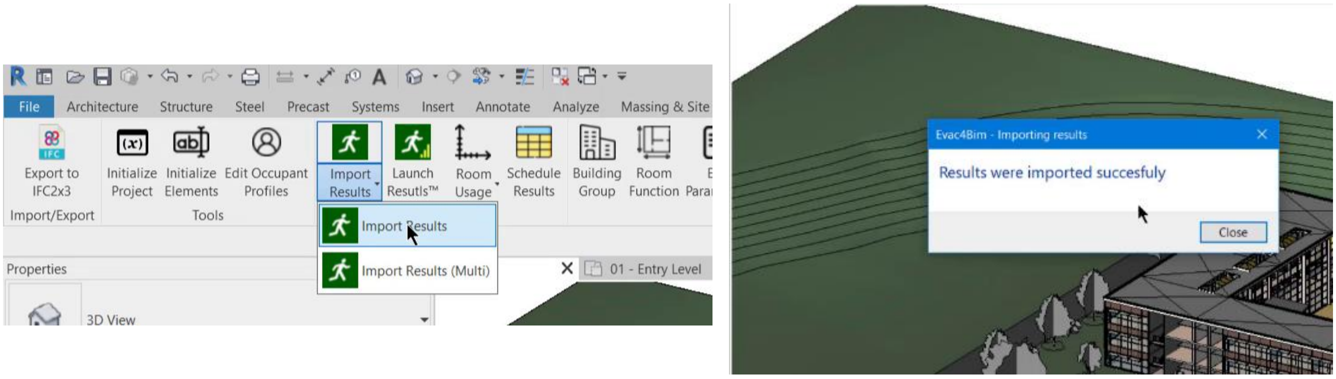


Figure 32 – Pathfinder result imported in Revit by the add-in (case study 1)

The results are stored in the Revit model and can be displayed to the user, Figure 33.

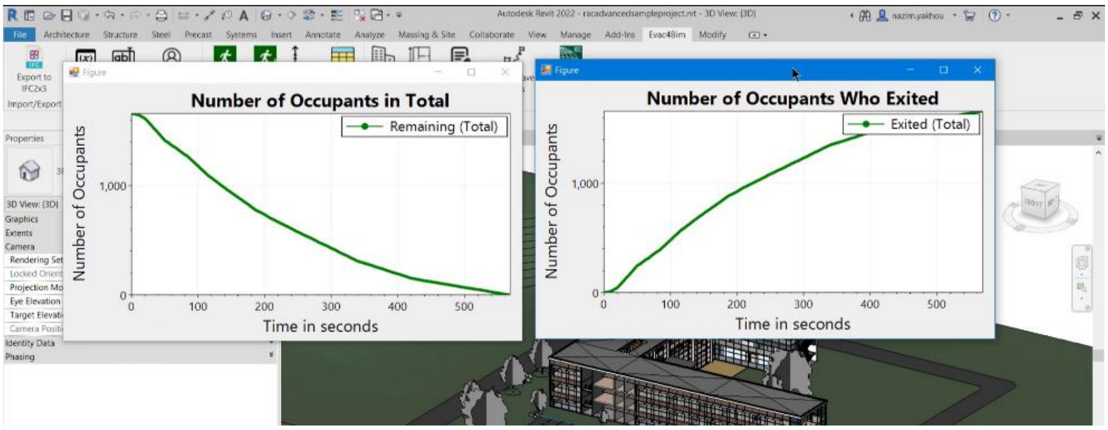
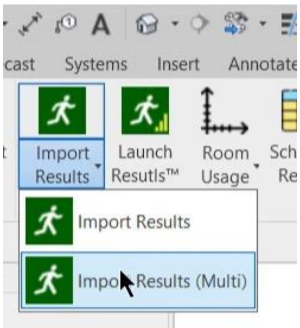


Figure 33 – Illustration of Pathfinder results displayed in Revit (case study 1)

To ensure the results were not altered, the author performed a manual assessment by comparing results stored in the model to those produced by Pathfinder at the end of the simulation. In this case, the assessment was successful.

The procedure was repeated for the case with multiple runs. In fact, Pathfinder offers the possibility to perform Monte Carlo simulations, where an evacuation simulation is executed multiple times and input parameters are randomized at each run. This aims to reduce the uncertainty related to human behavior as explained by (Ronchi et al., 2014).

The prototype add-in can capture the results and postprocess them. Results are stored in the model as an enumeration of key statistical properties: average, standard deviation, minimum and maximum of each parameter listed in Table 9. The formatting is explained in the Appendix A: List of Property Sets for the proposed IFC schema.



<Room Schedule (Evac4Bim)>

A	B	C	D	E
Level	Name	IfcName	Area	EvacuationTime
01 - Entry Level	Vest.	Vest._177056	39 m²	
01 - Entry Level	Lobby	Lobby_177304	324 m²	avg=410.9,min=410.9,max=410.9,std=0
01 - Entry Level	Cafeteria	Cafeteria_177305	144 m²	avg=36.33,min=36.33,max=36.33,std=0
01 - Entry Level	Prep/Dish	Prep/Dish_177306	22 m²	avg=11.47,min=11.47,max=11.47,std=0
01 - Entry Level	Dry Storage	Dry Storage_17730	8 m²	
01 - Entry Level	Electrical	Electrical_177308	6 m²	
01 - Entry Level	Conference	Conference_177309	41 m²	avg=14.93,min=14.93,max=14.93,std=0
01 - Entry Level	Office	Office_177310	15 m²	avg=9.28,min=9.28,max=9.28,std=0
01 - Entry Level	Admin	Admin_177311	16 m²	avg=22.75,min=22.75,max=22.75,std=0
01 - Entry Level	Storage	Storage_177312	10 m²	
01 - Entry Level	Toilet	Toilet_177313	6 m²	
01 - Entry Level	Stair	Stair_177314	19 m²	
01 - Entry Level	Corridor	Corridor_177315	52 m²	avg=75.38,min=75.38,max=75.38,std=0
01 - Entry Level	Sprinkler	Sprinkler_177316	9 m²	
01 - Entry Level	Electrical	Electrical_177317	17 m²	
01 - Entry Level	Instruction	Instruction_177318	48 m²	avg=31.48,min=31.48,max=31.48,std=0
01 - Entry Level	Lobby	Lobby_177319	39 m²	avg=416.07,min=416.07,max=416.07,std
01 - Entry Level	Conference	Conference_177320	31 m²	avg=15.68,min=15.68,max=15.68,std=0
01 - Entry Level	Instruction	Instruction_177321	125 m²	avg=32.73,min=32.73,max=32.73,std=0
01 - Entry Level	Stair	Stair_177322	19 m²	
01 - Entry Level	Electrical	Electrical_177324	7 m²	
01 - Entry Level	Lounge	Lounge_177325	38 m²	avg=24.55,min=24.55,max=24.55,std=0
01 - Entry Level	Men	Men_177326	14 m²	
01 - Entry Level	Women	Women_177328	13 m²	
01 - Entry Level	Corridor	Corridor_177329	133 m²	avg=208.18,min=208.18,max=208.18,std
01 - Entry Level	Instruction	Instruction_177330	88 m²	avg=45.67,min=45.67,max=45.67,std=0
01 - Entry Level	Instruction	Instruction_177331	47 m²	avg=20.5,min=20.5,max=20.5,std=0
01 - Entry Level	Instruction	Instruction_177332	96 m²	avg=46.05,min=46.05,max=46.05,std=0
01 - Entry Level	Instruction	Instruction_177333	47 m²	avg=27.48,min=27.48,max=27.48,std=0
01 - Entry Level	Conference	Conference_177334	47 m²	avg=38.7,min=38.7,max=38.7,std=0
01 - Entry Level	Stair	Stair_177335	19 m²	

Figure 34 – Importing multi-run simulation results in Revit (case study 1)

Thus, the add-in succeeded in enabling a two-way communication with the simulation by passing the necessary data to perform the analysis, capturing the results in the BIM model, and displaying them to the user.

Step 6: Export into a final IFC model which combines geometry and assessment results.

The final step is to ensure that the integrity of data (input and output from assessment tools) is preserved when exporting into IFC.

First, a manual assessment is performed by the author to ensure that the values in the IFC file match those stored in the Revit model.

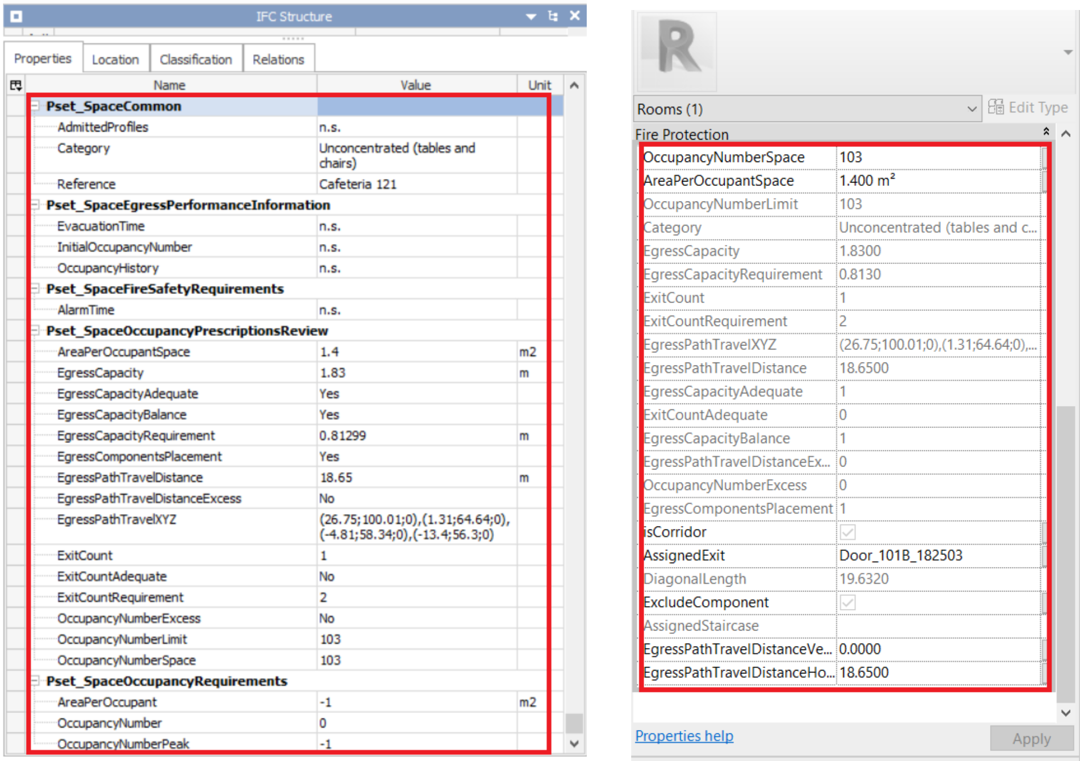


Figure 35 – Comparison between exported IFC properties and properties in Revit model (case study 1)

Next, a validation is performed in Solibri to ensure the IFC files have the correct structure (i.e the property was exported under the right category / property set and with the correct name).

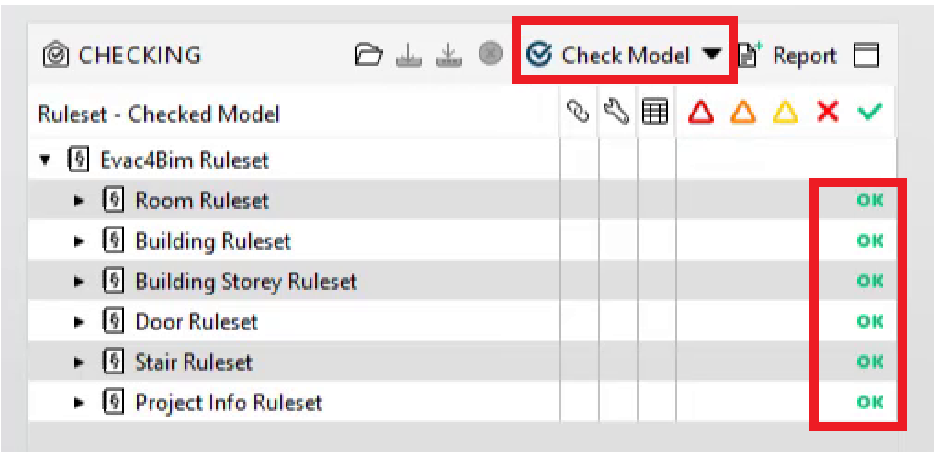


Figure 36 – Illustration of the validation in Solibri (case study 1)

In the end, both evaluations were positive. Therefore, the add-in succeeded in exporting data points required for FSE evacuation assessment according to the specifications set by the author, in terms of preservation of values and units, and correct mapping of properties (i.e correct names, correct categories, etc.).

In summary, the add-in fulfilled all the requirements for validation in this case study, as shown in Table 18.

Table 18 – Validation results for case study 1

Criterion	Evaluation	Expected outcome
Prescriptions are implemented correctly	**Passed**	Generate data related to prescriptive assessments (for testing purposes)
Required input data is passed to the assessment tool	**Passed**	Effective 2-way data exchange between Revit – assessment tool
Output data is captured in the BIM model	**Passed**	
Required Input data is passed to the assessment tool (Pathfinder)	**Passed**	Effective 2-way data exchange between Revit – assessment tool
Output data is captured in the BIM model	**Passed**	
Values and units are preserved	**Passed**	Data integrity is preserved during the exchange process Effective coupling of Revit and assessment tools
Parameters are exported with the correct name	**Passed**	
Parameters are mapped correctly in the IFC schema	**Passed**	
Required data points for FSE evacuation are stored correctly in the Revit BIM model	**Passed**	Golden thread of information Integration of FSE evacuation in the BIM workflow Collaboration between stakeholders – informed decision making
The data points can be accessed and displayed to the user dynamically in the Revit interface	**Passed**	

Case study 2: Hotel building

This second case study follows the same steps as the first one in order to establish the validity of the prototype add-in.

The first and second steps (respectively “Model initialization” and “Model preparation”) are performed using the specific commands described in the previous section and are not reported to avoid repetition. Note that the building group of this hotel according to the IBC code is R1 (Residential).

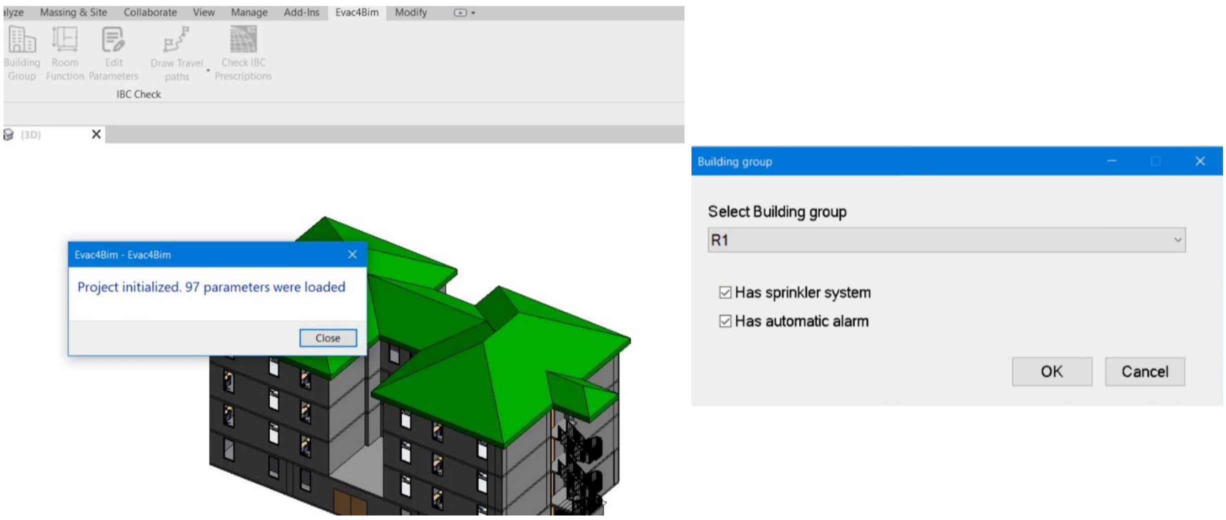


Figure 37 – Model initialization in the Revit add-in (case study 2)

The remaining steps are reported, starting with step no. 3.

Step 3: Perform a code review with the built-in reviewer to generate data on prescriptive assessment

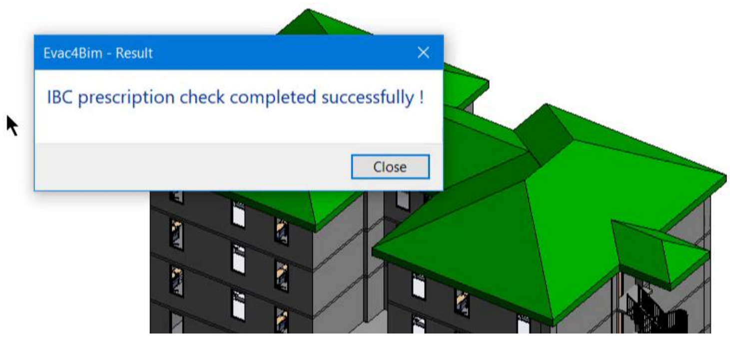


Figure 38 – Prescriptive review execution in the Revit add-in (case study 2)

The results from the automated prescription review are stored in the Revit model, according to the specifications introduced in Section 3.3. The results are also displayed in the main Revit interface in the form of color schemes, schedules, and annotations, Figure 39.

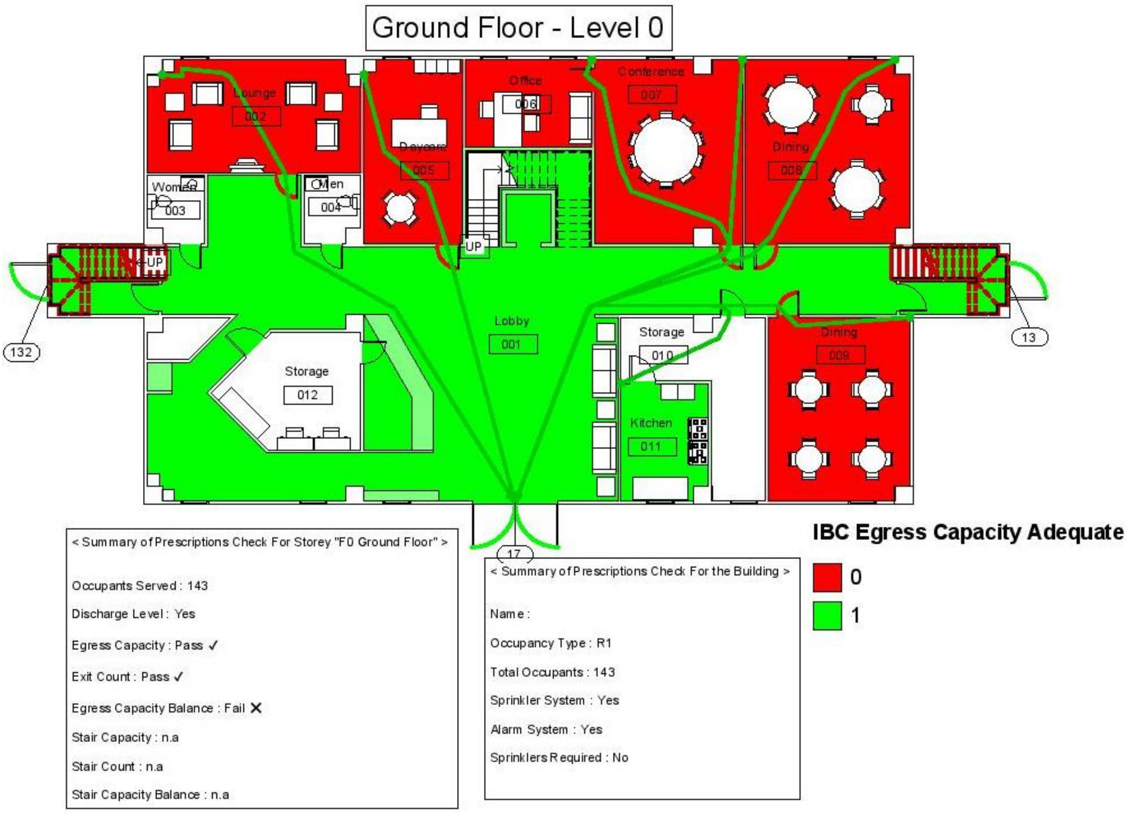


Figure 39 – Prescription review results (case study 2)
Rooms are colored based on the outcome: Green: Pass – Red: Fail

The complete set of results is presenter in the Appendix C: Prescriptive review results.

It can be noticed that some prescriptions are not fulfilled, notably with regards to the number of exits and door dimensions. Because the review process is automated and streamlined, it is possible to modify the model in order to comply with the requirements. To illustrate this, the following modifications were performed:

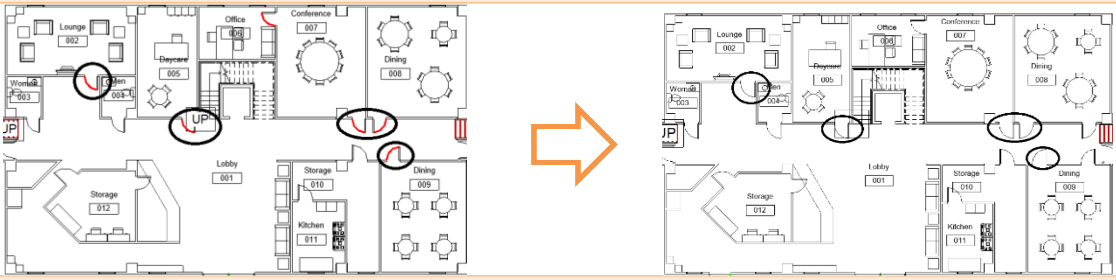
- Door widths increased to a minimum of 813 mm in order to fix errors related to inadequate door size and insufficient evacuation capacity (width).
- For dining rooms and conference rooms, extra exits were added since the number of occupants requires two exit doors instead of just one.
- On the ground floor, the main exit takes up more than 50% of the total available capacity (implying half of the available capacity can be lost if that particular door is blocked). So, an additional discharge exit is added with a width of 1200 mm.

After running the reviewer again, the errors were resolved, as shown in Table 19.

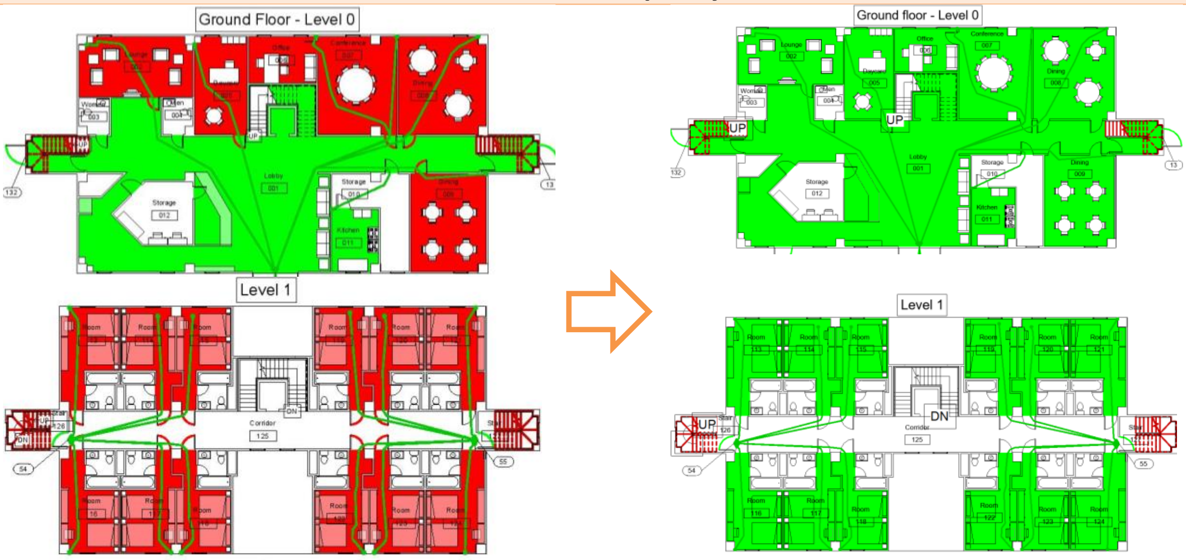
Table 19 – Review results for original and corrected models in case study 2

Original model	Corrected Model

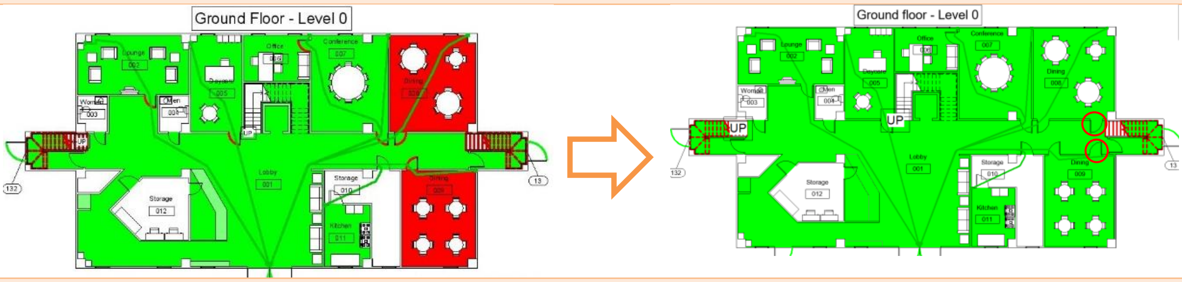
Exit door dimensions



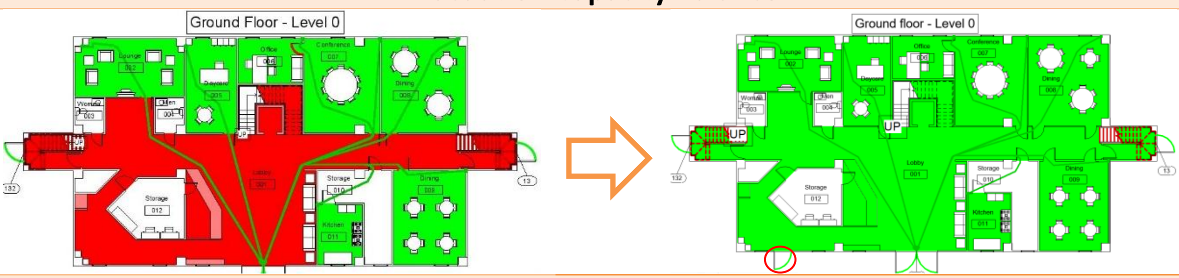
Evacuation Capacity



Exit Count



Evacuation Capacity Balance



Legend

Fail

Pass

*Doors highlighted in red have incorrect dimensions (width < 813 mm)

The results from this automated review are assessed by the author to ensure the prescriptions are well implemented. The results are shown in Table 20.

Table 20 - Prescriptive review validation checklist for case study 2

Criterion	Comment	Result
Evac. capacity allocation per occupant according to (§1005.3.2) *	Building is sprinklered + occupancy type R1 → 3.8 mm / occ	**Pass**
Stair allocation per occupant according to (§1005.3.1) *	Building is sprinklered + occupancy type R1 → 5.1 mm / occ	**Pass**
Evacuation travel distance limit according to (§1017.2) *	Type R1 + Sprinklered => 250 ft = 76.2 m	**Pass**
Total number of occupants extracted correctly (for of all rooms)		**Pass**
Area per occupant matches the space function (Table 1004.5) * for each room		**Pass**
Occupancy number limit is computed correctly (Area of the room / Area per occupant)		**Pass**
The required evacuation capacity for each room estimated correctly based on IBC (§1005.3.2) *	3.8 mm * number of occupants with a minimum of 813 mm	**Pass**
The available evacuation capacity retrieved correctly		**Pass**
The required number of exits for each room estimated correctly based on IBC (§1006.3.2) *	At least 2 exits if the number of occupants exceeds 10 or the travel distance exceeds 22.87 m (Table 1006.2.1) Building is sprinklered + occupancy type R1	**Pass**
The number of exits for each room retrieved correctly		**Pass**
Prescription evaluated correctly (i.e Adequate exit count and Adequate evacuation capacity)		**Pass**
Total number of occupants estimated correctly (Sum of all the rooms in the storey)		**Pass**
The required evacuation capacity for each storey estimated correctly based on IBC (§1005.3.2) *	Building is sprinklered + occupancy type E → 3.8 mm / occ	**Pass**
The available evacuation capacity retrieved correctly		**Pass**
The required number of discharge exits for each storey estimated correctly based on IBC (§1006.3.2) *	Less than 501 occupants => 2 exits	**Pass**
The available number of discharge exits for each storey retrieved correctly		**Pass**
Prescription evaluated correctly (i.e Adequate exit count and Adequate evacuation capacity)		**Pass**
The required stair capacity for each storey estimated correctly based on IBC (§1005.3) *	5.1 mm * number of occupants with a minimum of 914 mm (less than 50 occupant per storey)	**Pass**
The available stair capacity retrieved correctly		**Pass**
The required number of stairs for each storey estimated correctly based on IBC (§1006.3.2) *		**Pass**
The number of stairs for each storey retrieved correctly		**Pass**

*(International Code Council, 2018)

Therefore, the add-in succeeded in enabling a two-way communication with the prescriptive assessment tool by passing the necessary data to perform the analysis, capturing the results in the BIM model, and displaying them to the user. Moreover, the automated code reviewer successfully implemented the selected prescriptions from IBC code, which helped showcase the data exchange between Revit and prescriptive assessment tools.

Step 4: Export to IFC and generate a Pathfinder model

Similar to the previous test case, input data is passed from the Revit model to Pathfinder via IFC. The IFC file comprises, in addition to the geometry, additional specifications introduced previously in Table 8, such as occupant profiles, pre movement times, state of doors …etc. Some of these specifications were edited from within Revit thanks to dedicated commands.

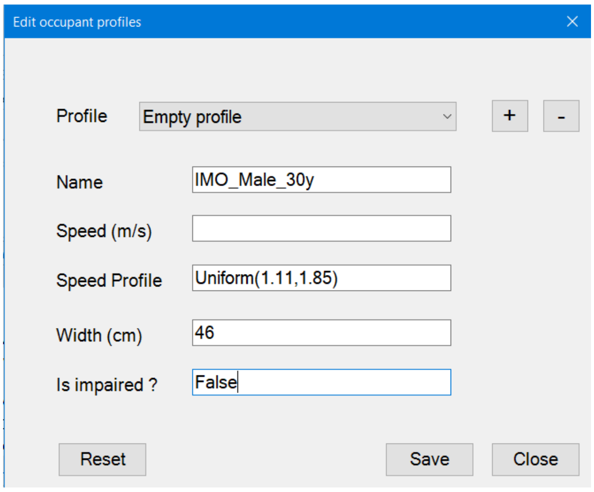


Figure 40 – Add-in command for Pathfinder input specification

The IFC file is then imported into Pathfinder, which parses the geometry as well as the additional input parameters, Figure 41. Once again, the experimental feature described in Section 3.4 Implementation of the prototype Revit add-in was employed. The resulting Pathfinder model is then simulated.

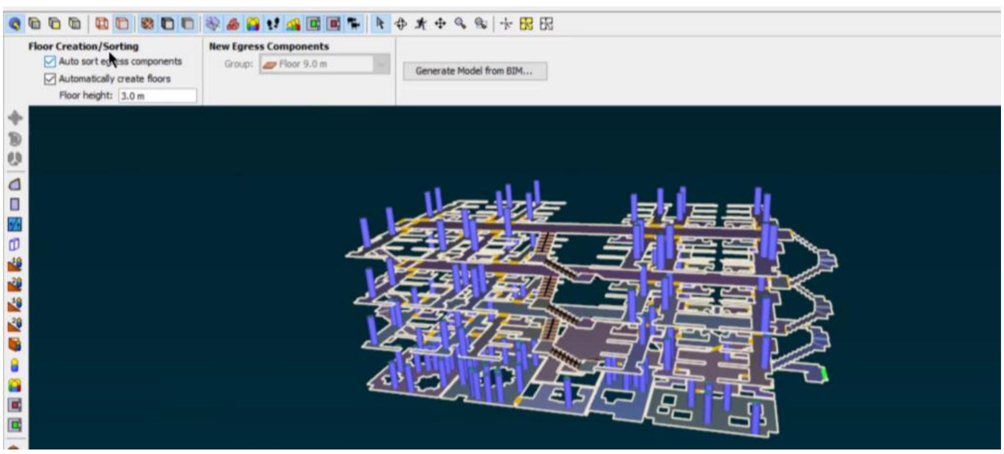


Figure 41 – Preview of the model imported in Pathfinder (case study 2)

Step 5: Import Pathfinder simulation results

After running the simulation, the results are imported back into the Revit model to close the data loop via the dedicated command provided by the add-in.

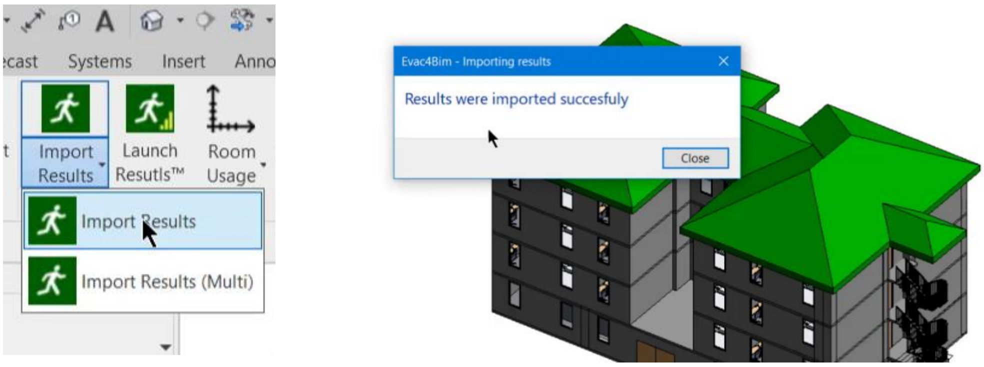


Figure 42 - Pathfinder result imported in Revit by the add-in (case study 2)

The results are stored in the Revit model and can be displayed to the user, Figure 43.

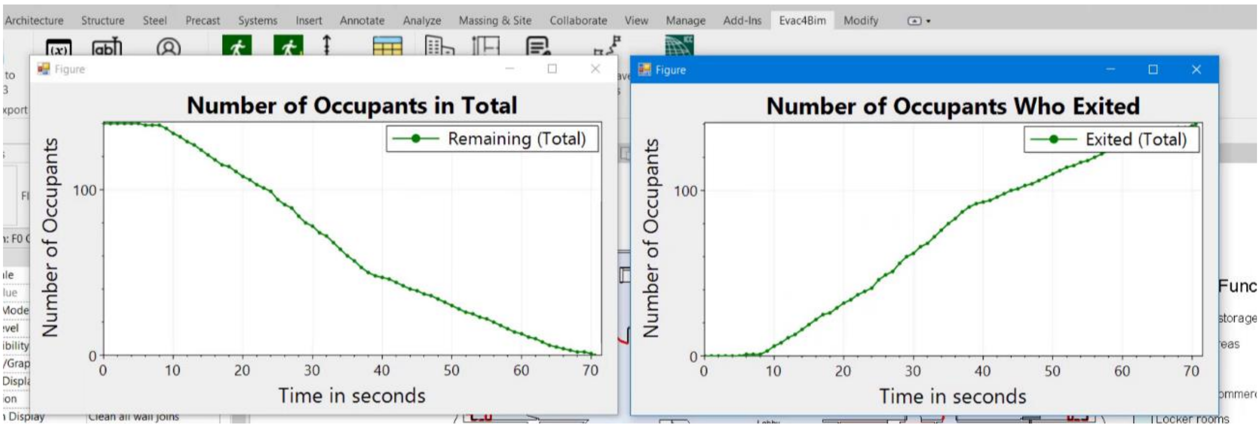
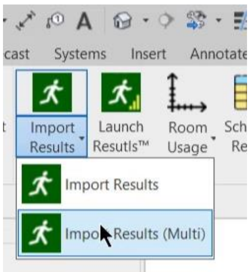


Figure 43 - Pathfinder result displayed in Revit by the add-in (case study 2)

To ensure the results were not altered, the author performed a manual assessment by comparing results stored in the model to those produced by Pathfinder at the end of the simulation. In this case, the assessment was successful. The procedure was also repeated for the case with multiple runs, Figure 44.



<Room Schedule (Evac4Bim)>

A	B	C	D	E
Level	Name	IfcName	Area	EvacuationTime
F0 Ground Floor	Lobby	Lobby_505438	165 m²	avg=69.96,min=68.62,max=71.15,std=1.27
F0 Ground Floor	Lounge	Lounge_505441	26 m²	avg=7.35,min=6.78,max=8.07,std=0.66
F0 Ground Floor	Women	Women_505444	4 m²	n.s.
F0 Ground Floor	Men	Men_505447	4 m²	n.s.
F0 Ground Floor	Daycare	Daycare_505450	20 m²	avg=9.08,min=8.7,max=9.35,std=0.34
F0 Ground Floor	Office	Office_505453	12 m²	avg=1.28,min=0,max=2.48,std=1.24
F0 Ground Floor	Conference	Conference_505456	29 m²	avg=24.37,min=23.73,max=25.15,std=0.72
F0 Ground Floor	Dining	Dining_505459	33 m²	avg=26.71,min=25.25,max=28.2,std=1.48
F0 Ground Floor	Dining	Dining_505462	28 m²	avg=23.04,min=22,max=24.62,std=1.39
F0 Ground Floor	Storage	Storage_505465	17 m²	avg=22.26,min=16.05,max=26.98,std=5.62
F0 Ground Floor	Kitchen	Kitchen_505468	11 m²	avg=2.19,min=0.9,max=2.83,std=1.11
F0 Ground Floor	Storage	Storage_505471	16 m²	avg=0,min=0,max=0,std=0
F1 First Floor	Room	Room_505733	16 m²	avg=3.57,min=2.8,max=3.95,std=0.66
F1 First Floor	Room	Room_505737	15 m²	avg=4.89,min=3.35,max=5.85,std=1.35
F1 First Floor	Room	Room_505740	14 m²	avg=4.17,min=3.27,max=4.78,std=0.8
F1 First Floor	Room	Room_505743	16 m²	avg=3.91,min=3.38,max=4.35,std=0.49
F1 First Floor	Room	Room_505746	15 m²	avg=4.36,min=2.52,max=5.85,std=1.69
F1 First Floor	Room	Room_505749	14 m²	avg=4.71,min=4.47,max=5.17,std=0.4
F1 First Floor	Room	Room_505752	14 m²	avg=3.77,min=3.27,max=4.15,std=0.45
F1 First Floor	Room	Room_505755	15 m²	avg=3.84,min=2.83,max=5.28,std=1.28
F1 First Floor	Room	Room_505758	16 m²	avg=5.51,min=5.17,max=5.83,std=0.33
F1 First Floor	Room	Room_505761	14 m²	avg=3.81,min=3.6,max=4.17,std=0.32
F1 First Floor	Room	Room_505764	15 m²	avg=2.08,min=1,max=3.25,std=1.13
F1 First Floor	Room	Room_505767	16 m²	avg=2.64,min=1.55,max=3.48,std=0.99
F1 First Floor	Corridor	Corridor_505770	67 m²	avg=18.66,min=17.07,max=21.3,std=2.3
F1 First Floor	Stair	Stair_505773	8 m²	n.s.
F1 First Floor	Stair	Stair_505776	8 m²	n.s.
F2 Second Floor	Room	Room_505906	16 m²	avg=3.72,min=3.1,max=4.2,std=0.56
F2 Second Floor	Room	Room_505913	15 m²	avg=4.21,min=3.02,max=5.47,std=1.23
F2 Second Floor	Room	Room_505916	14 m²	avg=4.38,min=3.55,max=5.33,std=0.9
F2 Second Floor	Room	Room_505919	14 m²	avg=2.69,min=2.4,max=3.15,std=0.4
F2 Second Floor	Room	Room_505922	15 m²	[illegible]

Figure 44 – Importing multi-run simulation results in Revit (case study 2)

Thus, the add-in succeeded in enabling a two-way communication with the simulation by passing the necessary data to perform the analysis, capturing the results in the BIM model, and displaying them to the user.

Step 6: Export into a final IFC model which combines geometry and assessment results.

Finally, the last step is to ensure that the integrity of data (input and output from assessment tools) is well preserved when exporting into IFC. First, a manual assessment is performed by the author to ensure that the values in the generated IFC file match those stored in the Revit model, Figure 45.

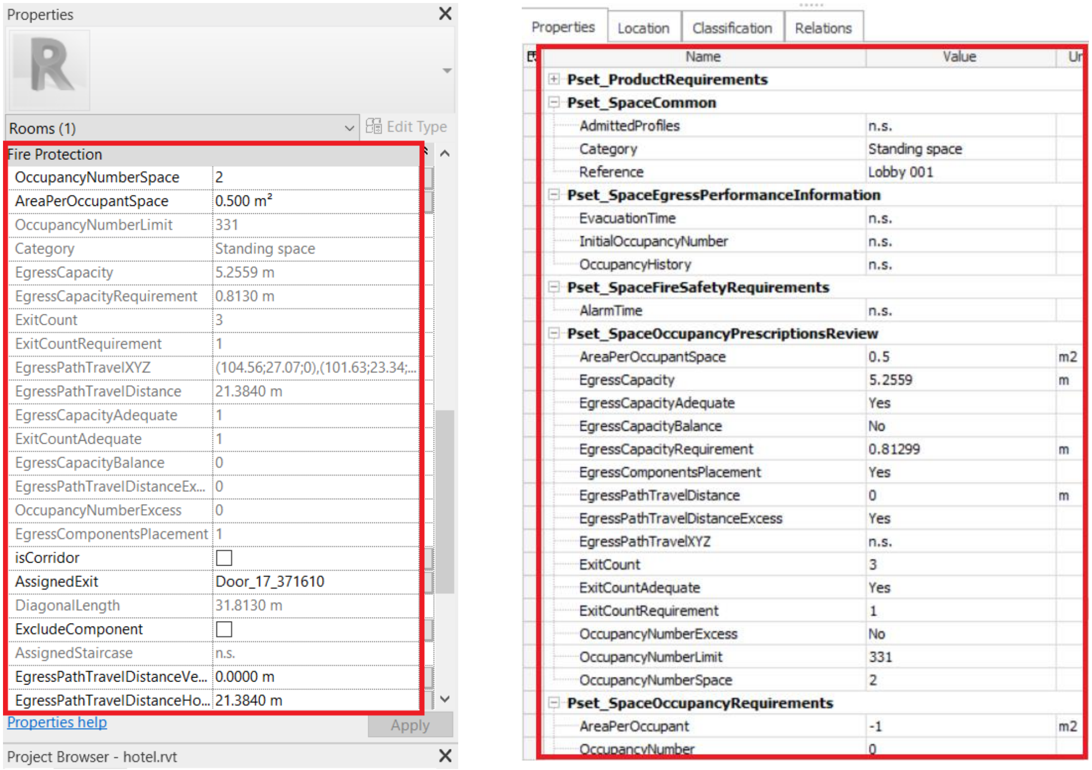


Figure 45 – Comparison of exported IFC properties and properties in Revit model (case study 2)

Next, a validation is performed in Solibri to ensure the IFC files have the correct structure (i.e the property was exported under the right category / property set and with the correct name).

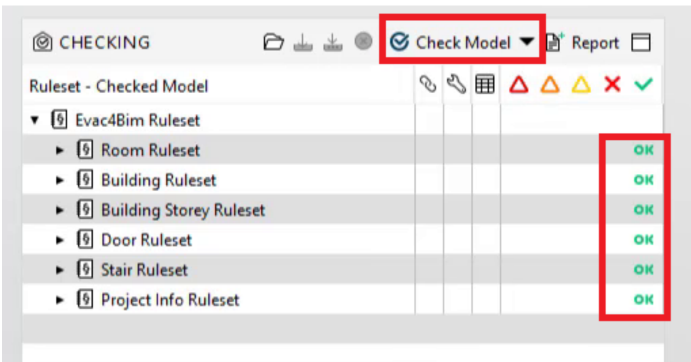


Figure 46 - Preview of the validation in Solibri (case study 2)

In the end, both evaluations were positive. As a result, the add-in succeeded in exporting data points required for FSE evacuation assessment according to the specifications set by the author, in terms of preservation of values and units, and correct mapping of properties (i.e correct names, correct categories, etc.).

In summary, the add-in fulfilled all the requirements for validation in this case study, as shown in Table 21.

Table 21 - Validation results for case study 2

Criterion	Evaluation	Expected outcome
Prescriptions are implemented correctly	**Passed**	Generate data related to prescriptive assessments (for testing purposes)
Required input data is passed to the assessment tool	**Passed**	Effective 2-way data exchange between Revit – assessment tool
Output data is captured in the BIM model	**Passed**	
Required Input data is passed to the assessment tool (Pathfinder)	**Passed**	Effective 2-way data exchange between Revit – assessment tool
Output data is captured in the BIM model	**Passed**	
Values and units are preserved	**Passed**	Data integrity is preserved during the exchange process Effective coupling of Revit and assessment tools
Parameters are exported with the correct name	**Passed**	
Parameters are mapped correctly in the IFC schema	**Passed**	
Required data points for FSE evacuation are stored correctly in the Revit BIM model	**Passed**	Golden thread of information Integration of FSE evacuation in the BIM workflow Collaboration between stakeholders – informed decision making
The data points can be accessed and displayed to the user dynamically in the Revit interface	**Passed**	

4.4 Open-source project repository

The author released the source code and the assemblies on a public online repository which is accessible to all interested parties. Therefore, it is possible for anyone to test the tool on their own. It also makes the project transparent and open for future development by others.

Moreover, the files related to the case studies were released online. This includes the Revit models, IFC files, Pathfinder models as well as the Solibri rulesets used for validation. Additionally, two videos recorded while performing these tests are included.

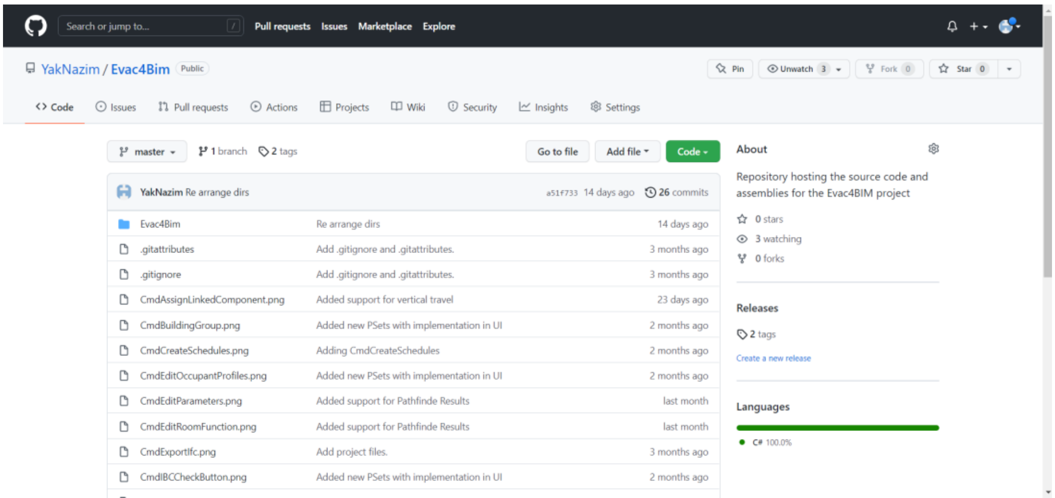


Figure 47 – Preview of the online repository

The online repository can be accessed through these links:

- https://github.com/YakNazim/Evac4Bim (Prototype add-in)
- https://github.com/YakNazim/Revit-IFC-Master (Custom IFC exporter)
- https://mega.nz/folder/TPpyjAQC#VJr5T6PZo0-9qF5yHBNvPw (recordings, case studies)
- https://github.com/YakNazim/Evac4Bim/wiki/Code-reference (Code reference)

5. DISCUSSION

5.1 Review of objectives and outcomes

In the first chapter, the research question was formulated, and the scope of the study was delimited. The research question was: **For fire safety engineers, how can we solve the current disconnect between BIM and evacuation assessment tools in order to join up a workflow and achieve a "Golden Thread of Information"?**

In order to answer this question, 6 objectives were established. Following is a description of how they were addressed.

Identify, evaluate, and select key properties related to evacuation from a Revit BIM model that are required for prescriptive checks of acceptable quality.
This objective was tackled in Chapter 2. The International Building Code was selected as an example and a review was performed by the author in order to identify data requirements related to occupant evacuation. The main focus was evacuation design, i.e., design rules in the geometric form, and limitations of escape routes such as maximum length of routes, the width, flow capacities and number of exits. This led to the identification of suitable data points and parameters for prescriptive assessments conducted with the IBC as well as output data. The methodology can be extended to cover additional prescriptive codes.

Identify key inputs and outputs that are imported to/from evacuation simulation tools.
In Chapter 2, the data requirement for performance studies of occupant evacuation in the context of FSE were analyzed. This relates to input properties for evacuation modelling tools and output results they generate. In the prototyping work, the study focused on Pathfinder, but the work can be adapted in the future to support additional packages.

By addressing the first two objectives, the research enables storing fire evacuation information in the model so that it can be shared with all stakeholders for informed decision making.

Draft a proposal for a data schema that enables exchange and sharing of evacuation safety data that was identified in steps 1 and 2.
This was tackled in Chapter 3 where the data requirements for fire evacuation assessment identified in steps 1 to 3 were compared to the current IFC Specifications and new entities were defined and incorporated to the IFC model. This resulted in the development of a new IFC schema covering the data requirements for fire evacuation. This data scheme provides a standard format defining properties names, units, and mapping.

By fulfilling this objective, this research enables the coupling of BIM models and engineering tools via a vendor-neutral format (IFC) and contributes to the drafting of the new MVD for FSE in development by buildingSMART.

Prototype an add-in package for Revit, which will implement the coupling of the BIM model in Revit with fire evacuation assessment tools

In chapter 3, the prototype add-in was introduced. It was developed using the Revit API. The working sequence of the add-in comprises: (1) Extraction of information required to perform assessments (2) Passing the extracted data to evacuation assessment tools (3) Capturing the results from evacuation assessment tools and displaying them to the user within the Revit interface (4) Storing data according to an extended IFC schema. The add-in also comprises a prototype regulatory-code reviewer that acts as a perspective assessment tool and demonstrates data exchange.

By addressing this objective and implementing the data loop, evacuation assessment information can be stored and serve as a golden thread for asset management, auditing, and forensics - post accident assessment. This also supports the efforts aiming to progress BIM into a high level of integration, described by Bew and Richards as Level 2 of BIM Maturity.

Evaluate the tool to ensure the integrity of simulation data that that is being transferred and the correctness of the prescriptive checks that are performed.

This was addressed in Chapter 4 where the add-in was tested on two case studies. For this purpose, a checklist was established to validate the add-in on key aspects, notably:

1. Prescriptions are implemented correctly
2. Required input data is passed to the assessment tool
3. Output data is captured in the BIM model
4. Data integrity is preserved during the exchange process
5. Parameters are mapped correctly according to the IFC schema
6. The data points can be accessed and displayed to the user dynamically in the Revit interface.

The add-in fulfilled all the requirements for validation in both test cases.

Based on the above, it can be concluded that the objectives of the study were fulfilled, and the research question has been tackled.

5.2 Contribution to knowledge

An important outcome of this thesis was the identification of data requirements for prescriptive and performance fire evacuation assessments.

This led to the definition of an IFC schema covering the data requirements for fire evacuation. The proposed IFC schema can contribute to the drafting of the MVD for Fire Safety Engineering which is in development by (buildingSMART, 2020). It also offers a broad definition which allows future developments to add support for alternative packages.

Another contribution of this research is that it demonstrated the feasibility of two-way data exchange between a BIM platform (Revit) and evacuation assessment tools.

Moreover, it enabled prototyping the golden thread of information by embedding fire evacuation information in the BIM model.

Finally, it was demonstrated that performance and prescriptive workflows can effectively be implemented in a BIM environment (in this case Revit) which offers capabilities for storing information and provides a visual feedback of assessment results for a better insight of evacuation performance and informed decision making

Added value to previous research

The added value of this study introduced in Chapter 2 is summarized here. This research successfully filled gaps that were identified in previous projects as follows:

- Creating a data loop enabling two-way data exchange from a BIM platform (Revit) to fire evacuation assessment tools.
- Storing data in a standard format for seamless data transfer.
- Implementing an updated IFC data schema which includes semantic data related to fire evacuation.
- Extending Revit and assessment tools to support import/export of IFC files featuring this new schema.
- Integration into Revit BIM by developing an add-in. This removes the need for external software packages or databases.
- Releasing the prototyped tools as open-source for transparency and to enable the community to carry out further development.
- Visual feedback and animation of time-dependent properties in Revit's interface for better understanding of evacuation performance and informed decision making.
- Collaboration with software vendors (Thunderhead Engineering) to enhance assessment tools and enable support of the two-way data exchange.

5.3 Potential future work

The development work presented in this thesis can be expanded and elaborated in different ways. The following items are suggested:

Expand the automated prescriptive-rules reviewer

- Better automation of model initialization (for instance, recognizing exit doors, better handling of multi storey stairways, door orientation, etc.)
- Support for additional IBC prescriptions such as Occupant Evacuation Elevators – OEEs (Chapter 30), refuge areas, spiral stairways, and requirements for different types of buildings (e.g., high-rise buildings).
- Support for specifications related to fire protection (active and passive) and structural integrity, in addition to evacuation design.
- Extraction of net area for spaces and rooms (currently only gross area is extracted, but the area of walls, columns and structural elements should be subtracted)
- Support for alternative prescription codes in addition to the IBC.

Expand the scope of data exchange with simulations tools

- Extraction of contour files generated by Pathfinder (e.g Level of service, density)
- Expand Pathfinder to support/parse additional input properties from the proposed IFC schema.
- Export simulation results into IFC directly from within the simulation tool, according to the proposed IFC schema
- Support for additional evacuation simulation tools in the market.
- Export and store object ID's (such as doors, rooms, stairs, etc.) for proper referencing when importing the results back.

Widen the applicability of data exchange with prescriptive tools:

- Analysis of alternative prescriptive codes to ensure proper coverage by the proposed IFC schema

Customizations for the prototype add-in

- Enable edition of configuration files in the Revit UI via specific commands (currently, configuration files can be edited outside Revit, as text files (csv format).

Expand and enhance the proposed IFC Schema and Revit IFC export

- Export IDs instead of IfcName
- Better support for complex datasets (such as lists, enumerations, and arrays)
- Currently, empty fields are not exported by Revit which results in missing data points in the IFC file. As a result, the add-in automatically fills empty fields with default values. For future applications, it is advised to allow exporting empty fields as void.

6. CONCLUSION

This research highlighted the need for better integration of FSE in BIM. This requirement was in fact established by key players in the field (such as IFSS and buildingSMART) following dramatic accidents such as the Grenfell Tower fire.

The key challenges and limitations facing the integration of FSE in the context of BIM were identified and an assessment of the current situation demonstrated that the data exchange between BIM and assessment tools is traditionally one-way and limited to geometrical information, with no explicit provision for the capture of results generated by these assessment tools. This leads to data loss and fragmentation of review processes.

In order to address these issues, a framework prototype was proposed which enabled the creation of a "round trip" data loop, linking BIM software (in this case Revit) to evacuation assessment tools and resulted in an effective two-way data exchange comprising not only geometry but also input properties necessary to conduct these assessments. The results from such evaluations can also be captured and sent back to the BIM model to be stored along with geometrical information

Development work in support of this framework was carried out and included the identification of suitable data points and parameters for prescriptive and performance fire evacuation assessments as well as output data. This work was based on rough pre-existing draft definitions (Abualdenien et al., 2021; A. A. Siddiqui, 2019) that were extended in collaboration with these authors. Furthermore, a prototype add-in was developed using the Revit Application Programming Interface to demonstrate sharing of data between BIM and fire evacuation assessment tools.

The prototype add-in was then tested according to a predefined sequence and the results were presented and discussed.

In the end, it is hoped that this prototype will form the template for further developmental work associated with an update to the buildingSMART IFC standard for occupant movement and fire safety engineering.

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APPENDICES

Appendix A: List of Property Sets for the proposed IFC schema

Table 22 – Proposed IFC properties for Project (ifcProject)

Property Set Name	Property Name	IFC Type	Description	Format
Pset_SimulationID	EvacuationModelName	IfcText	Name of the evacuation model used for the simulation	e.g "Pathfinder"
	EvacuationModelVersion	IfcText	Version of the evacuation model	e.g "2021.2.0525"
	EvacuationModelVendor	IfcText	Developer/vendor	e.g "www.thunderheadeng.com/pathfinder"
	EvacuationSimulationBrief	IfcText	Comment / description of the simulation	

Table 23 – Proposed IFC properties for Spaces (ifcSpace)

Property Set Name	Property name	IFC Type	Description	Format
Pset_SpaceFireSafetyRequirements	AlarmTime	IfcTimeMeasure	Time to Detection + Notification in a space/room [seconds]	e.g., "120"
Pset_SpaceEvacuationPerformanceInformation	InitialOccupancyNumber	IfcTimeMeasure	Initial number of agents assigned to a room/space before simulation starts [pers]	Single run > e.g., "5" Multiple runs > "n.a"
	EvacuationTime	IfcTimeMeasure	Time from start of simulation until agents exit a space/room [seconds]	Single run > e.g "60" Multiple runs > "avg=41.53,min=41.35,max=41.7,std=0.18"
	OccupancyHistory	IfcCountMeasure	Array representing the evolution of agent count in a space/room over time, throughout the simulation	Single run > "time,value;time,value;" e.g., "0,0;1,0;2,0;3,3;" Multiple runs > "n.a"
Pset_SpaceOccupancyRequirements	OccupancyNumber	IfcCountMeasure	Required number of occupants to populate the space/room [pers]	e.g "10"
	AreaPerOccupant	IfcAreaMeasure	Required density of occupants for the space/room [m^2/pers]	e.g "1"
	OccupancyNumberPeak	IfcCountMeasure	Maximum number of occupants allowed in the space/room	e.g "10"
Pset_SpaceCommon	AdmittedProfiles	IfcPropertyTableValue	List of agent profiles that are allowed in a component	"occupantProfile1,occupantProfile5"
	Category	IfcLabel	Category of space usage or utilization of the area. It is defined according to the IBC code § 1004.5	String value

Pset_SpaceOccupancyPrescriptionsReview	OccupancyNumberSpace	IfcCountMeasure	Actual number of occupants in the space/room	e.g "10"
	OccupancyNumberLimit	IfcCountMeasure	Maximum number of occupants allowed in the space/room	e.g "10"
	AreaPerOccupantSpace	IfcAreaMeasure	Required density of occupants for the space/room [m²/pers]	e.g "1"
	EvacuationCapacity	IfcLengthMeasure	Actual combined width of exits serving a space/room [mm]	e.g "1600"
	EvacuationCapacityRequirement	IfcLengthMeasure	Exit width required by IBC code (§1005.3.2) for a space/room [mm]	e.g "1600"
	ExitCount	IfcCountMeasure	Actual number of exits serving a space/room	e.g "2"
	ExitCountRequirement	IfcCountMeasure	Number of exits required by IBC code (§1006.2) for a space/room	e.g "2"
	EvacuationPathTravelDistance	IfcLengthMeasure	Actual distance to room/space to an exit [mm]	e.g "20000"
	EvacuationCapacityAdequate	IfcBoolean	Indication whether the combined width of exits serving a space/room is sufficient compared to the number of occupants	"String value "TRUE","FALSE"
	ExitCountAdequate	IfcBoolean	Indication whether the of exits serving a space/room is sufficient compared to the number of occupants	"TRUE","FALSE"
	EvacuationCapacityBalance	IfcBoolean	Indication whether the evacuation capacity is well distributed over the available exits (IBC (§1005.5)	"TRUE","FALSE"

	EvacuationPathTravelDistanceExcess	IfcBoolean	Indication whether the maximum allowed travel distance is exceeded (EvacuationPathTravelDistanceLimit)	"TRUE","FALSE"
	OccupancyNumberExcess	IfcBoolean	Indication whether the number of occupants exceeds the limit set by the IBC code (OccupancyNumberLimit)	"TRUE","FALSE"
	EvacuationPathTravelXYZ	IfcText	Coordinates of the vertices defining the curve line of the travel path	
	EvacuationComponentsPlacement	IfcBoolean	Indication whether the exits are placed correctly according to IBC code (§1007.1.1)	"TRUE","FALSE"

Table 24 – Proposed IFC properties for Building (ifcBuilding)

Property set name	Property name	IFC Data type	Description	Format
Pset_BuildingEvacuationPerformanceInformation	EvacuationTimeOverall	IfcTimeMeasure	Time from start of simulation until all agents exit the building [seconds]	Single run > e.g "60" Multiple runs > "avg=41.53,min=41.35,max=41.7,std=0.18"
	MinTravelDistance	IfcLengthMeasure	Minimum distance travelled by any agent [meters]	Single run > e.g "60" Multiple runs > "avg=10.39,min=8.69,max=11.51,std=1.49"
	MaxTravelDistance	IfcLengthMeasure	Maximum distance travelled by any agent [meters]	Single run > e.g "60" Multiple runs > "avg=10.39,min=8.69,max=11.51,std=1.49"
	AverageTravelDistance	IfcLengthMeasure	Average distance travelled by agents [meters]	Single run > e.g "60" Multiple runs > "avg=10.39,min=8.69,max=11.51,std=1.49"
	MinEvacuationTime	IfcTimeMeasure	Minimum evacuation time recorded for any agent [seconds]	Single run > e.g "60" Multiple runs > "avg=25.07,min=24.8,max=25.37,std=0.29"
	AverageEvacuationTime	IfcTimeMeasure	Average evacuation time recorded for agents [seconds]	Single run > e.g "60" Multiple runs > "avg=25.07,min=24.8,max=25.37,std=0.29"
	OccupancyHistoryOverall	IfcCountMeasure	Array representing the evolution of agent count for the whole building over time, throughout the simulation (total remaining / total exited vs time)	"time,remining,exited; time,remaining2,exited;"

Pset_BuildingCommon	OccupancyDistributionDayNight	IfcPropertyTableValue	Array describing the evolution of occupancy over the day by applying a multiplication factor at various times of the day.	"<HH , fraction> ; <HH , fraction > ..." E.g: Office building at full capacity between 8am to 5pm with reduced occupancy at lunch break "0,0 ; 8,0 ; 9,1 ; 12,0.5 ; 14,1 ; 17.5,0"
	OccupancyType	IfcLabel	Occupancy type for this building. It is defined according to the IBC code § 302.1	String value
	EmergencyCommunication	IfcLabel	Indication whether the building equipped with an emergency communication system (true) or not (false).	"TRUE","FALSE"
	SprinklerProtection	IfcLabel	Indication whether the building is sprinkler protected (yes) or not (No).	"TRUE","FALSE"
Pset_BuildingOccupancyRequirements	PreEvacuationTime	IfcTimeMeasure	Delay between the time evacuation is notified and the time agents start moving [pers]	Discrete value > "30" Distribution : "Uniform(Min,Max)" "Normal(Min,Max,Mean,Std dev)" "LogNormal(Min,Max,Location,Scale)"
	OccupantProfilesList	IfcPropertyTableValue	A set of profiles describing the desired characteristics for agents : speed, width...	{name;speed;speedProfile;diameter; isMobilityImpaired}{...} e.g "{name=Fruin2;speed=;speedProfile=Normal(0.6, 1.8,1.2,0.2); diameter=45.58;isMobilityImpaired=False}”

Pset_BuildingOccupancyPrescriptionsReview	OccupancyNumberBuilding	IfcCountMeasure	Actual overall number of occupants in the building	e.g "100"
	StairCountContinuity	IfcBoolean	Indication whether the number of stairs used for evacuation is maintained at each storey (IBC (§1005.4)	"TRUE","FALSE"
	StairCapacityContinuity	IfcBoolean	Indication whether the capacity of the stair system used for evacuation is maintained at each storey (IBC (§1005.4)	"TRUE","FALSE"
	StairCapacityPerOccupant	IfcLengthMeasure	Required stair width per occupant unit [mm/pers]	e.g "3.8"
	EvacuationCapacityPerOccupant	IfcLengthMeasure	Required exit width per occupant unit [mm/pers]	e.g "3.8"
	OccupancyNumberLimitSingleExitSpace	IfcCountMeasure	Maximum allowed number of occupants in a space/room having a single exit IBC (§1006.2.1)	e.g "50"
	EvacuationPathTravelDistanceLimit LowOccupancy	IfcLengthMeasure	Maximum allowed travel distance in a space/room having a single exit and less than 30 occupants (§1006.2.1)	e.g "78000"
	EvacuationPathTravelDistanceLimit HighOccupancy	IfcLengthMeasure	Maximum allowed travel distance in a space/room having a single exit and more than 30 occupants - Or equipped with sprinkler protection (§1006.2.1)	e.g "80000"

	EvacuationPathTravelDistanceLimit	IfcLengthMeasure	Maximum allowed distance to room/space to an exit [mm] (§1017.2)	e.g "75000"
Pset_BuildingFireSafetyPrescriptionsReview	SprinklerProtectionRequirement	IfcBoolean	Indication whether a sprinkler system is required by the IBC code (§1017.2)	"TRUE","FALSE"
	SprinklerProtectionLacking	IfcBoolean	Indication whether a sprinkler system is required by the IBC code (§1017.2) but is not provided	"TRUE","FALSE"

Table 25 – Proposed IFC properties for Doors (ifcDoor)

Property set name	Property name	IFC Data type	Description	Format
Pset_DoorEvacuationPerformanceInformation	FirstOccupantInTime	IfcTimeMeasure	Time to first agent crossing the component [seconds]	Single run > e.g "60" Multiple runs > "avg=41.53,min=41.35,max=41.7,std=0.18"
	LastOccupantOutTime	IfcTimeMeasure	Time to last agent crossing the component [seconds]	Single run > e.g "60" Multiple runs > "avg=41.53,min=41.35,max=41.7,std=0.18"
	AverageOccupantFlowrate	IfcReal	Average flow rate though component [pers/seconds]	Single run > e.g "60" Multiple runs > "avg=0.12,min=0.12,max=0.13,std=0.01"
	TotalUse	IfcCountMeasure	Total number of agents crossing the component	Single run > e.g "10" Multiple runs > "avg=10,min=5,max=15,std=5"
	DoorFlowrateHistory	IfcCountMeasure	Array representing the evolution of flow rate through component over time, throughout the simulation	Single run > "time,value1;time,value2;" e.g "0,0;1,0;2,0;3,0;4,0;5,0;" Multiple runs > "n.a"
	OccupancyHistory	IfcPropertyTableValue	Array representing the evolution of agent count in a space/room over time, throughout the simulation	Single run simulation > "time,value1;time,value2;" e.g "0,0;1,0;2,0;3,3;4,5;5,8;6,13;7" Multiple runs > "n.a"

Pset_DoorCommon	isAccessible	IfcBoolean	Door state (open/closed)	e.g "true"
	RequiredDoorFlowrate	IfcReal	Required flow rate through component [pers/sec]	e.g "1"
	FireExit	IfcBoolean	Indication whether the component is a fire exit	"TRUE","FALSE"
	DischargeExit	IfcBoolean	Indication whether the component serves as a storey/building discharge exit	"TRUE","FALSE"
	DimensionAdequate	IfcBoolean	Indication whether the door has adequate dimensions according to IBC code (§1010.1.1)	"TRUE","FALSE"

Table 26 – Proposed IFC properties for Stairs (ifcStair)

Property set name	Property name	IFC Data type	Description	Format
Pset_StairEvacuationPerformanceInformation	FirstOccupantInTime	IfcTimeMeasure	Time to first agent crossing the component [seconds]	Single run > e.g "60" Multiple runs > "avg=41.53,min=41.35,max=41.7,std=0.18"
	LastOccupantOutTime	IfcTimeMeasure	Time to last agent crossing the component [seconds]	Single run > e.g "60" Multiple runs > "avg=41.53,min=41.35,max=41.7,std=0.18"
	AverageOccupantFlowrate	IfcReal	Average flow rate though component [pers/seconds]	Single run > e.g "60" Multiple runs > "avg=0.12,min=0.12,max=0.13,std=0.01"
	OccupancyHistory	IfcPropertyTableValue	Array representing the evolution of agent count in a space/room over time, throughout the simulation	Single run simulation > "time,value1;time,value2;" e.g "0,0;1,0;2,0;3,3;4,5;" Multiple runs > "n.a"
Pset_StairCommon	AdmittedProfiles	IfcPropertyTableValue	List of agent profiles that are allowed in a component	"occupantProfile1,occupantProfile5"
Pset_StairPrescriptionsReview	RiserHeightAdequate	IfcBoolean	Indication whether the stair has an adequate riser height (§ 1011.5.2)	"TRUE","FALSE"
	TreadLengthAdequate	IfcBoolean	Indication whether the stair has an adequate tread length (§ 1011.5.2)	"TRUE","FALSE"
	FireEvacuationStair	IfcLabel	Indication whether the stair can serve for fire evacuation	"TRUE","FALSE"

Table 27 – Proposed IFC properties for Building storey (IfcBuildingStorey)

Property set name	Property name	IFC Type	Description	Format
Pset_BuildingStoreyCommon	EntranceLevel	IfcLabel	Indication whether this building storey is an entrance level to the building (yes), or (no) if otherwise	"TRUE","FALSE"
Pset_BuildingStoreyOccupancyPrescriptionsReview	OccupancyNumberStorey	IfcCountMeasure	Actual overall number of occupants in the storey	e.g "10"
	EvacuationCapacityStorey	IfcLengthMeasure	Actual combined width of exits serving a storey [mm]	e.g "1600"
	EvacuationCapacityRequirementStorey	IfcLengthMeasure	Exit width required by IBC code (§1005.3.2) for the storey [mm]	e.g "1600"
	ExitCountStorey	IfcCountMeasure	Actual number of exits serving a space/room	e.g "2"
	ExitCountRequirementStorey	IfcCountMeasure	Number of exits required by IBC code (§1006.3.2) for the storey	e.g "2"
	EvacuationCapacityAdequateStorey	IfcBoolean	Indication whether the combined width of exits serving the storey is sufficient compared to the number of occupants	"TRUE","FALSE"
	ExitCountAdequateStorey	IfcBoolean	Indication whether the number of exits serving the storey is sufficient compared to the number of occupants	"TRUE","FALSE"
	EvacuationCapacityBalanceStorey	IfcBoolean	Indication whether the evacuation capacity is well distributed over the available exits (IBC (§1005.5)	"TRUE","FALSE"

	StairCount	IfcCountMeasure	Actual number of stairs serving the storey	e.g "2"
	StairCapacity	IfcLengthMeasure	Actual combined width of stairs serving the storey	e.g "1600"
	StairCountRequirement	IfcCountMeasure	Required number of stairs for the storey according to IBC code (§1006.3.2)	e.g "2"
	StairCapacityRequirement	IfcLengthMeasure	Required stair capacity for the storey according to IBC code (§1011.2)	e.g "1600"
	StairCountAdequate	IfcBoolean	Indication whether the number of stairs serving the storey is sufficient compared to the number of occupants	"TRUE","FALSE"
	StairCapacityAdequate	IfcBoolean	Indication whether the combined width of stairsserving the storey is sufficient compared to the number of occupants	"TRUE","FALSE"
	StairCapacityBalance	IfcBoolean	Indication whether the evacuation capacity is well distributed over the available stairs on the storey(IBC (§1005.5)	"TRUE","FALSE"

Appendix B: Floor plans from the case studies

School building

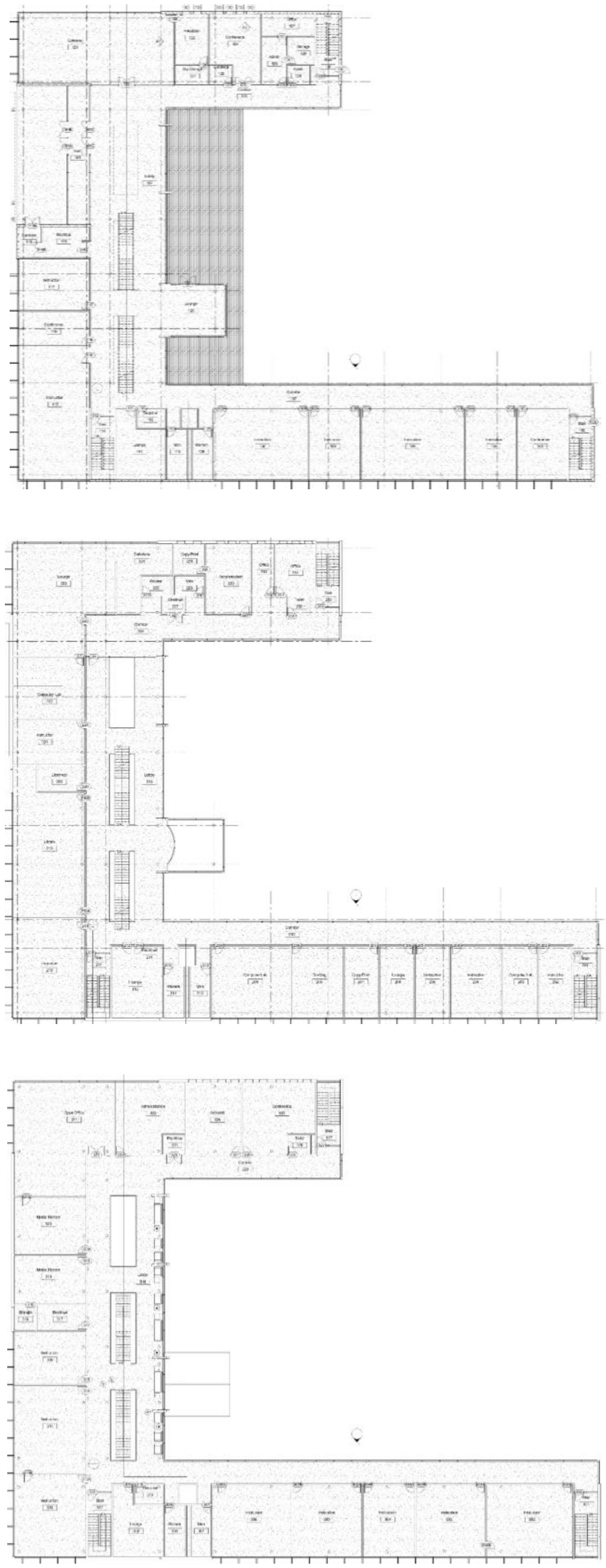


Figure 48 – Floor plans for the school building
From top to bottom: Ground floor – Level 2 – Level 3

Hotel building

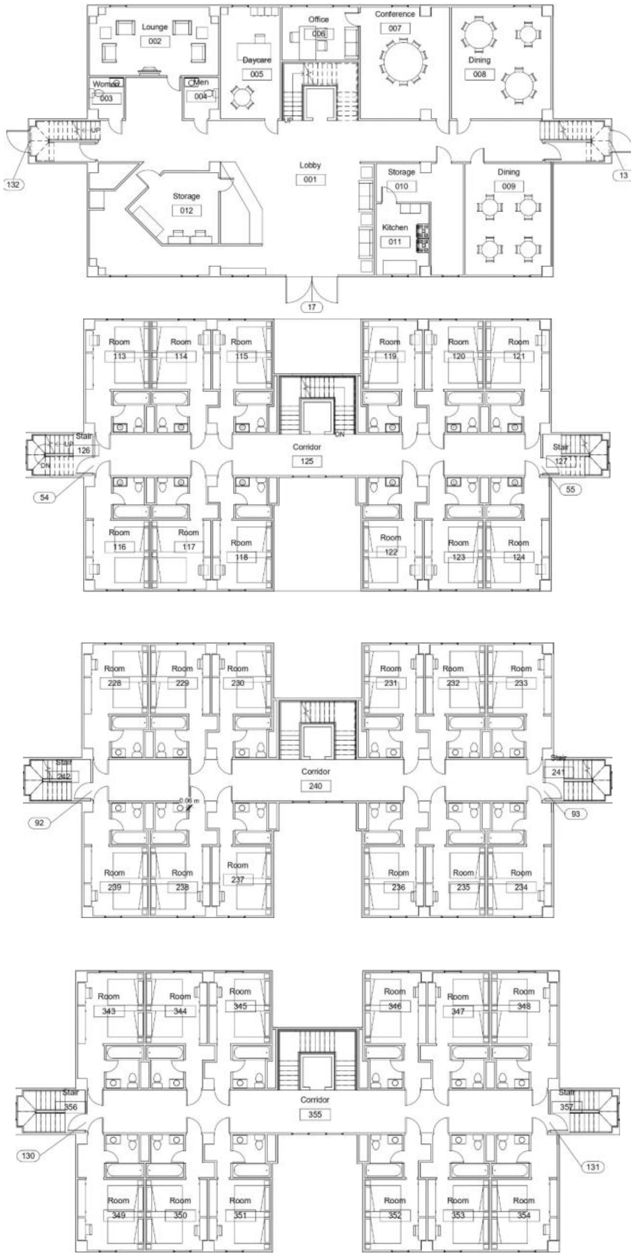
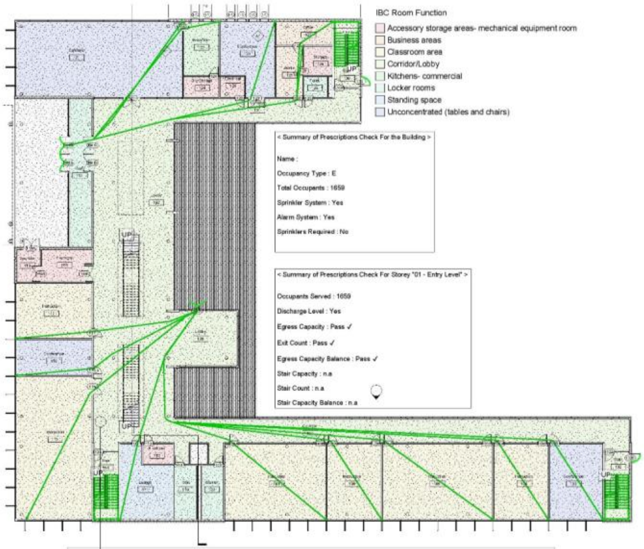


Figure 49 - Floor plans for the hotel building

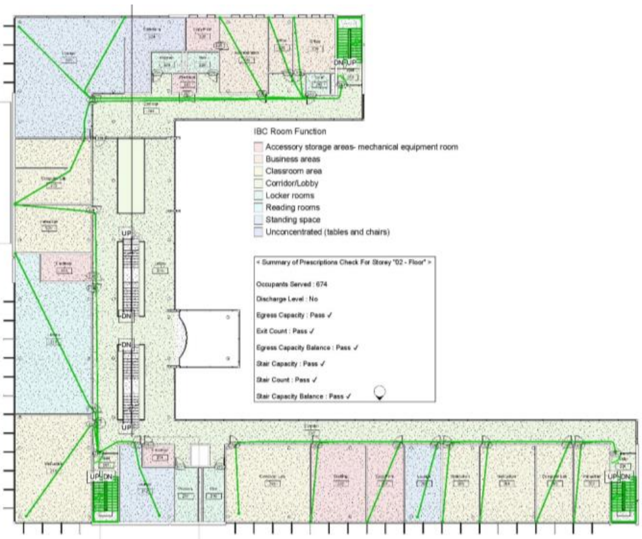
From top to bottom: Ground floor –Level 1 - Level 2 – Level 3

Appendix C: Prescriptive review results

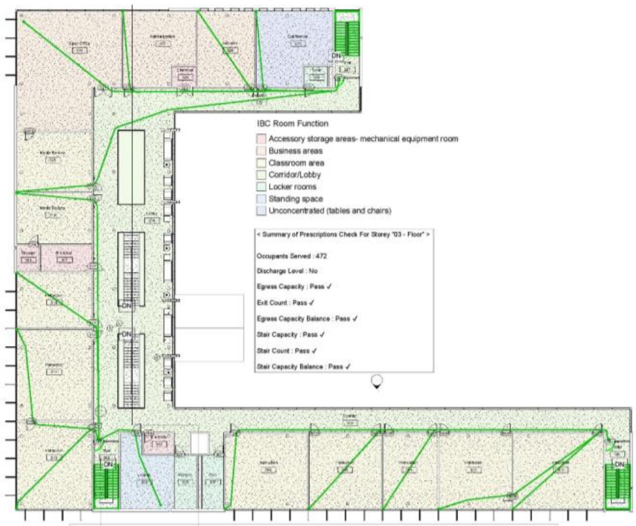
School building



Ground floor - Level 1



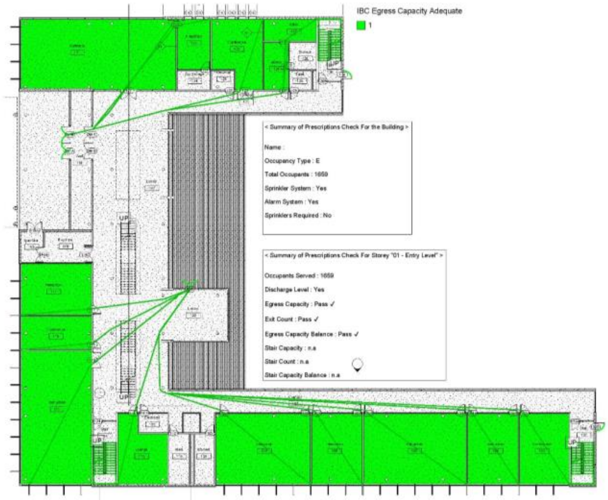
Level 2



Level 3

Table 28 – Legend for prescriptive review results (case study 1)

Pass	Fail



Ground floor - Level 1

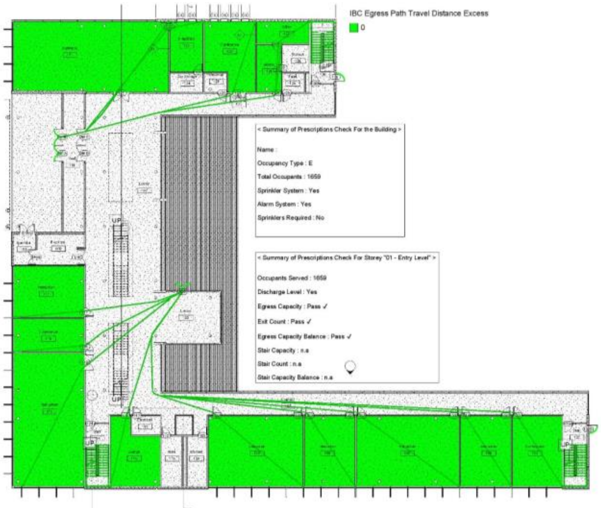
Level 2

Level 3

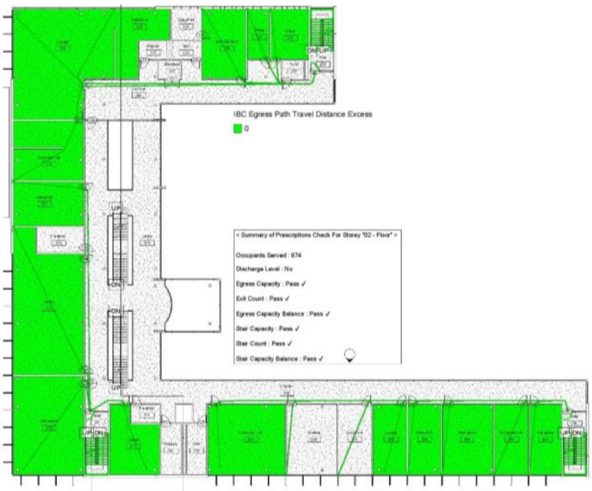
Ground floor - Level 1

Level 2

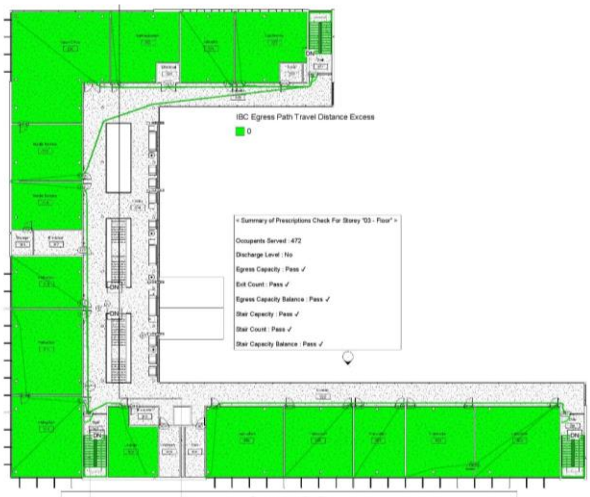
Level 3



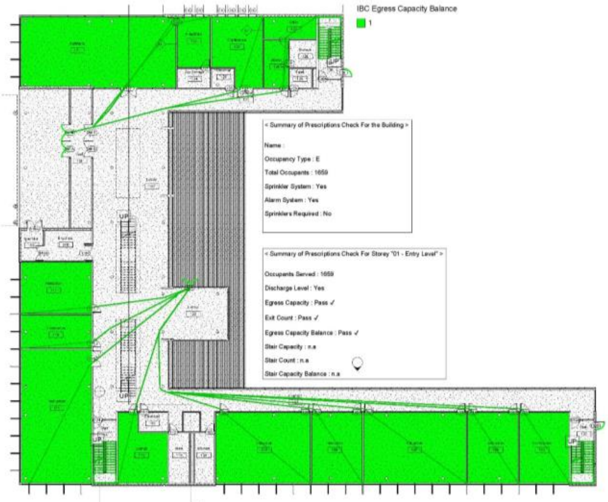
Ground floor - Level 1



Level 2



Level 3



Ground floor - Level 1

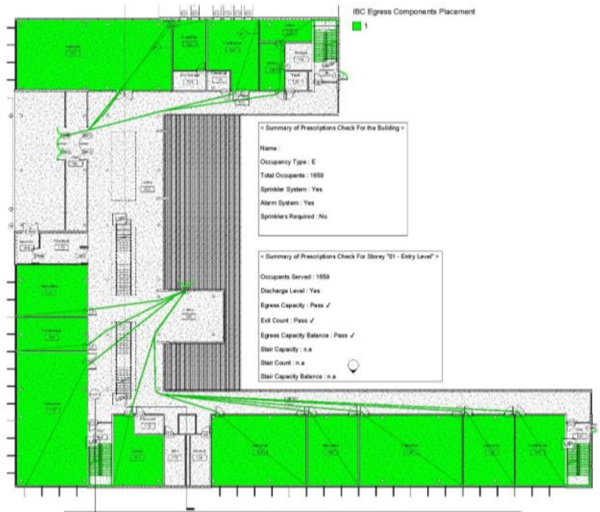
Level 2

Level 3

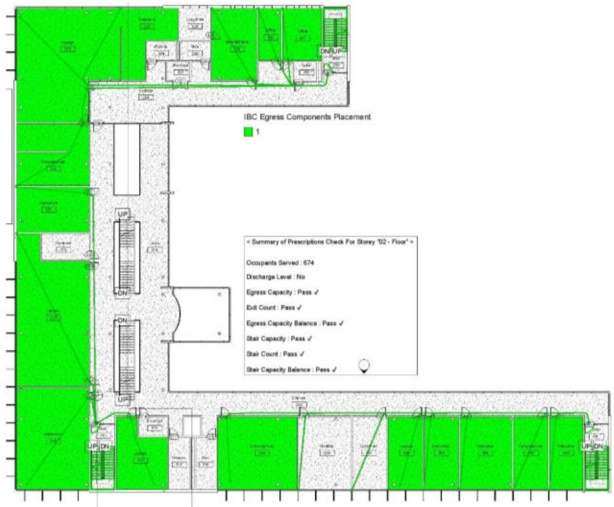
Ground floor - Level 1

Level 2

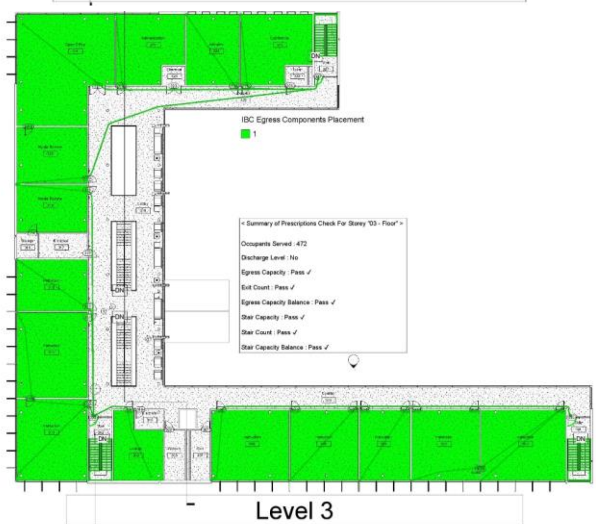
Level 3



Ground floor - Level 1



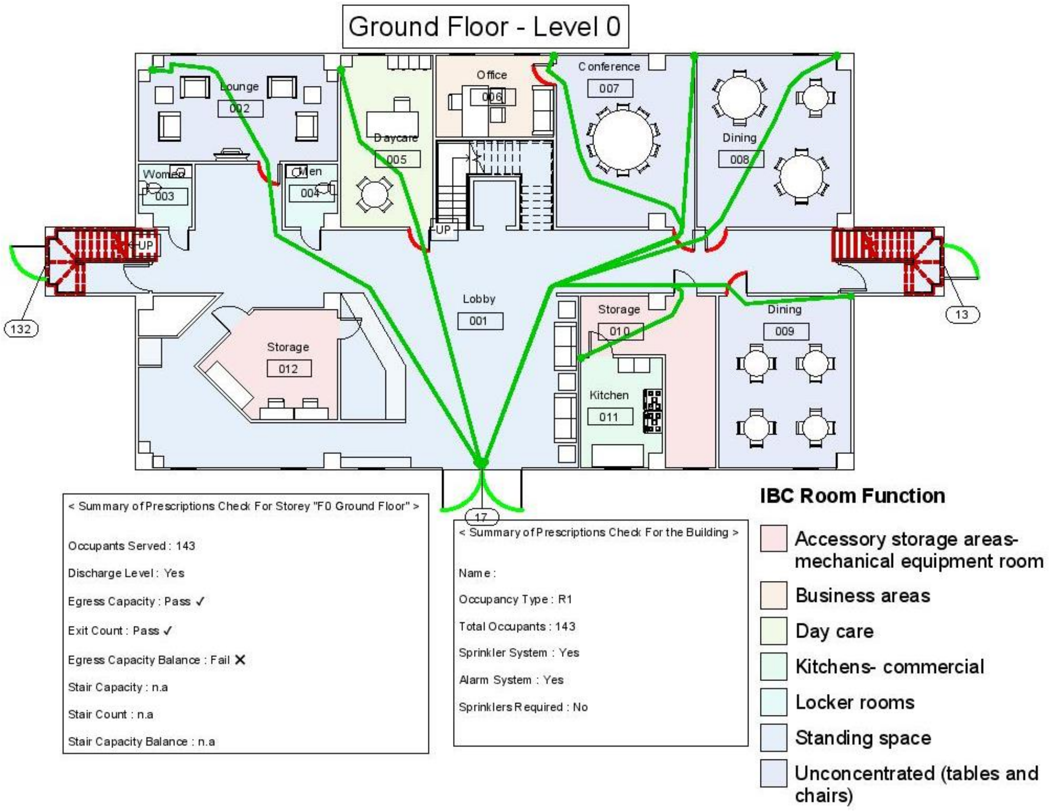
Level 2



Level 3

Hotel building

Note: Since the three upper floors have a similar layout of guest rooms, only the first floor is reported.



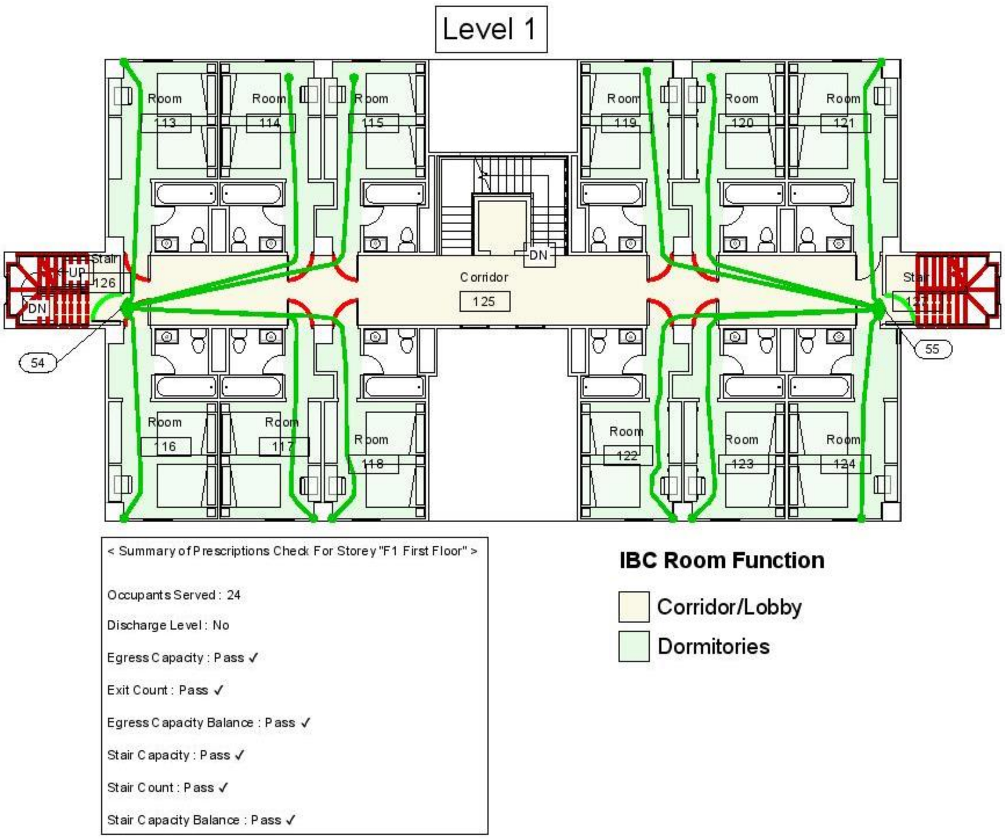
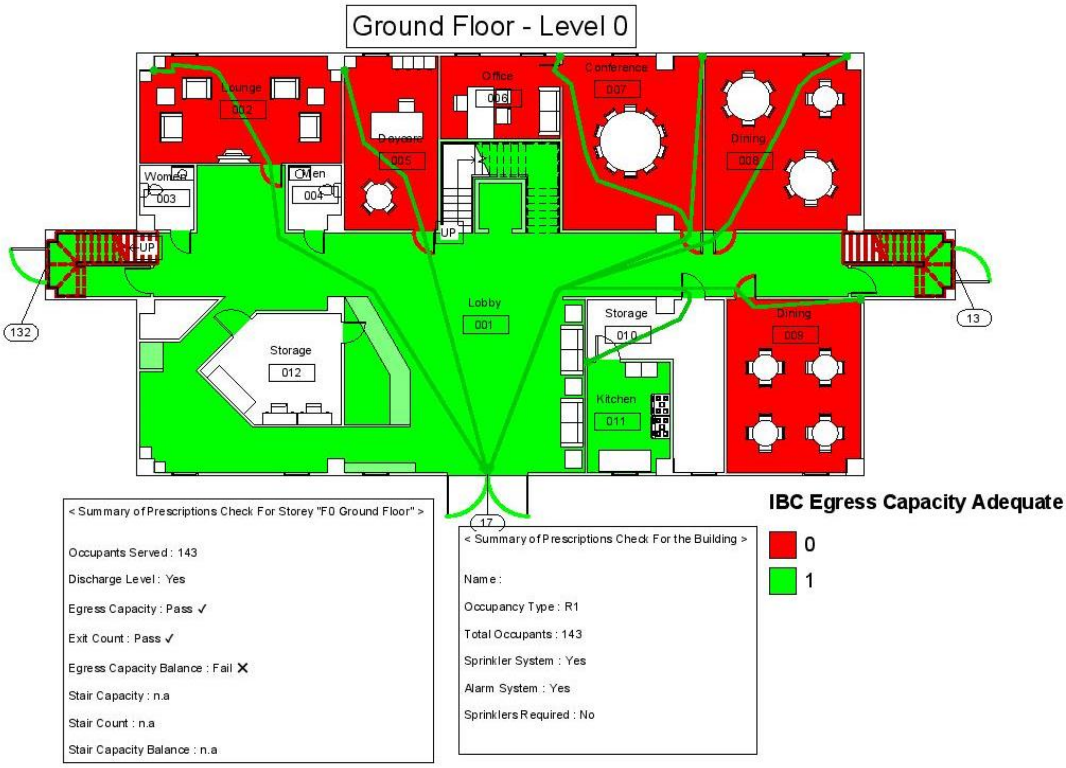
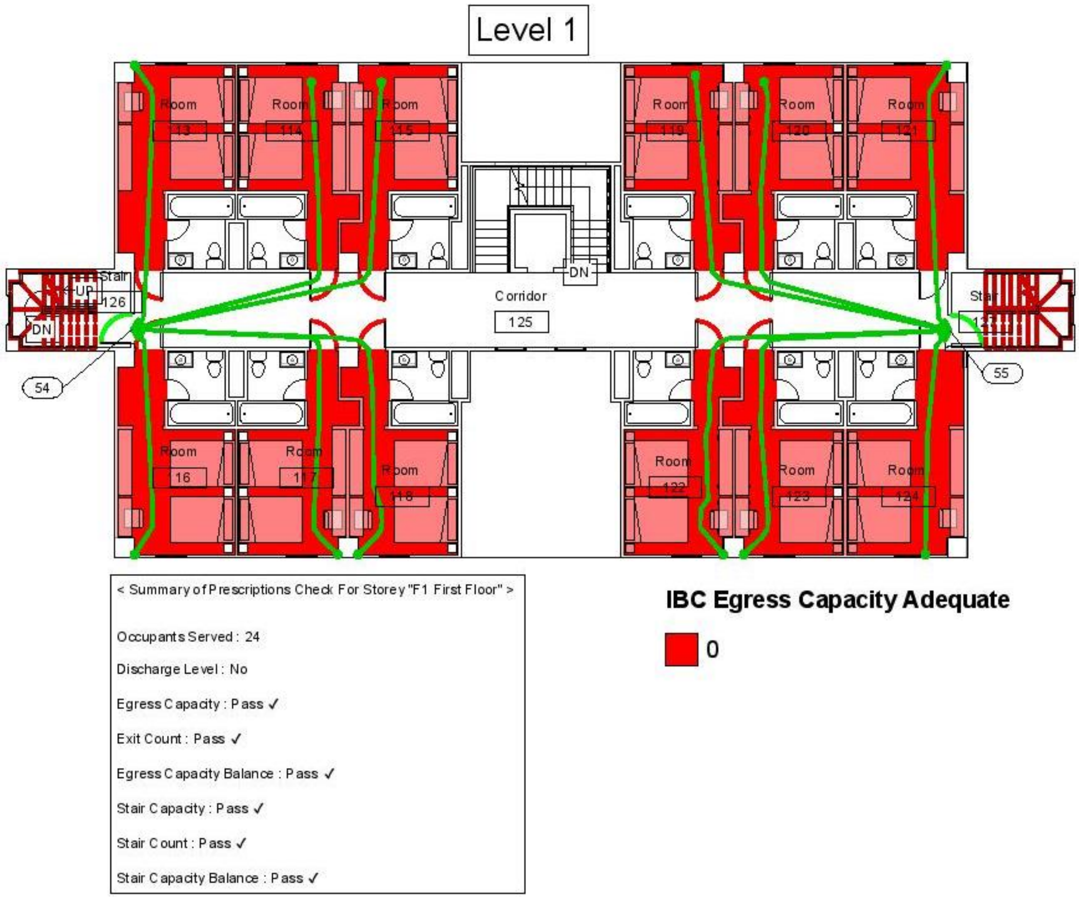
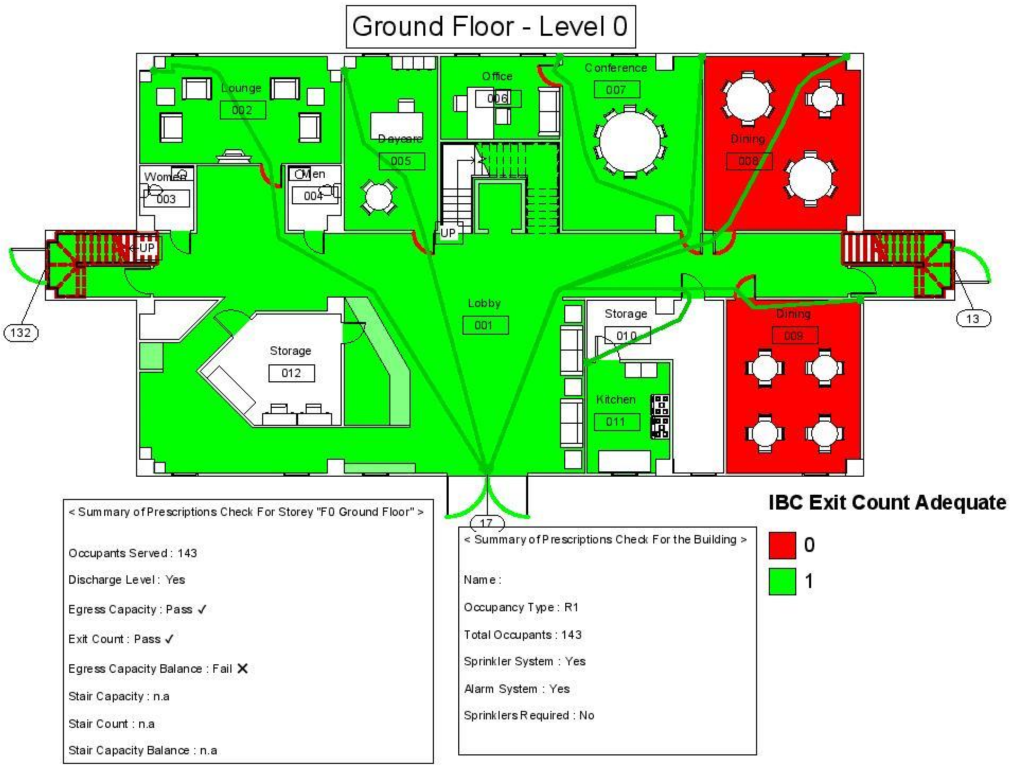


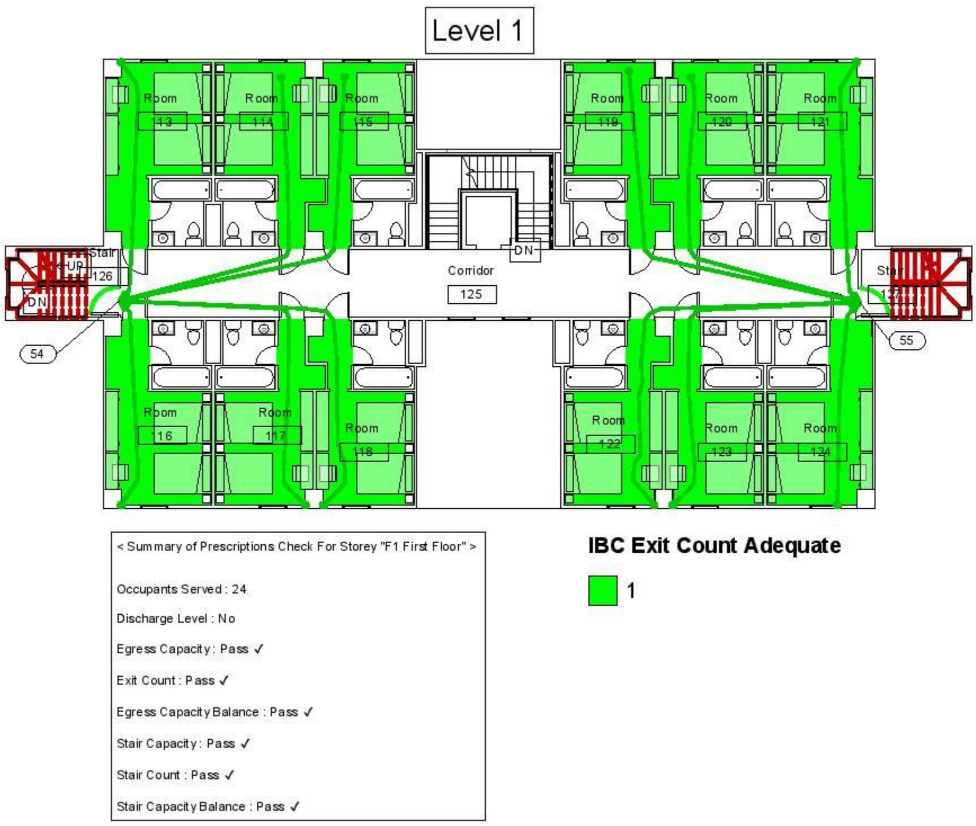
Table 29 – Legend for prescriptive review results (case study 2)

Pass	Fail

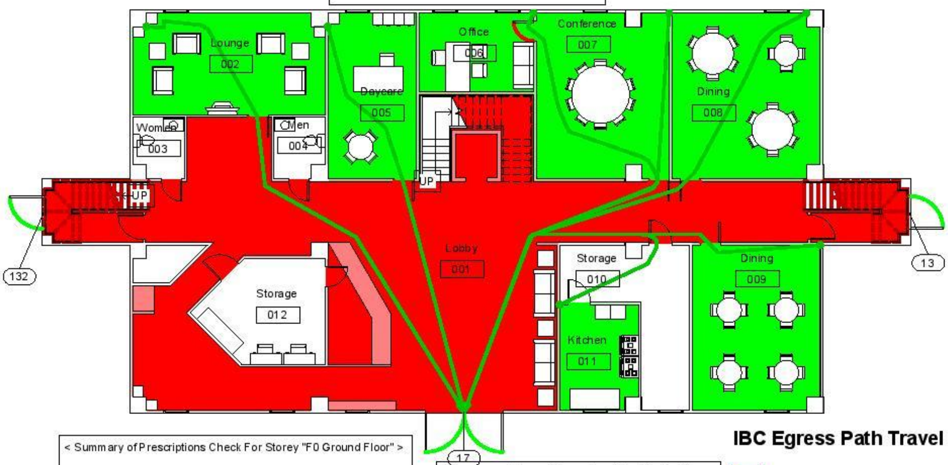





Ground Floor - Level 0
Lounge
002
Office
006
Conference
007
Dining
008
Daycare
005
Women
003
Men
004
UP
Lobby
001
Storage
010
Dining
009
Storage
012
Kitchen
011
132
13
17
< Summary of Prescriptions Check For Storey "F0 Ground Floor" >
Occupants Served : 143
Discharge Level : Yes
Egress Capacity : Pass ✓
Exit Count : Pass ✓
Egress Capacity Balance : Fail ✕
Stair Capacity : n.a
Stair Count : n.a
Stair Capacity Balance : n.a
< Summary of Prescriptions Check For the Building >
Name :
Occupancy Type : R1
Total Occupants : 143
Sprinkler System : Yes
Alarm System : Yes
Sprinklers Required : No
IBC Exit Count Adequate
0
1


Level 1
Room
113
Room
114
Room
115
Room
119
Room
120
Room
121
Stair
126
UP
DN
Corridor
125
Stair
Room
116
Room
117
Room
118
Room
122
Room
123
Room
124
54
55
< Summary of Prescriptions Check For Storey "F1 First Floor" >
Occupants Served : 24
Discharge Level : No
Egress Capacity : Pass ✓
Exit Count : Pass ✓
Egress Capacity Balance : Pass ✓
Stair Capacity : Pass ✓
Stair Count : Pass ✓
Stair Capacity Balance : Pass ✓
IBC Exit Count Adequate
1

Ground Floor - Level 0



< Summary of Prescriptions Check For Storey "F0 Ground Floor" >

Occupants Served : 143

Discharge Level : Yes

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Fail ✕

Stair Capacity : n.a

Stair Count : n.a

Stair Capacity Balance : n.a

< Summary of Prescriptions Check For the Building >

Name :

Occupancy Type : R1

Total Occupants : 143

Sprinkler System : Yes

Alarm System : Yes

Sprinklers Required : No

IBC Egress Path Travel Distance Excess

- 0
- 1

Level 1

< Summary of Prescriptions Check For Storey "F1 First Floor" >

Occupants Served : 24

Discharge Level : No

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Pass ✓

Stair Capacity : Pass ✓

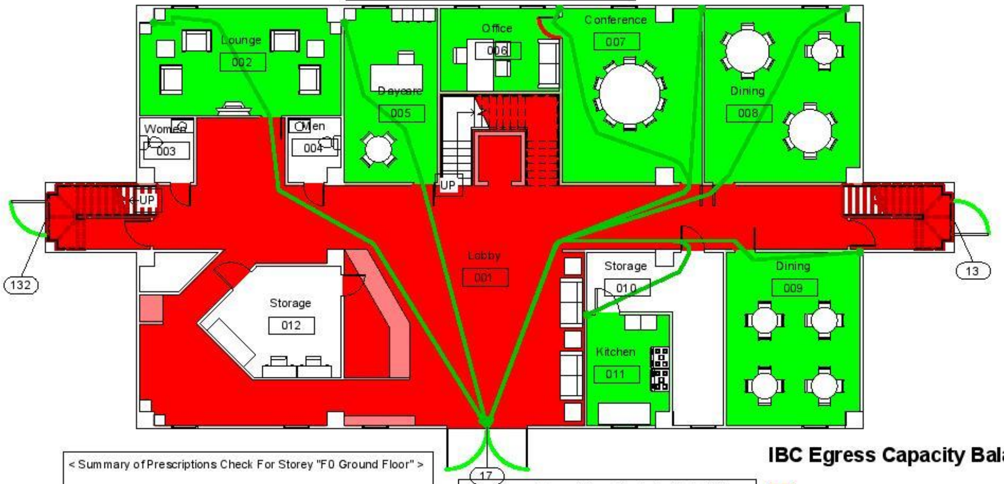
Stair Count : Pass ✓

Stair Capacity Balance : Pass ✓

IBC Egress Path Travel Distance Excess

- 0

Ground Floor - Level 0



< Summary of Prescriptions Check For Storey "F0 Ground Floor" >

Occupants Served : 143

Discharge Level : Yes

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Fail ✕

Stair Capacity : n.a

Stair Count : n.a

Stair Capacity Balance : n.a

< Summary of Prescriptions Check For the Building >

Name :

Occupancy Type : R1

Total Occupants : 143

Sprinkler System : Yes

Alarm System : Yes

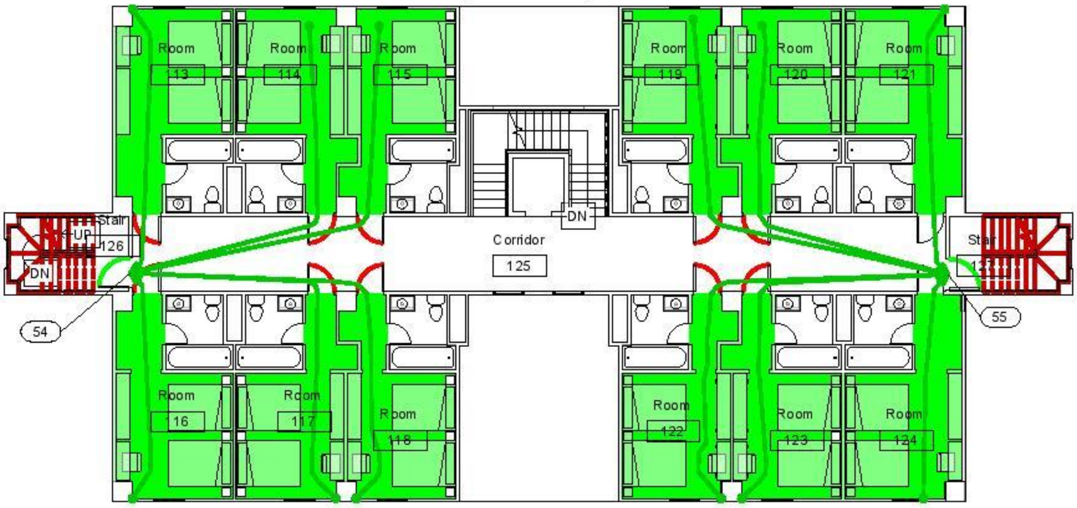
Sprinklers Required : No

IBC Egress Capacity Balance

0

1

Level 1



< Summary of Prescriptions Check For Storey "F1 First Floor" >

Occupants Served : 24

Discharge Level : No

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Pass ✓

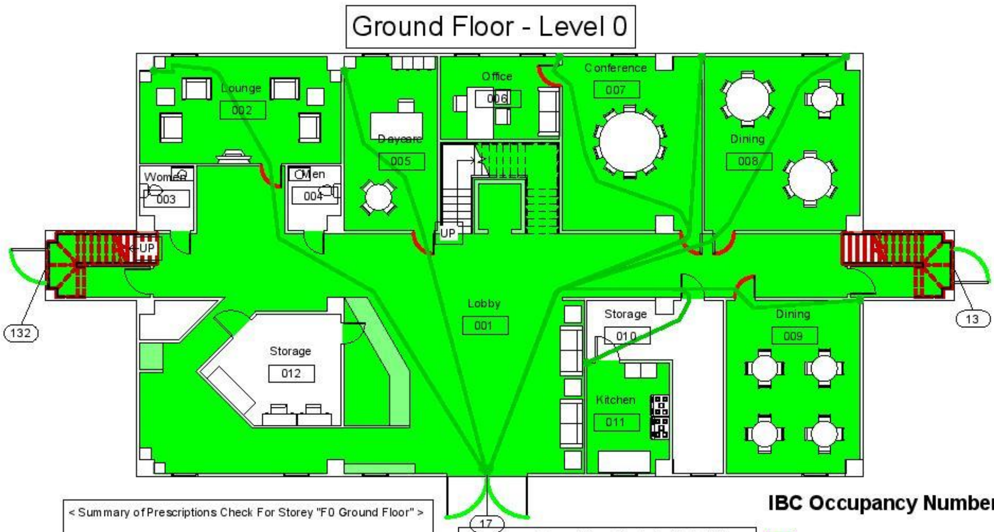
Stair Capacity : Pass ✓

Stair Count : Pass ✓

Stair Capacity Balance : Pass ✓

IBC Egress Capacity Balance

1



< Summary of Prescriptions Check For Storey "F0 Ground Floor" >

Occupants Served : 143

Discharge Level : Yes

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Fail ✗

Stair Capacity : n.a

Stair Count : n.a

Stair Capacity Balance : n.a

< Summary of Prescriptions Check For the Building >

Name :

Occupancy Type : R1

Total Occupants : 143

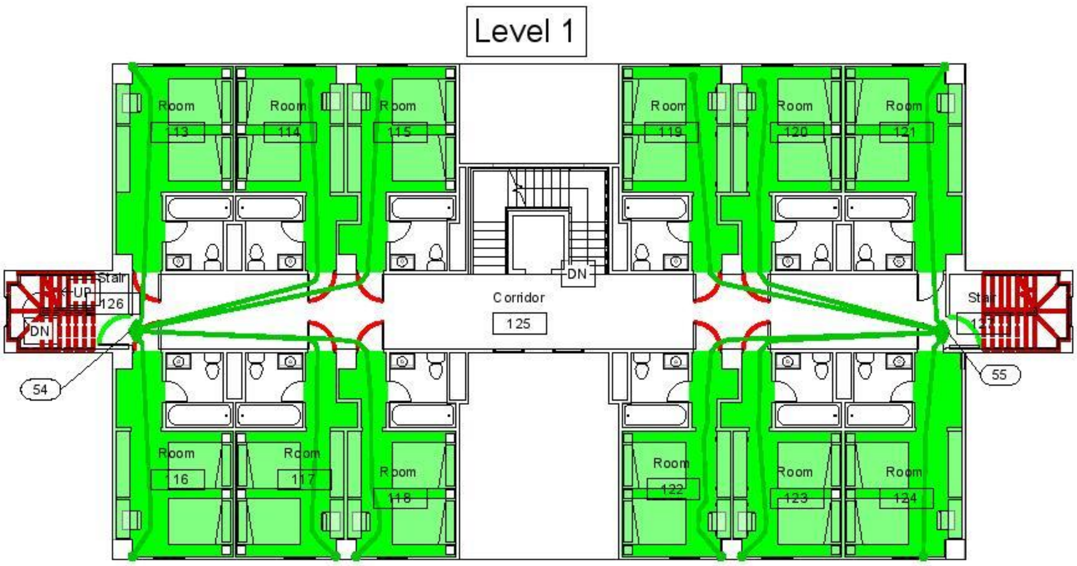
Sprinkler System : Yes

Alarm System : Yes

Sprinklers Required : No

IBC Occupancy Number Excess

0



< Summary of Prescriptions Check For Storey "F1 First Floor" >

Occupants Served : 24

Discharge Level : No

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Pass ✓

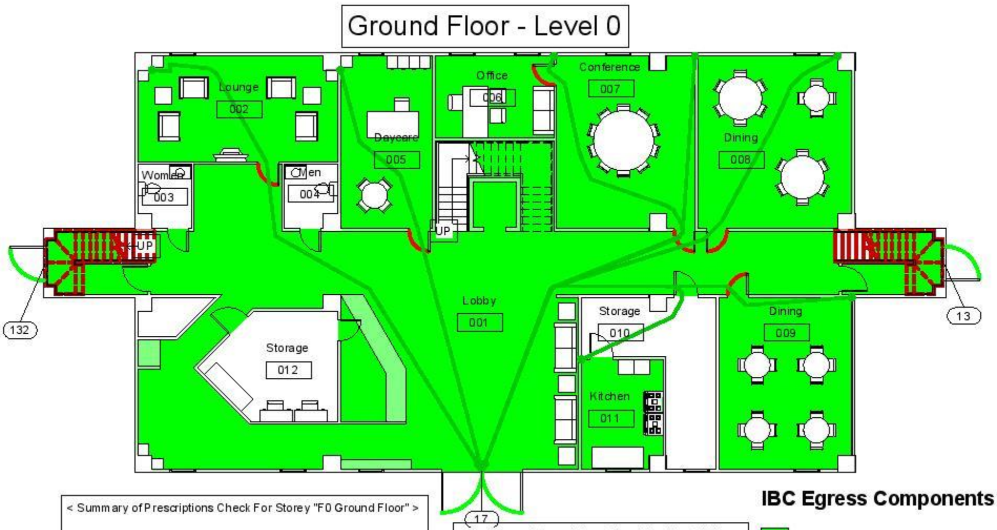
Stair Capacity : Pass ✓

Stair Count : Pass ✓

Stair Capacity Balance : Pass ✓

IBC Occupancy Number Excess

0



< Summary of Prescriptions Check For Storey "F0 Ground Floor" >

Occupants Served : 143

Discharge Level : Yes

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Fail ✕

Stair Capacity : n.a

Stair Count : n.a

Stair Capacity Balance : n.a

< Summary of Prescriptions Check For the Building >

Name :

Occupancy Type : R1

Total Occupants : 143

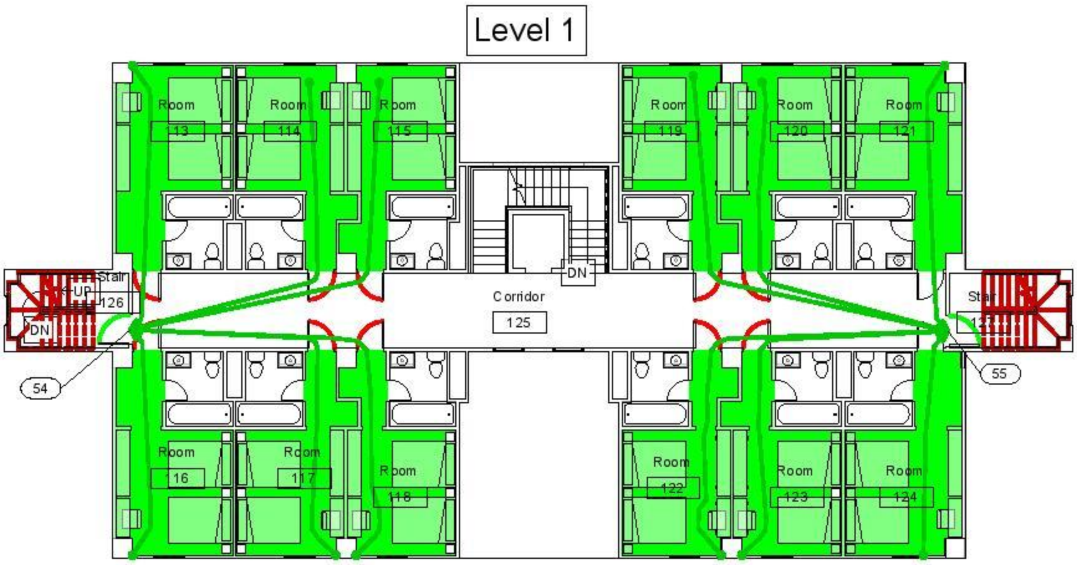
Sprinkler System : Yes

Alarm System : Yes

Sprinklers Required : No

IBC Egress Components Placement

1



< Summary of Prescriptions Check For Storey "F1 First Floor" >

Occupants Served : 24

Discharge Level : No

Egress Capacity : Pass ✓

Exit Count : Pass ✓

Egress Capacity Balance : Pass ✓

Stair Capacity : Pass ✓

Stair Count : Pass ✓

Stair Capacity Balance : Pass ✓

IBC Egress Components Placement

1

Appendix D: Code reference

This is a short overview of the source code for the Revit add-in. This add-in was developed using Revit API in the Visual Studio .Net environment.

Reference

Following is a list of some useful resources and documentation related to the code implementation

- Revit Developer Center
  https://www.autodesk.com/developer-network/platform-technologies/revit
- Revit API tutorial
  (https://knowledge.autodesk.com/search-result/caas/simplecontent/content/my-first-revit-plug-overview.html)
- Revit API Developers Guide
  https://help.autodesk.com/view/RVT/2021/ENU/?guid=Revit_API_Revit_API_Developers_Guide_html
- Revit SDK samples
  https://github.com/jeremytammik/RevitSdkSamples
- Training material
  https://github.com/ADN-DevTech/RevitTrainingMaterial
- API documentation
  https://www.revitapidocs.com/

Code structure

The main entry point to the program is the **Evac4Bim.MainApp** class. This class sets up the UI in Revit and includes calls to different "standalone" commands.

The standalone commands can execute several tasks such as reading files, defining new shared parameters, lookup and edit parameters, etc. They make use of the methods and objects offered by the Revit API. Each command consists of a class inheriting the **IExternalCommand** interface and implementing the **Execute** method which is called by Revit after the user runs it. The main argument of the Execute command is an **ExternalCommandData** object which gives access to the current Revit Document, UI and Project. The logic of each command/class is described in the comments written throughout the code

The standalone commands are listed in Table 30.

Table 30 – List of standalone commands from the add-in source code

Class	Description
CmdBuildingGroup.cs	This class allows the user to define the building group of the model. Then, it initializes variables which depend on the building group such as max travel distance and width per occupant
CmdCreateSchedules.cs	This class creates schedules in the Revit UI to display simulation results that were imported
CmdEditOccupantProfiles.cs	This class enables the user to edit/store occupant profiles in the model
CmdEditParameters.cs	This class schedules the fields that need to be edited prior the prescriptive check
CmdEditRoomFunction.cs	This class allows the user to define the function of a room. Then, it initializes variables which depend on the room function such as **AreaPerOccupantSpace**, load factor
CmdExport.cs	This class provides a shortcut for calling the IFC exporter. The IFC exporter must be loaded into Revit - at start-up - through a separate add-in. This class calls the exporter with pre-defined parameters. It will intercept the export and fill empty fields with default values
CmdGenerateInputFile.cs	This class allows user to export an extended pathfinder input file. The original input file (containing the geometry) is selected by the user then additional properties -extracted from the model - are appended to the input file
CmdIBCCheck.cs	This class performs an automated review of specific IBC prescriptions related to fire evacuation. It checks various requirements at different levels : space => storey => stair => building. The results are displayed in the form of text notes, colour schemes and object colouring (doors and stairs)
CmdImportParameter.cs	This class imports simulation results and stores them in shared parameters
CmdLaunchResults.cs	This class enables the user to launch Pathfinder results from the Revit UI (The path to the binary must be defined first in the project parameters => **PathfinderResultsBinary**)
CmdLoadParameters.cs	This class loads shared parameters in the Revit project. The shared parameters are parsed from a CSV file which contains name, type and applicable category
CmdMakePaths	This class generates travel paths from rooms to a specified exit. It can also store the horizontal travel distance
CmdSelectPreferredExit	This class allows user to assign an exit to a selected room
CmdSelectPreferredStair	This class allows user to assign a stairway to different rooms

CmdAssignLinkedComponent	This class allows to link individual stairs part of a multi-storey system in order to compute the vertical travel distance
CmdPlotCharts.cs	This class plots various charts from imported simulation results
CmdRenameItems.cs	This class sets the parameter "IfcName" for elements such as doors and rooms. The name includes the id of the element in the Revit model. The name is stored in the IFC model and used to query the elements when importing results
CmdResultAnimation	This project includes classes implementing the animation of simulation results via a modeless dialog

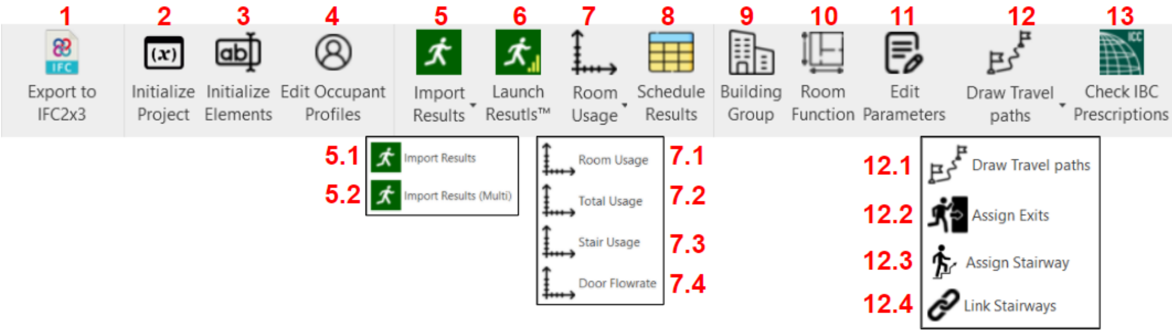


Figure 6 – Available commands in the Revit add-in

Configuration files

These files are used to store properties and tabulated data so it can be parsed by the add-in.

Table 31 – List of configuration files for the Revit add-in

File	Description
building-group.csv	List of Building Groups according to the IBC code
room-functions.csv	List of Room Functions and corresponding Occupant Load Factors according to IBC code (sqm/occupant)
shared-pramas-list.csv	List of shared parameters that can be imported into Revit by the add-in. It includes the definition and default values
Table-1006.2.1.csv	Copy of the Table n°1006.2.1 from the IBC code in CSV format
Table-1017-2.csv	Copy of the Table n°1017.2 from the IBC code in CSV format

IFC export

The IFC exporter was forked from the open-source Revit IFC exporter (Autodesk, 2022a). It allows to generate enriched IFC files supporting the fire evacuation data requirements of the draft FSE MVD.

The main entry point for IFC exporter is **Revit.IFC.Export.Exporter** namespace. In order to enable exporting additional property sets not supported natively by Revit, a delegate method is defined.

The implementation of the derived class can be found under **Revit.IFC.Export.Exporter.CustomExporter.cs.**

Code implementation

The typical working sequence of the standalone commands is presented in Figure 50.

When the user runs a command (by clicking the corresponding button in the UI as shown in Figure 6), its **Execute** member method is called. Typically, the command would query building elements from the model (such as doors, rooms, stairs…) then parse their properties (for instance, door width) via the **LookupParameter** method. It can then perform tasks (for example, comparing the door width against the minimal required value) and then optionally, write results back into the model.

The whole reading / writing process between the add-in commands and the main Revit environment is handled by API transactions.

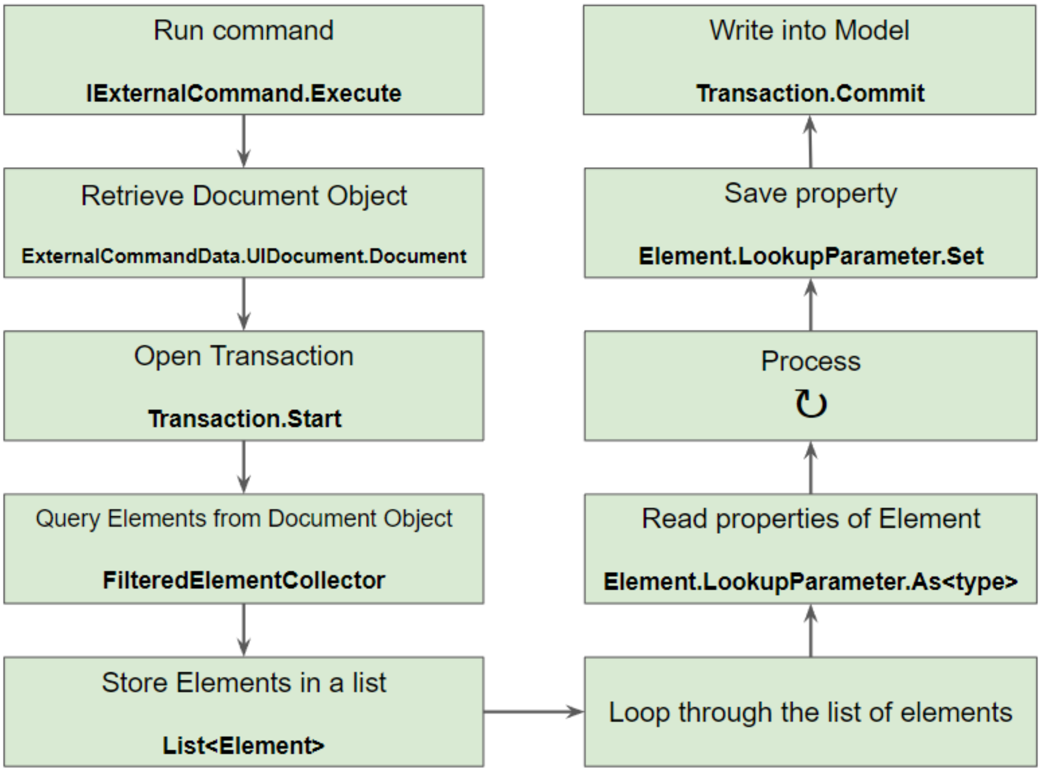


Figure 50 – Typical read-write sequence of an API command in Revit

The working sequence of the **ImportParameter** command is shown in Figure 51. This command is responsible for importing and storing Pathfinder simulation results into the Revit model.

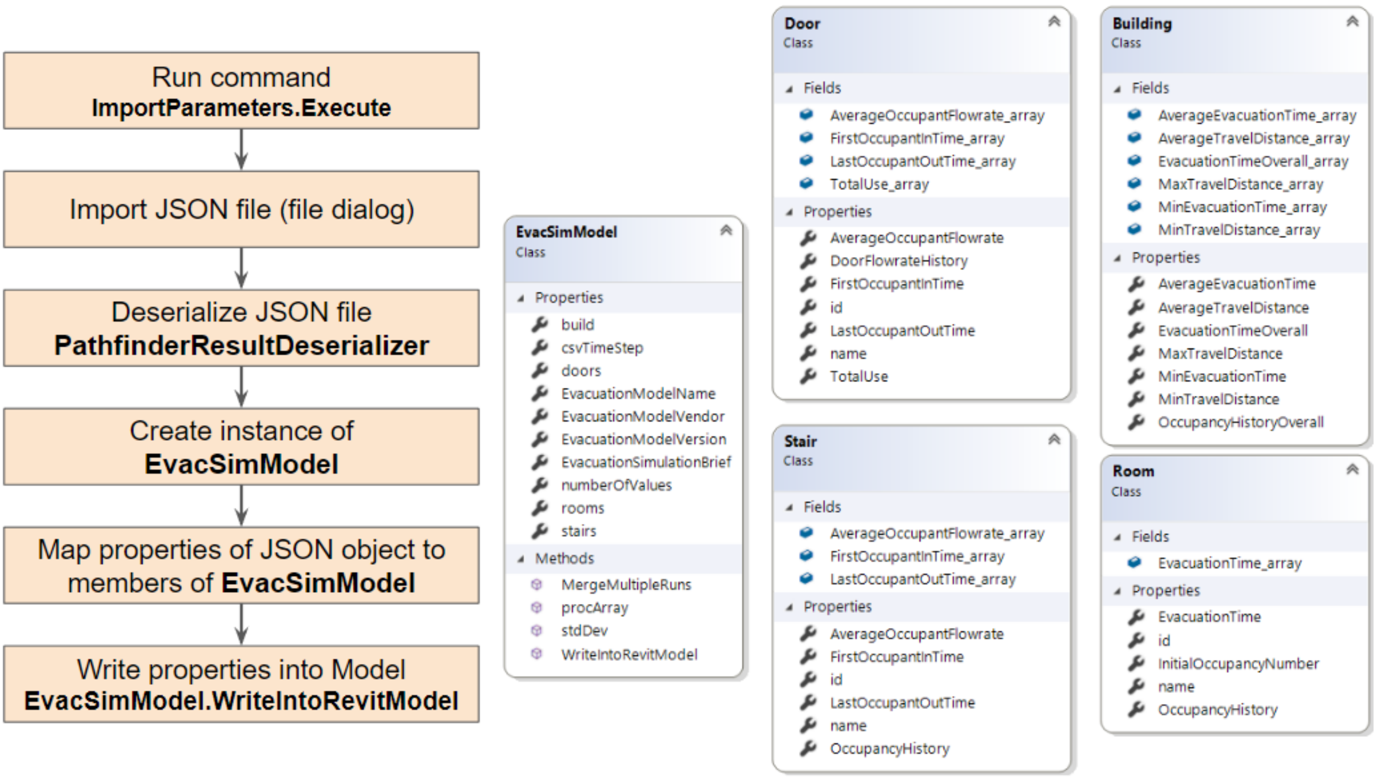


Figure 51 – Working sequence of the ImportParameter command from the Revit add-in

Overall, it follows the same sequence described previously with a few additional steps. Pathfinder generates a JSON file, which stores simple data structures and objects in JavaScript Object Notation (JSON) format (w3schools, 2022).

This JSON file is imported, and its content is "deserialized" (i.e, the data is decoded into a native format. In this case, it is converted into a class with properties and fields). Next, the properties of the "deserialized" object are copied into an instance of **EvacSimModel.**

The class **EvacSimModel** is a generic interface for storing egress simulation data. This class is meant to establish a level of abstraction so that it can store data from any evacuation simulator. The class diagram is shown in the same figure above. Its properties include lists of building elements such as rooms, stairs, and doors, which in turn store associated simulation results (for e.g a door has an id, an average flowrate, etc).

Once simulation results are imported, it is possible to plot graphs of time-dependent values such as the number of occupants in a room over time. This is done by running the **CmdPlotChart** command. Figure 52 shows its working sequence.

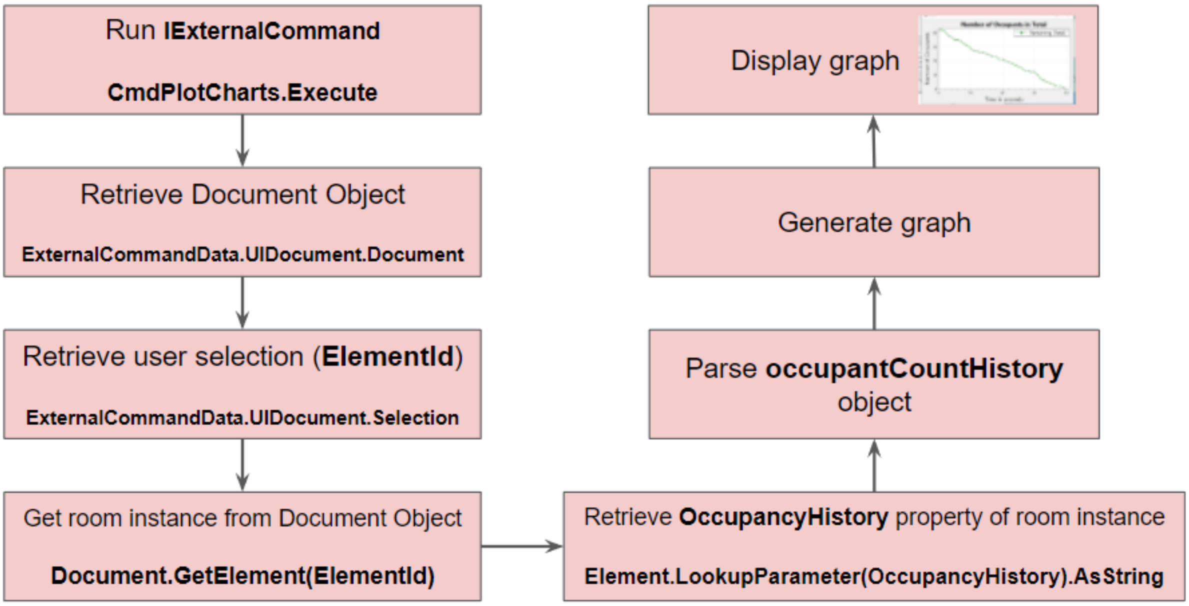


Figure 52 – Working sequence of the **CmdPlotChart** command form the Revit add-in

Lastly, the working sequence of the **CmdIBCCheck** command is presented in Figure 53.

This command performs an automated review of specific IBC prescriptions related to fire evacuation. It checks various requirements at successive levels : space ➔ storey ➔ stair ➔ building. The results are displayed in the form of text notes, color schemes and object coloring (doors and stairs). The review process is performed by specific methods described in Table 32. The selected rules/prescription are summarized in Tables 3,4 and 5.

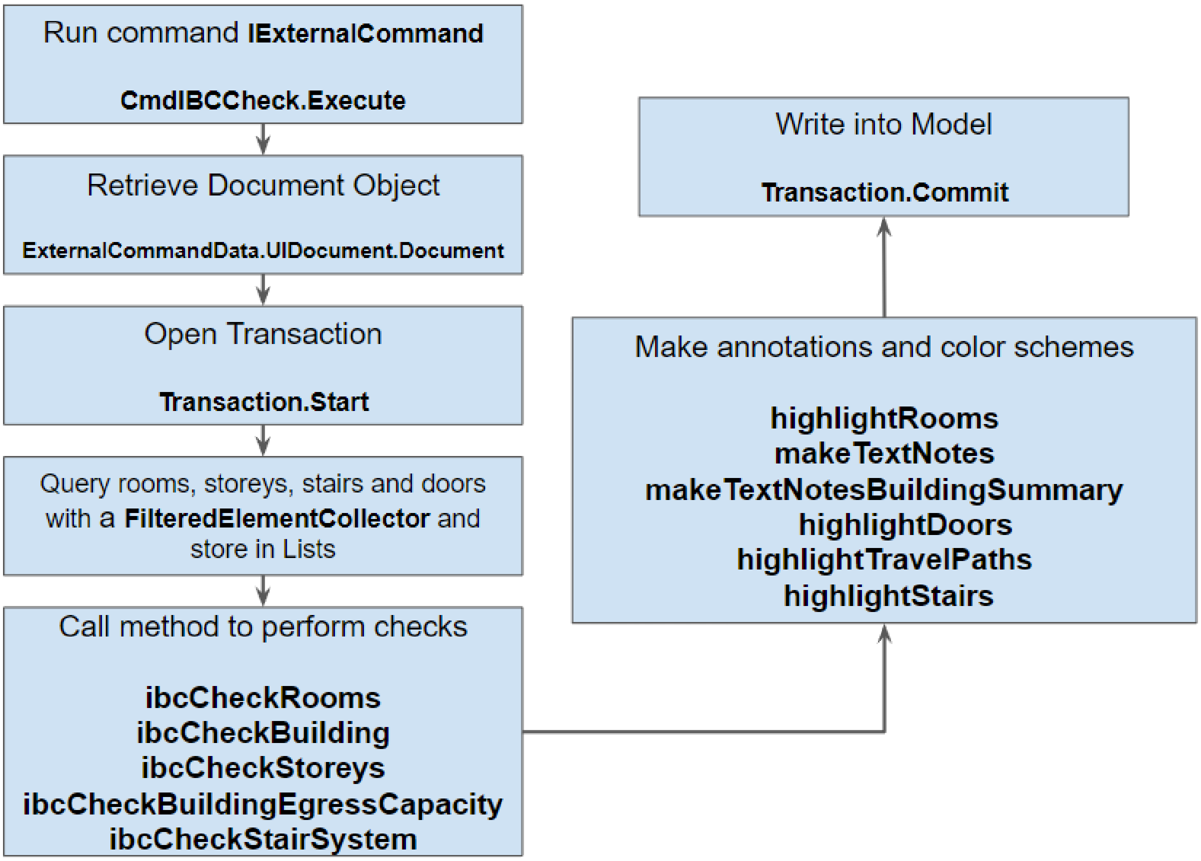


Figure 53 - Working sequence of the **CmdIBCCheck** command form the Revit add-in

Table 32 – Description of the code review process in the **CmdIBCCheck** command of the Revit add-in

Method	Description
ibcCheckRooms	- Exit doors have the required minimum size (§1010.1.1) : 813 mm x 2032 mm - The number of exit doors is sufficient (§1006.2.1 and §1006.2.2) : If the number of occupants > 1000 ⇒ 4 Else If 500 < number of occupants< 1000 ⇒ 3 Else If number of occupants> Max Occupant of Space or Travel distance > Limit ⇒ 2 exits (Table 1006.2.1) Else ⇒ 1 exit - The combined width of all doors (egress capacity) for that space is sufficient (§1005.3.2) 5.1 mm per occupant 3.8 mm if building class is not H / I-2 and there is sprinkler + voice alarm - This egress capacity is well balanced (§1005.5) i.e if one door is subtracted, the remaining capacity > 50% of the initial capacity - Distance between exits (§1007.1.1 and §1007.1.2) 2 doors : Distance between 2 doors > 50% room diagonal length > 2 doors : At least 2 doors are separated by a distance > 50 % of the diagonal distance If there are sprinklers and alarms => Consider a factor of ⅓
ibcCheckStoreys * Consider discharge exits i.e fire exits serving the whole storey	Consider the combined number of occupants of all the rooms in that storey - The number of exit doors is sufficient (§1006.3.2) Total number of occupants < 501 ⇒ 2 exits 501 < Total number of occupants < 1000 ⇒ 3 exits Total number of occupants > 1001 ⇒ 4 exits - Egress capacity) for that space is sufficient (§1005.3.2) 5.1 mm per occupant 3.8 mm if building class is not H / I-2 and there is sprinkler + voice alarm - Egress capacity is well balanced (§1005.5) i.e by subtracting one door, the remaining capacity does not drop below 50% of the initial capacity
ibcCheckBuildingEgressCapacity	Same as **ibcCheckStoreys**, but consider the total number of occupants in the whole building versus the discharge exits located at the evacuation floor (usually ground floor)
ibcCheckBuilding	Check if sprinklers are required, and if so, whether they are provided
ibcCheckStairSystem	Check stairs to ensure there are : - In sufficient number (§1006.3.2) - The combined width is sufficient with regards to the number of occupants served (§1005.3). 7.6 mm per occupant 5.1 mm if building class is not H / I-2 and there is sprinkler + voice alarm §1011.2 : If number of occupants < 50 ⇒ minimum width 36 in (914 mm) If number of occupants > 50 ⇒ minimum width 44 in (1118 mm) - Well-constructed : 102mm < Riser height < 178mm Tread depth > 279mm - The capacity is maintained over storeys (i.e same width at each storey to avoid bottlenecks) - The capacity is well balanced