DEVELOPING A BIM-BASED TOOL FOR AUTOMATED FALL SAFETY REVIEW

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DEVELOPING A BIM-BASED TOOL FOR AUTOMATED FALL SAFETY REVIEW

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To My Love & My Family,

ABSTRACT

Construction sites are globally known to be amongst the most dangerous working environments. Ensuring safety at sites can be difficult because it is not affected by just one parameter; but it is governed by the behavior of the workers, site conditions, and the design and implementation of the safety measures. Falling from a height and getting hit by moving or falling objects are statistically the most common type of accidents at sites, and can result in serious injuries and fatalities. Traditionally, health and safety (H&S) experts perform site investigations and use two-dimensional (2D) site drawings to plan and implement safety measures related to hazards at site. In other words, the majority of the risk identification and associated hazard identification tasks performed by H&S experts are mainly based on the review of 2D drawings, particularly during the earlier stages of a construction. The major shortcoming of this traditional method is that it is difficult to identify the potential hazards from a 2D drawing, especially during the construction as the project is progressing. Building Information Modeling (BIM) is considered to have the potential to overcome the challenges observed with the traditional 2D-based planning and implementation of safety measures. A BIM-based approach can provide a continuous assistance for the identification of hazards and the related safety measures throughout the construction of a building. It can provide an efficient solution to plan and design the safety measures of a construction project both during the design and construction phases. The 3D model can also enable effective safety review of buildings. Therefore, this study aims to develop a BIM-based automatic fall safety review tool by using Dynamo which is an open-source visual programming add-in for Autodesk's BIM tool, Revit. This tool automatically reviews a 3D building model to identify its hazardous locations and places the related safety measures for preventing fall-related hazards in the

building.

ÖZETÇE

İnşaat sahalarının en tehlikeli çalışma ortamları arasında olduğu tüm dünyada bilinmektedir. Şantiyelerde iş güvenliği sadece tek bir parametreye bağlı olmadığı ve işçilerin davranışları, şantiye koşulları ve iş güvenliği önlemlerinin tasarımı ve uygulanmasından da etkilendiği için şantiyelerde iş güvenliğinin sağlanması zor olabilmektedir. Yüksekten düşme ve yüksekten düşen nesnelerin vurması sonucu oluşan kazalar, istatistiki olarak görülen en yaygın kaza türüdür ve ciddi yaralanmalara ve ölümlere sebep olmaktadır. Genellikle iş saglıgı ve güvenliği (İSG) uzmanları şantiyedeki tehlikelerle ilgili güvenlik önlemlerini planlamak ve uygulamak için yerinde incelemeler yapmakta ve iki boyutlu (2B) proje çizimlerini kullanmaktadırlar. Başka bir deyişle, İSG uzmanları tarafından gerçekleştirilen risklerin ve ilgili tehlikelerin belirlenmesi görevlerinin çoğu, özellikle inşaatın ilk aşamalarında 2B çizimlerin incelenmesine dayanmaktadır. Bu geleneksel yöntemin en büyük eksikliği, potansiyel tehlikelerin 2B çizimlerden öngörülebilmesinin özellikle proje ilerledikçe daha da zor olmasıdır. “Yapı Bilgi Modellemesi” (Building Information Modeling - BIM)’nin, geleneksel 2B çizimlere dayalı iş güvenliği planlama ve uygulanması sırasında gözlenen zorlukların üstesinden gelme potansiyeline sahip olduğu düşünülmektedir. BIM-tabanlı bir yaklaşım, bir inşaat projesinin başlangıcından sonuna kadar tehlikelerin ve bu tehlikeleri önleyecek olan iş güvenliği önlemlerinin belirlenmesi için sürekli olarak kullanılabilir. Bu yöntem, bir inşaat projesinin iş güvenliği önlemlerini hem tasarım aşamasında hem de inşaatın her aşamasında planlamak ve tasarlamak için etkili bir çözüm sağlayabilir. Ayrıca, üç boyutlu (3B) model, binalardaki iş güvenliği önlemlerinin görsel olarak incelenmesini sağlayabilir. Bu nedenle, bu çalışmada, Autodesk'in BIM yazılımı olan Revit’in açık kaynaklı bir görsel programlama eklentisi olan Dynamo kullanılarak otomatik bir BIM

tabanlı düşme güvenliği inceleme aracı geliştirilmesi amaçlanmıştır. Bu araç, 3B bina modeli üzerinde düşme tehlikesi bulunan noktaları belirleyip, gerekli güvenlik önlemlerini otomatik olarak modelin üzerine yerleştirmektedir.

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ABBREVIATIONS

4D CAD	: Four-Dimensional Computer Aided Design
2D	: Two-Dimensional
3D	: Three-Dimensional
AFSR	: Automated Fall Safety Review
BIM	: Building Information Modelling
CM	: Current Model
DfS	: Design for Safety
H&S	: Health and Safety
HSE	: Health and Safety Executive
IFC	: Industry Foundation Classes
ILO	: International Labour Organization
MM	: Main Model
OHSA	: Occupational Health and Safety Act
OSHA	: Occupational Safety and Health Administration
PFASs	: Personal Fall Arrest Systems
VR	: Virtual Reality

CHAPTER I

INTRODUCTION

Construction industry is considered as one of the most hazardous industries. According to Occupational Safety and Health Administration (OSHA), 20.5% of fatalities occurred in the construction industry in 2014 (Kang, Siddiqui, Suk, Chi, & Kim, 2017a). International Labour Organization (ILO) indicates that 25-40% of all fatal workplace accidents occur at construction sites in industrialized countries (Suraji, Duff, & Peckitt, 2001).7.7% of total employment in Turkey is from the construction industry. Although its employment share is small, 32.1% of all the fatal occupational accidents between 2000 and 2016 occurred in the construction industry (Bilir & Gurcanli, 2018). Moreover, it has been identified that mostly new and young workers are likely to get hurt while working (Ministry of Labour, 2013).

There are various risks associated with construction works and the following are amongst the most common types of hazards in the construction industry: falls from height, struck by objects, contact with electricity, heavy equipment accidents, traffic accidents on site, building or structure collapses, cave-ins, fire or explosions (Gürcanli & Müngen, 2009; Perlman, Sacks, & Barak, 2014). Although all types of hazards must be identified and handled properly, especially falls from height and struck by objects require the majority of industry's attention, as these are the most common type of accidents at construction sites that lead to serious injuries and even fatalities. According to OSHA and ILO, fall from height and struck by objects are the most frequent types of accidents that cause deaths and injuries (Bilir & Gurcanli, 2018). Among the 681 accidents that were observed between the years 2000 and 2013, the number of fall from height and struck by object accidents are respectively 396 and 65. In other words, 67.7% of all fatal and non-fatal accidents occurred due to fall from height and struck by objects (Bilir & Gurcanli, 2018). Due to the frequency and importance of fall-related accidents in the construction industry, the focus of this thesis is determined as the fall-related occupational accidents.

There are many conventional safety measures to prevent such hazards, for instance Personal Fall Arrest Systems (PFASs), guardrails, and safety net systems (OSHA, 2015). Although the importance of safety measures is known by the construction professionals, and it is straightforward that the related safety measures should be used at hazardous places; one can fail to recognize all of the fall hazards in a project, and therefore may not use the proper safety measures where necessary. The main reason for this is that traditional methods to plan, design and implement safety measures still rely on two-dimensional (2D) drawings, although the construction projects have got more complex and larger.

Also, technology has been developed expeditiously throughout the years, enabling the use of new techniques and methods for construction which might pose new challenges in terms of safety. It is difficult to identify the potential hazards from a 2D drawing, especially while the project is progressing, because it is common that frequent changes in the design of a construction project are implemented as the construction continues. Despite the shortcomings of performing safety planning based on reviewing the 2D drawings to identify the risks and associated hazards; this is the method largely used in the construction industry. Moreover, in the current practice, the efficiency of the safety planning of a project depends on the experience of the Health and Safety (H&S) experts.

Building Information Modeling (BIM) can assist the H&S experts and construction professionals to overcome the challenges observed with the traditional safety planning process. BIM digitally represents buildings as three-dimensional (3D) models, which provides significant advantage over the 2D traditional representation in terms of visualization and understanding of a built environment. It enables a 3D model-based process that assists the stakeholders not only to construct and manage but also to plan and design structures. Therefore, a BIM-based approach can provide an efficient solution to plan and design the safety measures of a construction project both during the design and construction phases. Also, BIM-based safety review can minimize the time spent on manual safety review of buildings, and eliminate the human error when identifying the risks and hazards by means of automated rule-checking. Since frequent changes in the safety design of construction projects are commonly needed throughout the construction, BIM can ease the process of adjusting to the changes in safety measures while construction projects are progressing.

Objectives of the thesis

The main objectives of this thesis are to: (1) develop a BIM-based tool to automatically perform fall safety review of a building, and (2) identify hazardous locations on the building and automatically place the related safety measures at those locations.

To achieve these objectives, "Automated Fall Safety Review (AFSR)" rule-checking tool is developed by using Dynamo, the open source visual programming add-in for Autodesk Revit (Autodesk, 2019). AFSR tool reviews a 3D building model in Revit, and automatically identifies the hazardous places on the building, while showing the related safety measures for particularly preventing fall-related hazards. AFSR tool is specifically aimed to work during the design stage and while the structural works are being performed in a building project, and can directly run within a Revit file by using the Dynamo Player.

Scope of the thesis

The developed approach mainly assists in preventing fall-related accidents in building construction sites by identifying hazardous locations and installing appropriate safety measures (e.g., guardrails, safety nets, and shaft covers) at these locations in the digital building model. It is developed by using Dynamo, and works with Autodesk Revit. The hazardous locations are identified based on the predefined thresholds described by the users. Users can obtain the threshold information from any intended country-specific or job-specific safety regulation and standard. For instance, OSHA requires 1.82 meters or more above level to be checked for fall-related hazards (OSHA, 2015) while the Occupational Health and Safety Acts (OHSA) requires 3 meters or more as limits (OHSA, 2019). The developed automated fall safety review tool works regardless of the type of activities performed, and also, it is not dependent on the progress of construction and can work at any given time of a project.

The scope of the AFSR tool is buildings, and it is aimed to be used during the design and construction stages, especially during the structural works. However, it can easily be adapted to different types of projects other than buildings. Also, AFSR is currently limited to reviewing one building in a Revit file at a time. However, this might not be seen as a limitation in terms of fall-related hazards, because the literature shows that mostly at smaller construction projects, fall-related accidents happen (Cheng, Leu, Lin, & Fan, 2010; Kang, Siddiqui, Suk, Chi, & Kim, 2017b). Although the developed AFSR tool only reviews fall-related hazards, it can be modified and applied to other types of hazards in the future.

Methodology of this thesis

Figure 1.1 illustrates the methodology of this thesis. First, a literature review is performed to investigate the safety in construction with a focus on fall-related hazards (Figure 1.1.1).

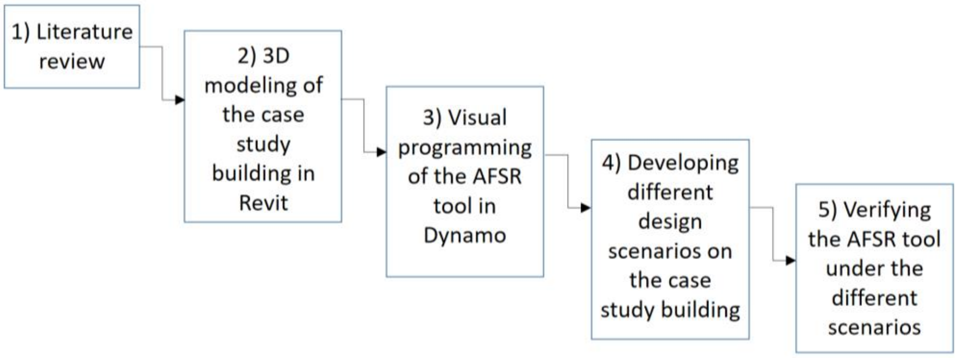


Figure 1.1 Methodology of the study presented in this thesis

Also, the design for safety concept is investigated and the previous related studies that developed tools for computer-aided safety in construction are examined. The review continued with examining the available BIM tools for developing an automated fall safety review tool. Autodesk Revit and its visual programming add-in Dynamo are investigated. In the second step of the thesis, Revit is used for 3D modeling of the case study building (Figure 1.1.2), and Dynamo is used to develop the AFSR tool (Figure 1.1.3). Different design scenarios are modeled on the case study building (Figure 1.1.4) and the AFSR tool is verified on the case study building by tests under these scenarios (Figure 1.1.5).

Organization of this thesis

Chapter 2 covers the literature review of the study which consists of the review of safety in construction, design for safety concept, and previous studies. Chapter 3 provides the methodology of this thesis and details on how the AFSR tool is developed. In Chapter 4, the application of the AFSR tool developed in this thesis and the results are provided. Finally, Chapter 5 finalizes the thesis with the concluding remarks. Contributions and future works of this thesis are discussed in this chapter.

CHAPTER II

LITERATURE REVIEW

This section provides background on the following: (1) safety characteristics of construction projects, (2) the concept of design for safety in construction, and finally, (3) tools developed for construction safety.

Safety in construction

Occupational accidents are a global problem for all industries, however, the construction industry has the largest share when compared to other industries. Furthermore, collecting the data for occupational accidents, especially for the accidents in the construction industry, is another problem because most of the cases might go unreported. For instance, 33% to 69% of actual accidents, which are occurred in the USA, are missed in the reports (Leigh, Marcin, & Miller, 2004). Despite the deficiencies in accessing actual occupational accident data in the construction industry; the available data is sufficient to identify the construction industry as the most dangerous industry (Leigh et al., 2004). For instance, in Turkey, 10.2% of all occupational accidents occurred in construction activities in 2010, and 32.9% of these accidents caused deaths (Talat Birgonul, Dikmen, Budayan, & Demirel, 2016). Moreover, fatal accidents in the construction sector that occurred in the time period between 1992 and 2003, have the largest share compared to other industries in Spain (Camino López, Ritzel, Fontaneda, & González Alcantara, 2008); where the construction workers represent almost 12% of the total workforce, the second-highest rate of EU-15 percentages (Meliá, Mearns, Silva, & Lima, 2008).

The construction industry includes many types of work performed for different purposes, such as, buildings, highways, railways, and bridges. Fall from height, struck by objects, contact with electricity, heavy equipment accidents, traffic accidents on site, cave-ins are at the top of the list of most common accidents that occur in construction projects. The rates of occurrence of occupational accidents depend on the type of construction. For example, in Turkey, traffic accidents are mostly observed in highway projects (18.3%), while it is rarely observed in demolition projects (1.3%) (Gurcanli & Mungen, 2009). Falls from height and struck by objects are recorded as the highest accidents that occurred in building constructions in Turkey (Gurcanli & Mungen, 2009). Moreover, it has been recorded that there were 34,563 accidents in total in the Malaysian construction industry between 2000 and 2009 (Chong & Low, 2014). Mostly the working environment conditions, transport and lifting equipment, other equipment and machines are causing occupational accidents (Chong & Low, 2014). According to detailed case reports; 17,106 accidents happened due to the working environment, and 12,810 accidents, which equals 37% of the total accidents, were fall-related hazards in buildings, caused by stairs, floor and wall openings (Chong & Low, 2014). Furthermore, fall from height, and struck by objects are the most common types of accidents observed in the United States, South Korea, and China between the years 2011 and 2015 (Choi, Guo, Kim, & Xiong, 2019). According to OSHA, 965 fall accident cases ended up with deaths and 566 of them occured in the construction industry between 1992-1995 (Janicak, 1998).

Design for Safety

The situation of the safety in construction industry highlighted in the previous section demonstrate the fact that designers actually have an important role in reducing the risks of falls in construction projects. This is because the decisions of the designers during the early stages of projects can potentially decrease the risks even before the construction starts and during the construction, as well. “Design for safety” (DfS) concept that covers this topic that has been studied in the construction for a long time.

All stakeholders of a project, such as the contractors, subcontractors, workers, are involved in safety design of a project in the DfS approach (Saunders et al., 2017). Therefore, in this method, safety designs should be understandable to the less experienced participants of a construction project for them to get involved in the safety responsibility, too. Automated safety design and review help to achieve this purpose since the project participants do not have to be experienced as much as H&S experts.

Risks of fall from height and struck by objects are decreased sharply if fall-related safety measures are designed and placed properly (Malekitabar, Ardeshir, Sebt, & Stouffs, 2016). A case study was conducted by the researchers in Bangladesh, and looked at the most fatal accidents occurred in three metropolitan cities of Bangladesh (Dhaka, Sylhet, and Chittagong) all due to fall-related accidents between 2008 and 2010 (Islam, Razwanul, & Mahmud, 2017). Moreover, the percentage of fall accidents, which was found to be related to the improper design of the safety measures, are respectively, 10% in Dhaka, 16.28% in Sylhet, and 17.65% in Chittagong.

Safety review tools developed for construction

Most of the previous studies in the safety domain are related to developing automated solutions for safety in construction (Cheng & Teizer, 2014; Li, Yu, & Liu, 2018; Lin, Zhang, Zhang, & Hu, 2019; Mneymneh, Abbas, & Khoury, 2017; Pradhananga & Teizer, 2013), and there are not many studies that developed solutions for automated construction safety review. Researchers have been working on developing tools to enhance safety review in construction. First practical studies on a computer were in the early 2000’s (Gambatese, Hinze, & Haas, 1997). The authors created a design tool to enable efficiency for project stakeholders in obtaining knowledge about the frequent changes in construction projects, and to have a control mechanism that is able to assess the risks in projects.

Researchers followed the lead to create practical solutions to enable safety review in the construction industry. For example, Hadikusumo et al. (2002) studied the design for safety subject in Virtual Reality (VR) environment and developed a tool. The tool first gets the name of a building component, which also includes the type of the building component, such as “Slab216” (Hadikusumo & Rowlinson, 2002). After that, it matches the type of the building component with the possible types of hazards related to this building component. Hazard information is provided as an input to the tool. Finally, the user is informed about the possible safety measures according to the identified hazards about the building component. The main limitation of this study is that the related safety measure for the identified hazards are not presented visually to the user, and instead, the possible solutions are provided to the user in written format. Also, the user needs to change the design of the building manually according to the suggested safety solutions.

In another study, Chantawit et al. (2005) developed the 4D CAD-Safety application to detect the fall safety hazards and the related measures. The application is designed for H&S experts to generate a safety plan, unlike the tool developed in this thesis that can be used not only by the H&S experts but also by the site office personnel and site engineers. This application by Chantawit et al. (2005) combines a building component and its tasks, as in the case of creating a 4D model. Four software are included in the study, namely AutoCAD, Microsoft (MS) Project, MS Access, and the 4D CAD-Safety application. AutoCAD is used to get the visualization of the building in 3D. Since it is a 4D-based tool, MS Project is used to create the project schedules. Furthermore, the safety library is imported as a database in MS Access. In this database, there are two ways to get the appropriate safety design for each element of the building. Firstly, each element of the building has a unique “GroupID” and each of them has “TaskID”. These TaskIDs represent unique task names. Moreover, they match with appropriate “SafetyID” and each SafetyID indicates the appropriate safety protection. For example, a column in the model is named as “Column 1” and the GroupID of this element is “G001”. This GroupID matches with four TaskIDs in the MS Access that are “T001”, “T002”, “T003”, and “T004”. T001 represents “Install RebarI” and there are two SafetyIDs that are matched with T001. These SafetyIDs are named as “S001” and “S002” that are respectively “Use Safety Helmet” and “Install Guardrail”. Therefore, appropriate safety planning for the first task of “Column 1” is manifested. Secondly, each activity in the project has a unique KeywordID. For instance, the activity “Excavation” matches with the KeywordID “K001”. KeywordIDs have SafetyIDs like TaskIDs. When SafetyIDs are identified for each activity, the process is similar to the safety planning of building elements which is described in the first way (Chantawit, Hadikusumo, Charoenngam, & Rowlinson, 2005). Unlike the AFSR tool developed in this thesis, the 4D CAD-Safety application gives the safety plan in the written format. Furthermore, since hazards and safety plans for each element type and activity should be identified before the application is used, it is not directly automated.

In more recent studies performed by researchers in construction, the developed solutions are more advanced in terms of visualization. For instance, a visual programming tool was developed by researchers in a study to visually show the fall safety measures to the user (Hongling, Yantao, Weisheng, & Yan, 2016). The developed tool detects the fall hazards of the building components according to the related parameters and shows the related safety measures. The 3D model is prepared in Revit, then Industry Foundation

Classes (IFC) format is used to import the 3D model into Unity 3D which is used for the visualization of the safety measures. The main advantage of the AFSR tool developed in this thesis over that study is that AFSR tool directly works on the native Revit file and no conversions to other formats is needed.

In another study, Zhang et al. (2015) developed a 4D-based tool that is called "RAPIDS Safety Rule Checker". It gives the schedule of installation and removal of safety measures exclusive of the project schedule. Besides, it informs the user about the appropriate fall safety measures in both written and visual format. The developed tool also enables the user to change thresholds, in accordance with the safety standard that is employed (Zhang et al., 2015). The safety review tool that is developed in this thesis applies a method similar to what is used in RAPIDS. One major difference is, however, that AFSR does not necessitate working with a specific schedule, and therefore, the user could identify the necessary fall safety measures at any stage of a project before the schedule is prepared. Also, the AFSR tool visually demonstrates the necessary safety measures and automatically modifies the 3D building model accordingly. This is to assist the H&S experts and the site personnel in designing and implementing the safety measures during the construction. Table 2.1 summarizes the similar studies in the literature.

Table 2.1 Literature review summary

Reference	Method used	Main functions of the developed solution	Limitations/strengths of the developed solution
Hadikusumo et al. (2002)	Virtual Reality (VR)	Automatically matching the building components with the related hazards	- Users are able to realize the fall-related safety hazards in VR format, however, possible accidents are given to the user in written format, and the model is not modified accordingly
Chantawit et al. (2005)	4D-based	Building components are matched with the related hazards	- A safety plan is provided in written format. - A database of hazards are imported into the tool by the users and the users need to identify the related hazards of building components before running the tool
Zhang et al. (2015)	4D-based	Users are informed about the fall safety measures in both written and visual format in the RAPIDS tool	- RAPIDS provides advanced detailed visualization of the safety measures - Dependent on a specific schedule to work
Hongling et al. (2016)	VR	Fall hazards of the building components are detected according to the related parameters	- Related safety measures are shown, however, the 3D building model needs to be converted to another format

CHAPTER III

DEVELOPING THE AFSR TOOL

This section describes how the BIM-based Automated Fall Safety Review (AFSR) rule-checking tool presented in this thesis is developed. Dynamo, which is the open-source visual programming add-in for Autodesk Revit, was used to create this tool particularly with a focus on fall-related hazards (i.e., falls from height and struck by objects). The main objective of this tool is to identify the hazardous locations on a building to automatically place the necessary safety measures at these locations in the 3D model of the building.

The developed approach compares two building models to achieve this objective. While one of these models is the complete design of the building, the other model represents the status of the building at a given stage throughout its construction. After performing the safety review, it notifies the user with messages about the required level of safety according to the thresholds that are either manually entered by the user or applied by default. Also, the necessary safety measures are automatically added to the BIM model, and the user can visualize these safety measures in 3D view of the building.

3.1. Software Tools Used

3.1.1. Revit

Revit is Autodesk's BIM tool is developed as a design and documentation platform that supports the design, drawings, and schedules (Autodesk, 2018). In the Revit model, every 2D and 3D view, and other views such as schedules, is a presentation of information from the same virtual building model, and the parametric change engine automatically coordinates changes made anywhere in the model (Autodesk 2018). The design components included in Revit could be used for not only architectural or structural design but also for Mechanical-Electrical-Plumbing (MEP), as well. All disciplines in a construction project can cooperatively work with each other since Revit has a worksharing cloud platform named BIM 360 (Autodesk, 2019). In this thesis, Revit is used to perform the 3D modeling of the case study building and to develop the AFSR tool by using Dynamo, the visual programming add-in of Revit. Details of the case study building model is provided in Section 3.2.

3.1.2. Dynamo

Dynamo was used for creating the AFSR tool in order to get the required information of the hazardous locations in the building design, based on the defined safety standard thresholds. Section 3.3.4 provides the details on the safety standard thresholds. Dynamo is a visual programming tool, which is an add-in for Autodesk Revit, and is installed as the part of Revit. It enables customizing the building information workflow and provides an open source visual programming platform (Autodesk, 2019).

Users could create scripts for various purposes, and then run these scripts from both Dynamo and Dynamo Player. By following these steps, users can access Dynamo inside Revit: Manage tab > Visual Programming panel > Dynamo. There are many codes that already exist in Dynamo that can be used by users for developing their own algorithms. Also, the users can reach codes from Dynamo packages, which are prepared by the other users, from the library if they cannot find the codes they need in the default code list of Dynamo. Furthermore, since Dynamo is an open-source visual programming tool, the users can share their scripts that can be downloaded by other users, and these users are able to modify the scripts according to their needs (Harrell & Mathews, 2018).

Dynamo is preferred by researchers and construction professionals for automation in the current practices of construction since it does not necessitate to be a programming expert to be able to use Dynamo. For instance, the Dynamo script generated by Vermeulen (2017) calculates the shortest way in between a room and all emergency exists and it shows the best way to escape from fire for normal room in case of emergency (Vermeulen, 2017). Other researchers developed a BIM-based scaffolding safety management model to analyze various scaffold-related risks (Feng & Lu, 2017). Dynamo was used to automate the process of developing the scaffolding system in BIM and various simulations based on the potential hazard events are conducted to educate workers. In a more recent study researchers used Dynamo to identify unsafe building locations using BIM for enhancing worker safety in dynamic environments(Arslan, Cruz, & Ginhac, 2019). Use of visual programming language for safety is also demonstrated in another study for safety planning during excavation works (Khan, Ali, Skibniewski, Lee, & Park, 2019).

3.1.3. Dynamo Player

Dynamo Player is a user interface to run Dynamo scripts in Autodesk Revit. Script files which are prepared by using Dynamo, are imported in the Dynamo Player. After the script prepared for the AFSR tool is imported into Dynamo Player, it is visible among the Dynamo Player list. To access Dynamo Player within Revit, users should follow these steps: Manage tab > Visual Programming panel > Dynamo Player. The main features of the Dynamo Player are described as follows (Autodesk, 2019b). There is a default directory of scripts for the users, it provides easy filtering of all the scripts in the Dynamo Player list, visualizes the status of the current scripts, runs the scripts, allows changing inputs, and reaching Dynamo interface to edit the scripts if needed.

3.2. Automated Fall Safety Review (AFSR) Tool

Figure 3.1 demonstrates the overview of the AFSR tool. As a BIM-based rule checking tool, AFSR consists of a Dynamo script to identify the safety measures needed in a building design and automatically places the necessary safety measures on the 3D model in Revit to the locations that are deemed hazardous. The user is asked to enter some data regarding the type of safety measure that will be used, or to change some of the safety standard thresholds manually.

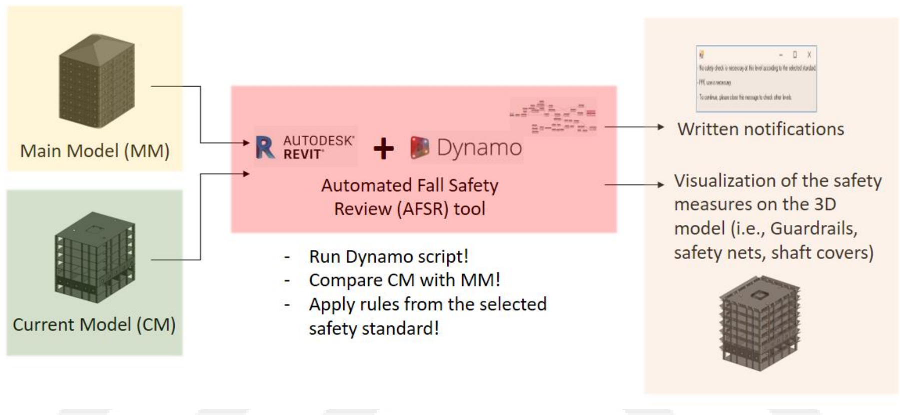


Figure 3.1 The Automated Fall Safety Review (AFSR) tool overview

The following paragraphs explain in more detail how the AFSR tool works and its main steps.

1) Comparison with the main model: There is a main model (i.e., MM) that represents the final view of the project, and a current model (i.e., CM) that can be at any given stage of a project throughout its construction. When the CM file is opened in Revit; the MM should be linked to it so that the AFSR tool can the Dynamo script to compare the CM with the MM.

2) Application of the safety rules: Countries might have different standards

defined by different safety agencies and authorities, such as the Occupational Safety and Health Administration (OSHA) in the United States, Occupational Health and Safety Act (OHSA) in Canada. OHSA Occupational Health and Safety Act, HSE (Health and Safety Executive) in the United Kingdom, and Health and Safety Regulation on Construction Works (Yapı İşlerinde Sağlık ve Güvenlik Yönetmeliği). Therefore, the safety limits and thresholds could differ from one country to another. For instance, different standards might suggest different height limits or different guardrail types to be implemented during the safety design of buildings. The AFSR tool leaves it to the user to define the thresholds that will be used to identify the hazards related to falls from height in the building. By using the Dynamo Player in Revit, the user enters the desired thresholds and runs the script, and the tool checks the fall-related hazards in accordance with the entered threshold, and shows the associated safety measures floor by floor in the building model.

The Dynamo Player is a user interface to run Dynamo scripts in Autodesk Revit. Script files which are prepared by using Dynamo, should be imported in the Dynamo Player. After the script prepared for the AFSR tool is imported into Dynamo Player file, it is visible among the Dynamo Player list. The user should check the “Edit Inputs” list on the AFSR to identify the thresholds according to the limits of the selected standard. For example, there is a height limit for the fall hazard and this is controlled with the “Elevation Limit to Check (mm)” parameter in AFSR. This parameter checks all the levels (i.e., floors in the building) for the height value entered in the “Elevation Limit to Check (mm)” field in the form of millimeters. The floor of the project to be checked for the height threshold is selected from the “Levels” category, which shows the floors of the CM in terms of Revit levels. Additionally, the AFSR tool checks the elevations of the window openings from the level of the floor, through the parameter named “window opening base offset limit”. Also, the area of the shaft openings is measured to identify the type of safety measure that will be used at a particular shaft opening (i.e., guardrail or shaft cover). The shaft opening area limit is left for the user to decide, depending on the type of preferred safety measure to be included in the model. Moreover, the user can change the type of the safety measures that will be viewed in 3D from the Dynamo Player interface. For instance, the user can change the guardrail type from the “Railing Types” category, to select among a list of different rail types, such as 1100 mm, 900 mm pipe. Details of the inputs related to safety rules are provided in Section 3.4.

3) Written notifications through pop-up messages: Users get a pop-up message once the threshold entered by the user is within the limits of the selected safety standard. For example, if the user prefers to use OSHA as the safety standard, the floor needs to be checked in terms of the fall-related hazards if the floor height is more than 1.82m (OSHA, 2015). More information to help preventing the fall-related hazards, such as highlighting the need for personal protective equipment, is shown to the user through these pop-up messages, as well. The content of these messages can be modified as needed.

4) Visualizing the safety measures: Once the user is notified by a pop-up message, the AFSR continues the process, and presents the safety measures visually to the user in different types and shapes (e.g., guardrails, safety nets, shaft covers). These are automatically placed at the locations that are deemed hazardous. In other words, the BIM is automatically modified to reflect these changes.

AFSR tool can perform the rule checking and identify the related safety measures for the hazardous locations of a building at any stage of the construction of the building. There are three main locations in the construction projects that are identified to cause fall incidents the most: 1) slab edges, 2) shaft openings, and 3) external wall openings. Therefore, the AFSR tool focuses on these locations in building designs and check these locations. The components to represent the safety measures are either created as new Revit Families or modified from existing ones. Figure 3.2 shows the safety measures that are added to the 3D model as needed. Details about the safety measures are provided in section 3.2.2.

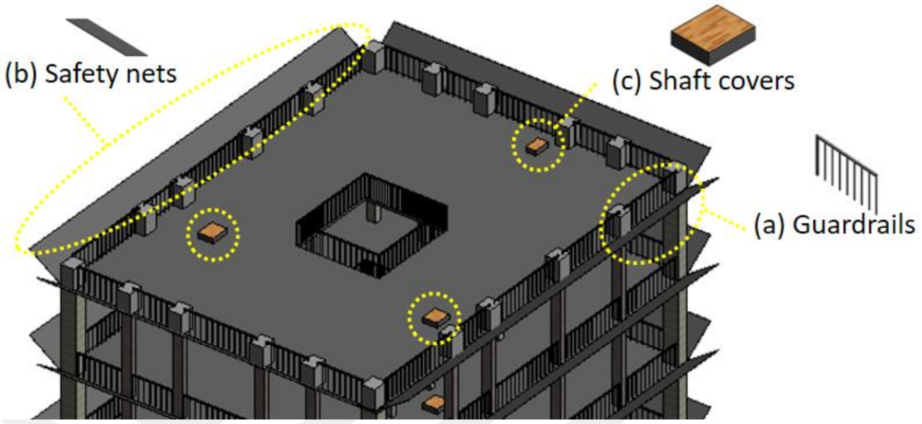


Figure 3.2 Components used in Autodesk Revit as the safety measures: (a) guardrails, (b) safety nets, (c) shaft covers.

3.2.1. Design constraints and modeling requirements of the AFSR tool

AFSR tool can be used with any Revit model once it is made sure that the model follows the constraints and modeling requirements given below:

1) Both the CM and MM should be in the same coordinates, so that the comparison of the two models could be performed on a location by location basis.
2) Structural column style should be "Vertical" (Figure 3.3), since the current version of the AFSR tool only handles the vertical structural columns automatically. If there is a slanted column in the project, the related safety measures should be added manually to the 3D model.

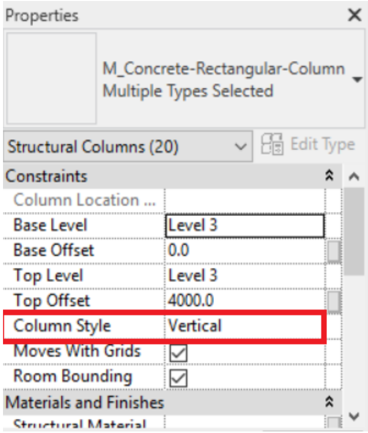


Figure 3.3 Column Style selected as "Vertical" in

the Properties window of Structural Column

3) The default parameter of the columns in AFSR is "Structural Column". If the columns are "Architectural Column" in the 3D models, users should change the default parameter to "Column" (Figure 3.4).

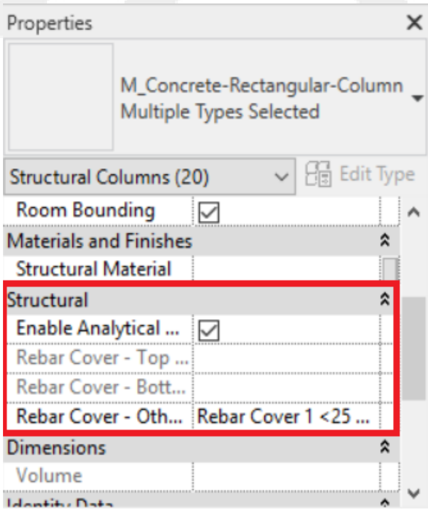


Figure 3.4 "Structural Column" selected as default

column type

4) AFSR identifies if the walls and columns are located on slab edges or around the shafts based on some predefined keywords. The walls and columns that are located on the slab edges are identified with the keyword "Exterior" in the

"Comment" parameter, and the walls around the shaft openings are identified with the keyword "Shaft" in the "Comment" parameter. The Comment parameter is empty by default, therefore the user should include the proper keyword to the walls and columns during the modeling (Figure 3.5).

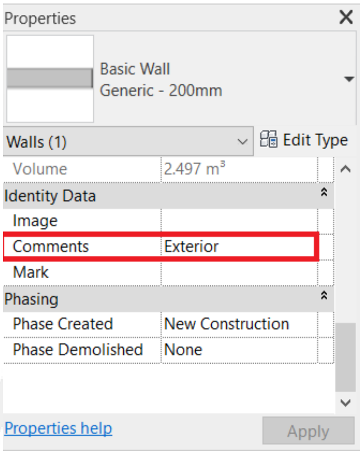


Figure 3.5 Adding the keyword to the "Comment" parameter

5) Shaft openings should be created from level to level in the Revit model. As mentioned before, levels in Revit represent the floors in the building. If one single shaft is created along the height of the whole building, it should be split at each level. Furthermore, shaft openings' base offsets should be equal to floor thickness and centerline of the shaft opening walls should come across shaft opening boundaries.

3.2.2. Safety Measures Used in AFSR

This section explains which safety measure are used at particular locations that are deemed hazardous on the building and shows how they are represented in the 3D view.

Guardrails along the slab edges: For the slab edges, AFSR automatically places guardrails if it identifies that the slab edge is not enclosed with a wall or a column.

Guardrail application can be seen in Figure 3.6a and 6b.

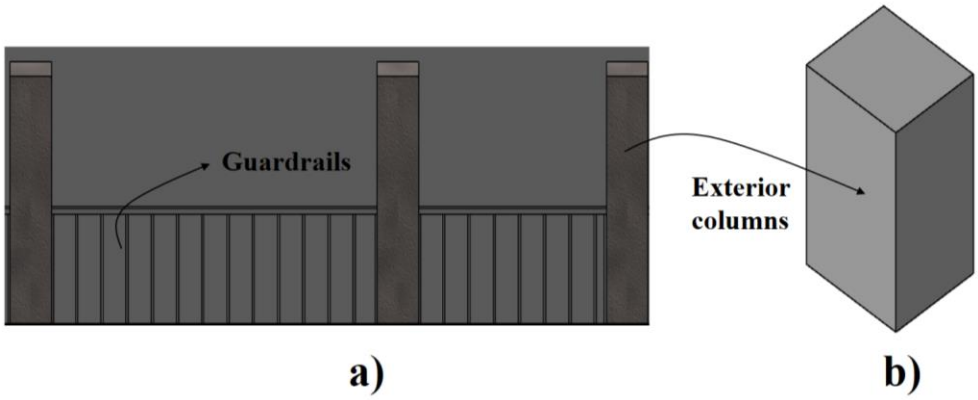
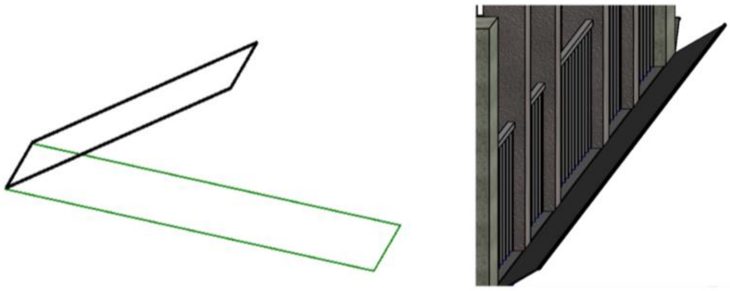


Figure 3.6 (a) Guardrail placed at the slab edges,
and **(b)** exterior column component used for placing
the guardrails at the slab edges

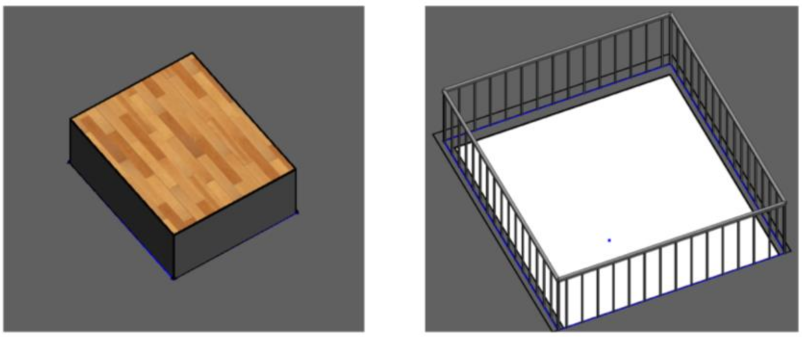
Safety nets along the slab edges: AFSR places safety nets along the slab edges to reduce the risk of falls from height, and also hits by moving or struck by objects. Revit does not include any object for safety nets in its default library, and no families created by other users are found for safety nets. Therefore, safety nets are created in Revit by using the Metric Generic Model line-based family template for the purposes of this thesis. The created safety net family is parametric and it adjusts its length based on the length of the slab edge where the safety net is placed in the model. The application of the safety net can be seen in Figure 3.7a and 7b.



a) b)

Figure 3.7 (a) New created Revit family for safety nets, and **(b)** safety net placed along the slab edges in the model

Shaft covers and guardrails along the shaft openings: AFSR tool first identifies the boundaries of the shaft opening. As stated before, there are two types of safety measure that can be viewed in this case: (1) shaft covers, and (2) guardrails. AFSR automatically places one of these safety measures according to the area limit of the shaft opening that is requested by the user: If the area of the shaft opening is smaller than the limit, then the tool places a shaft cover that is modified from Floor family in Revit. Otherwise, it places guardrails around the opening. The shaft covers and guardrails along the shaft openings can be seen in Figure 3.8a and 8b.



a) b)

Figure 3.8 (a) Shaft cover representation, and **(b)** placement of guardrails along the shaft openings

Safety measures around the wall openings: AFSR checks the elevations of the wall openings from their levels in the current model given by the user. If the elevation is lower than the limit that is requested by the standard that is entered by the user manually; it is deemed hazardous and a related safety measure (e.g., guardrail) is placed at that location. The 3D view of safety measures around wall openings can be seen in Figure 3.9.

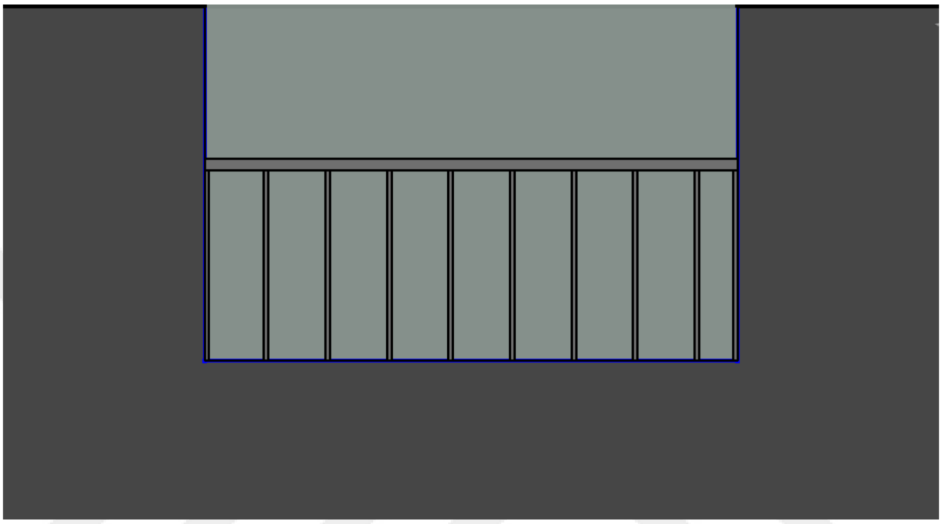


Figure 3.9 Guardrails around the wall openings

Overall look of the safety measures for fall prevention in AFSR tool, and their implementation under different conditions are shown in more detail in Section 3.2.

3.2.3. Dynamo Codes and Packages Used in AFSR

As mentioned in Sec. 3.1.2, external packages developed by other users were used in AFSR since the default nodes in Dynamo were not enough to achieve the purpose of this thesis. Therefore, these external packages were downloaded from the Dynamo interface via Packages > Search for a Package. Below are the list of nodes and corresponding packages used in Dynamo for AFSR (Table 3.1).

Table 3.1 Names of the nodes and corresponding packages used in Dynamo for AFSR

Name of the node	Package by	Name of the node	Package by
Levels	Revit	List.Chop	Core
Level.Elevation	Revit	String.ToNumber	Core
Categories	Revit	List.Create	Core
All Elements of Category	Revit	List.TakeItems	Core
Element.GetParameterValueByName	Revit	Code Block	Core
Family Types	Revit	>=	Operators
FamilyInstance.ByPointAndLevel	Revit	==	Operators
Element.SetParameterByName	Revit	*	Operators
Floor Types	Revit	<	Operators
Floor.ByOutlineTypeAndLevel	Revit	-	Operators
Element Types	Revit	Logic.If	designtech
All Elements of Type	Revit	Railings	designtech
Element.Geometry+	Revit	Railing.Create	designtech
Number	Core	PolyCurve.Curves	Geometry
List.FilterByBoolMask	Core	Vector.ByCoordinates	Geometry
Watch	Core	Point.ByCoordinates	Geometry
String	Core	Line.ByStartPointDirectionLength	Geometry
String from Object	Core	Vertex.PointGeometry	Geometry
String.Split	Core	Point.Z	Geometry
List.Clean	Core	Line.ByStartPointEndPoint	Geometry
List.TakeEveryNthItem	Core	Flatten	BuiltIn
		SetDifference	BuiltIn

3.3. Coding of the AFSR Tool

This section provides a detailed explanation of the coding of the AFSR tool that is performed in Dynamo.

3.3.1. Reasoning Mechanisms of the AFSR

Mainly, AFSR consists of two reasoning mechanisms that work together: First is for displaying written notifications to the user, and the other is for identifying the related safety measures.

The first reasoning mechanism of AFSR tool is given in Figure 3.10. Users get a pop-up message based on the comparison of the level height with the thresholds identified by the selected standard. If the floor height is above the thresholds of the selected standard, then it necessitates a safety review in terms of fall-related hazards, and therefore the users get a notification through a pop-up message that is shown in Figure 3.11(a). It notifies the user that there are safety measures applied to the model and the user should check them. Otherwise, the message in Figure 3.11(b) is shown to the users which states that there is no need for safety review at the selected level, since the floor height is less than the threshold identified in the selected standard. These pop-ups are created by using "Phyton Script" node, and Figure 3.12 shows the related codes of this node. These pop-up messages should be closed by the user manually in order to proceed to the next mechanism.

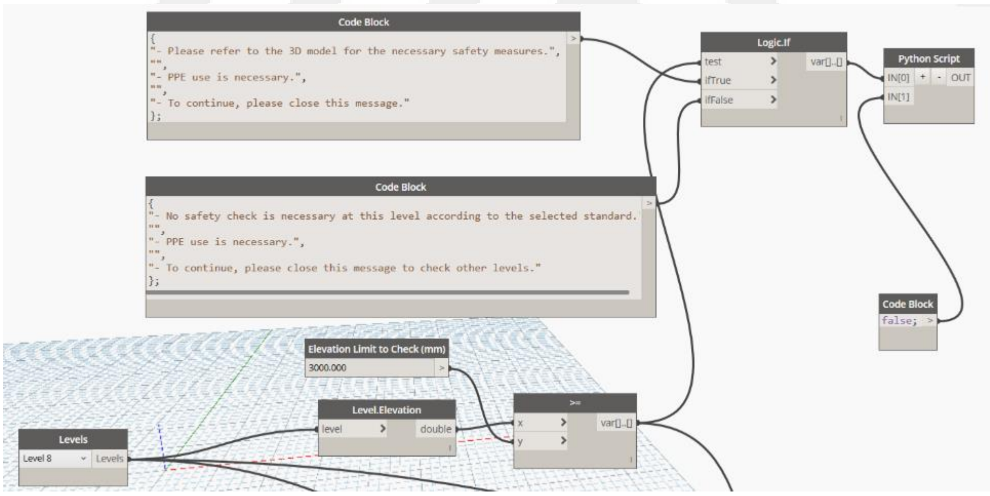
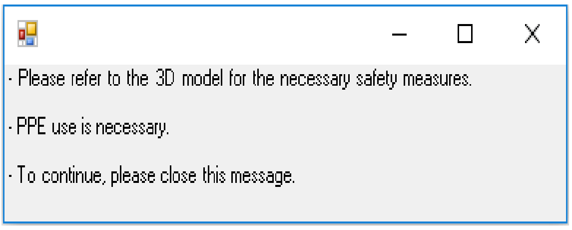
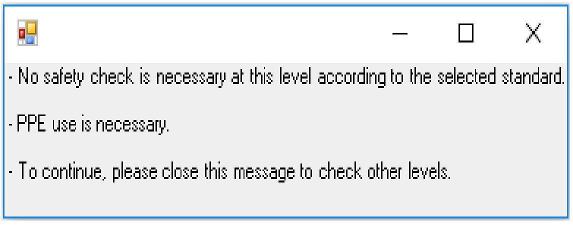


Figure 3.10 The first reasoning mechanism of AFSR tool



(a)



(b)

Figure 3.11 (a) Pop-up message when safety measures are created automatically in the 3D model, and **(b)** pop-up message when no safety check is needed.

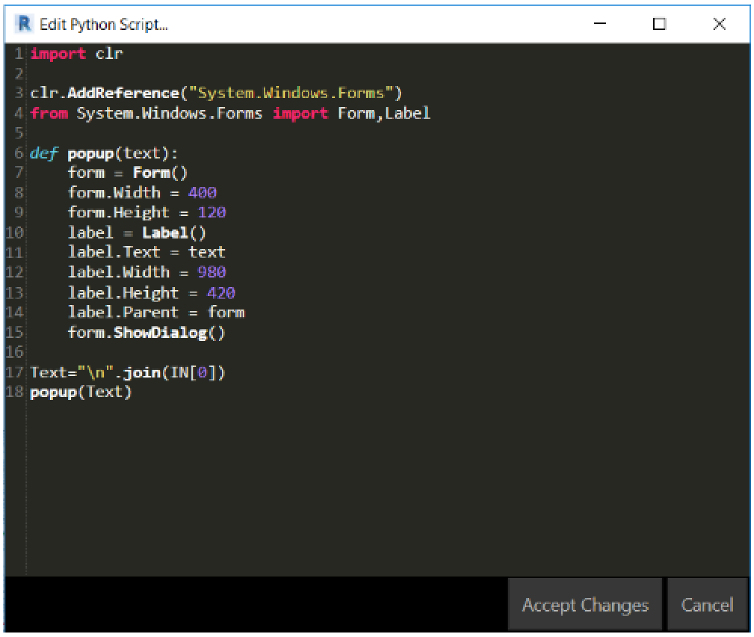


Figure 3.12 Phyton codes for the pop-up messages

The second reasoning mechanism of AFSR tool is for comparing the threshold of the selected standard with the elevation of the selected floor to determine the necessary type safety measures to be applied on the 3D model. If the elevation of the floor is less than the threshold, this means that no safety check is necessary at that level according to the selected standard and this is already determined by the first mechanism. In other words, AFSR stops at that point and does not apply fall-related safety measures for that particular level. Otherwise, if the elevation of the floor is higher than the threshold, it proceeds with analyzing the selected floor. As explained before, countries might have different standards defined by different safety authorities, and thus, the limits and thresholds could differ from country to country. For instance, different standards might suggest different height limits or different guardrail types to be implemented during the safety design of buildings. The default value in AFSR is arranged as 3000mm (3m) for the height limit as OHSA suggests (OHSA, 2019), however, it can be modified by the user in accordance with another standard or based on a desired value. This second reasoning mechanism is shown in Figure 3.13.

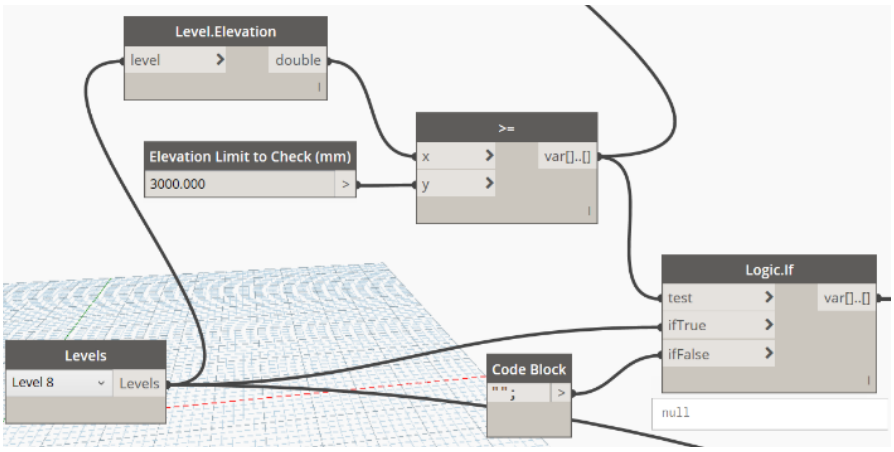


Figure 3.13 The second reasoning mechanism of AFSR tool

Then, to call the linked model in Dynamo, AFSR calls the linked MM model by "Get Documents" node, and the elements of MM are filtered by the node "Get All

Elements From Linked Model" that uses categories of the elements (Figure 3.14). How this reasoning mechanism determines the hazardous locations and then assigns the necessary safety measures are explained in detail in the following paragraphs.

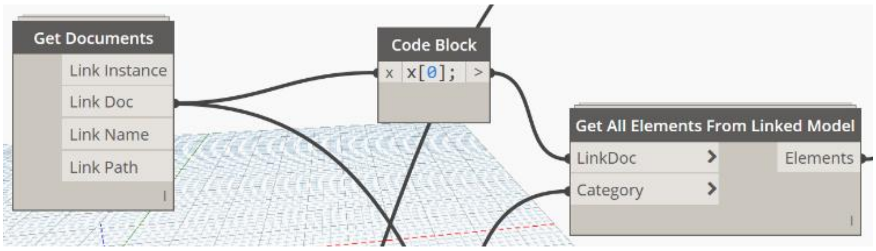


Figure 3.14 The beginning of the code that gets the elements of linked model (i.e., MM)

3.3.2. Detecting the Hazardous Locations and Placing the Related Safety measures

As explained earlier, the slab edges, shaft openings, and external wall openings are identified to cause fall incidents in construction projects. Thus, AFSR tool focuses on the locations of these components in the 3D building model to check the hazardous locations in accordance with the selected standards, and assigns the fall-related safety measures. As mentioned earlier, there should be two building models named the Main Model (i.e., MM) that represents the final view of the project, and the Current Model (i.e., CM) that is at any given stage of the project throughout its construction for using the AFSR tool. These two models are used for comparison to identify the hazardous locations at a given phase of a project. This comparison process is the main operating logic of the tool.

Detecting the external walls on the slab edges

By comparing the external wall locations of both the CM and MM, AFSR detects the slab edge locations. Below steps explain how the detection of the slab edge locations is performed:

AFSR selects the walls from the CM and MM with the “Categories” node. All of the walls are selected in the models regardless of being interior or exterior walls. They are filtered by the node “Element.FilterByLevel” in order to get the requested floor’s walls. Figure 3.15 shows the codes of CM for this step.

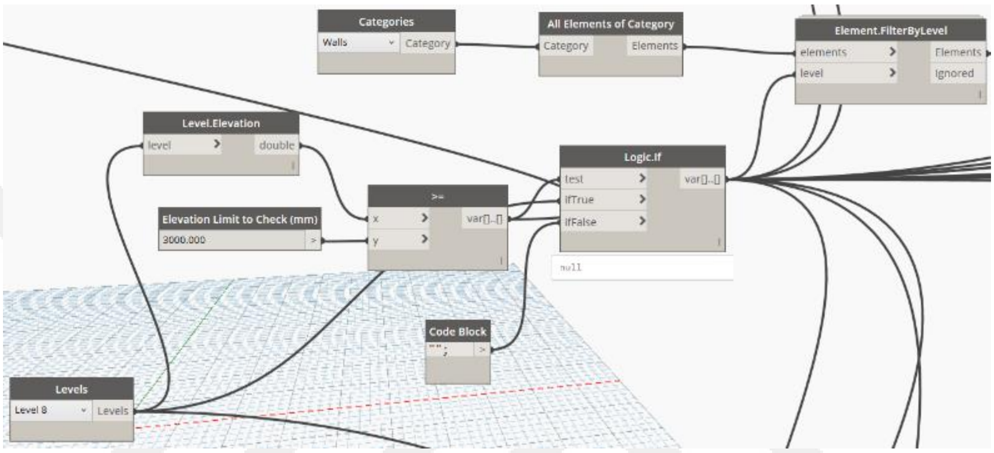


Figure 3.15 Getting wall elements of CM and MM for the selected floor

The same procedure is also applied for the linked model for the selection of the walls of MM. Figure 3.15, 3.16, 3.17 represent the CM, however, the same procedures apply to MM, and these are combined with each other at “Set.Difference” node, which is shown in Figure 3.17.

“Element.GetParameterValueByName” node is used to check the “Comments” parameter of the walls that are obtained from the first step to see if they have the “Exterior” keyword. Walls are considered as external walls by using “List.FilterByBoolMask” if their comments parameters are equal to “Exterior”.

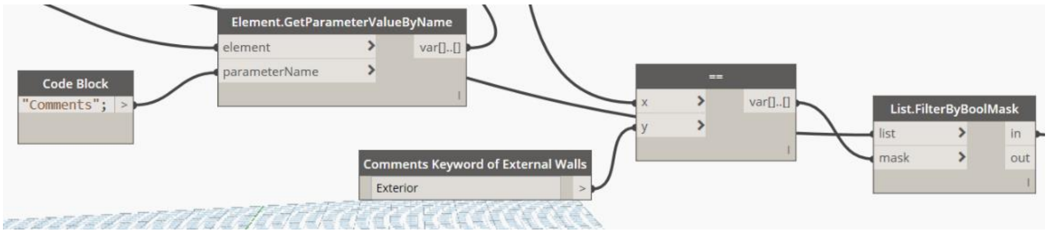


Figure 3.16 Getting exterior walls of CM and MM

The locations of the external walls could be obtained by “Element.Location+” as curves. “SetDifference” is used to compare the CM and MM. The curves of the external walls must be changed to a string since the node “SetDifference” only works with strings. It gives the locations of the external walls that belong to the MM only, and not the CM.

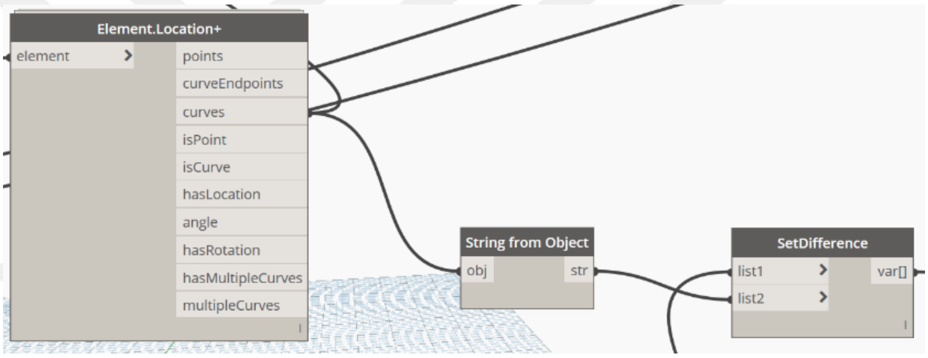
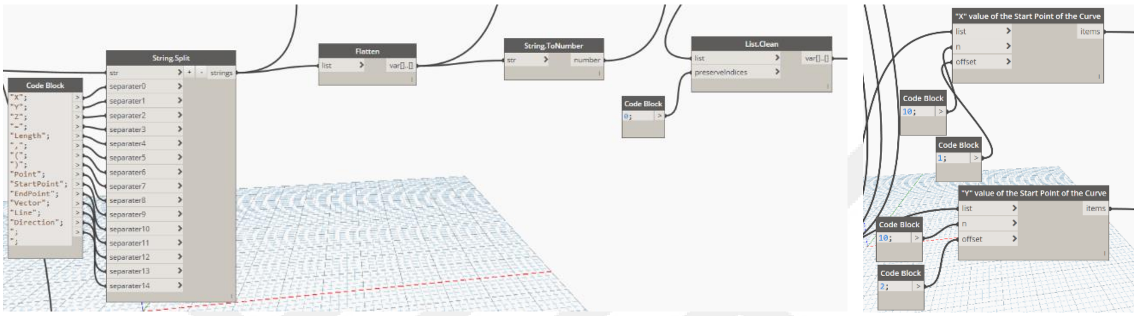


Figure 3.17 Checking locations of missing exterior walls in CM in comparison with MM

The previous step gives the locations of the slab edges as string. However, they have to be converted to curve again in order to draw the guardrails at the locations of the slab edges. This is due to the fact that the node “Railing.Create” only works with the curves. “String.Split” is used to remove the letters and words from the list of the Set.difference to get the coordinate values. Furthermore, each slab edge location is listed as a sublist after performing the “String.Split”. Therefore, “Flatten” node is used to combine all the sublists to one list. Moreover, “List.Clean” is used to remove the “null” values from the list since the letters and words are already erased by the “String.Split”.

By this way, each coordinate value has a unique offset in the list and constant periodicity. For instance, the “X” value of the start point of the curve is equal to 1 and “Y” value is equal to 2 at the list. On the other hand, their periodicities are the same with each other that is equal to 10. Points of the start points and vectors of the curves are obtained by using the “List.TakeEveryNthItem” node with matching unique offsets and constant periodicities. This step is shown in Figure 3.18(a) and 3.18(b) below.



(a) **(b)**

Figure 3.18 Creating curves for the locations of missing exterior walls in CM

Coordinate values of the curves are obtained after the previous step. They have to be combined as a point by using the “Point.ByCoordinates” and a vector by using the “Vector.ByCoordinates” in order to get the curves of the slab edges again. By this way, the “Line.ByStartPointDirectionLength” could be used to create slab edge coordinates. Since the curves are listed together in a one list, they have to be converted by the “List.Chop” to create unique lists for each curves. Finally, guardrails are created as a safety measure for slab edges with using the “Railing.Create” node. Railing type could be changed by the user with the node “Railings” which lists all the available railing types in the model. The final step of the slab edge can be seen in Figure 3.19.

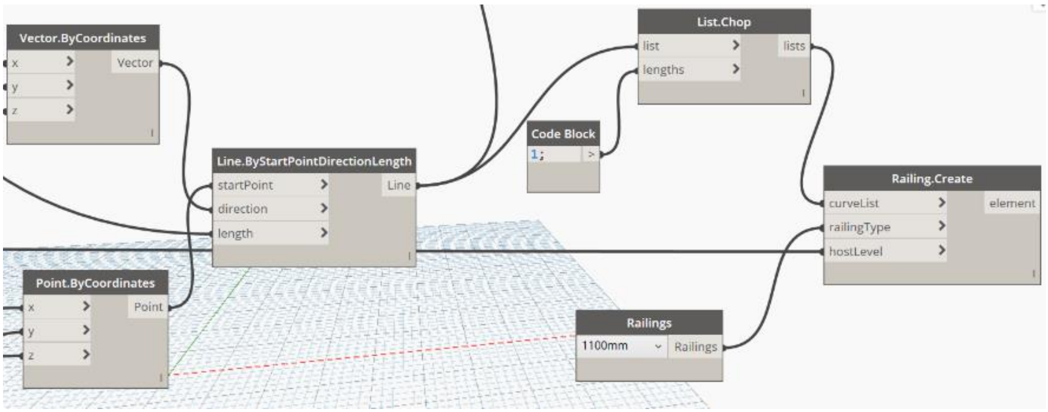


Figure 3.19 Creating guardrails at the locations of the missing exterior walls in CM

Detecting the columns on the slab edges

In addition to the external walls, the columns, which are located at the slab edges, are also considered as hazardous locations in terms of falls. Steps that are similar to the identification of the external walls are followed in Dynamo for the columns. The distinctive steps and features for the columns are given below.

“Structural Columns” should be selected in “Categories” node (Figure 3.20).

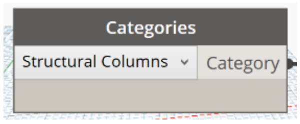


Figure 3.20 Category selection for the columns of CM and MM

The main difference between the columns and walls is that by default, the columns are modeled as points while the walls are modeled as curves in Autodesk Revit. Thus, “points” should be selected as an output instead of “curves” at the “Element.Location+” node (Figure 3.21).

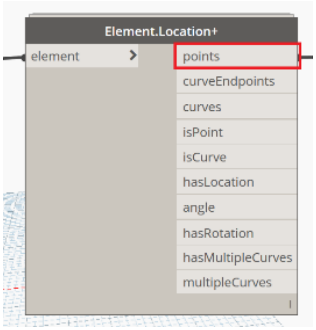


Figure 3.21 Getting points of columns of CM and MM

Only X and Y values are used to create points by using "Point.ByCoordinates" since Z values, which are the outputs of "Element.Location+" node, are equal to 0. In order to solve this, the "Level.Elevation" is used to get the exact Z values of these points. Offsets of X and Y are entered as "1" and "2" respectively, and the periodicity for these values are entered as "3" at the "List.TakeEveryNthItem" (Figure 3.22).

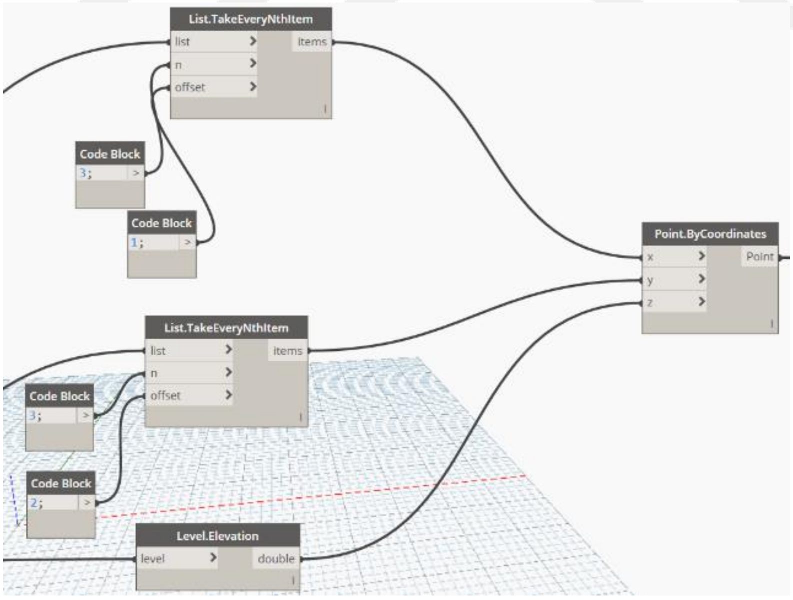


Figure 3.22 Creating point for the points of missing exterior columns in CM

Final step applied for the columns is different than the external walls. Since railings cannot be drawn with the list of points, a component should be created for the columns, which is named as the “Column Component” in this study. This component should be selected in the “Family Types” node. The “FamilyInstance.ByPointAndLevel” should be used with the appropriate inputs as given in Figure 3.23. Moreover, the “Offset” parameter of the component has to be arranged as 0 by using the “Element.SetParameterByName”.

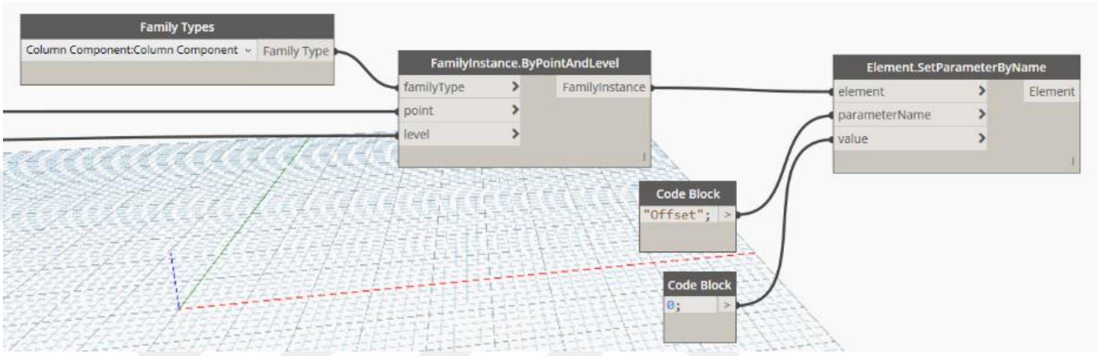


Figure 3.23 Creating column components to the points of missing exterior columns in CM

Placing the safety nets around the slab edges

Final part is to place the safety nets at the slab edge locations. Safety nets should be available in the building throughout its construction, even after the external walls are built. Therefore, the floor boundaries of the levels in the CM are enough to obtain the necessary curves to place the safety nets. Steps for placing the safety nets in the 3D model are listed below.As described above, floor boundaries of CM are used to identify where to place the safety nets. Thus, the “Floor” is selected among the options of the “Categories” node. All floors are selected in the CM by using the “All Elements of Category”. Since AFSR perform the checks floor by floor: the “Element.FilterByLevel” is used to filter the elements of the required floor. Besides, the floors have eight boundary curves, four at the bottom and four at the top of each floor. Therefore, these boundary curves are obtained by using the “Floor.GetBoundaryPolyCurves” node. Since safety nets are created with using the Metric Generic Model line-based family template, poly curves must be converted to curves with the node named “PolyCurve.Curves” (Figure 3.24).

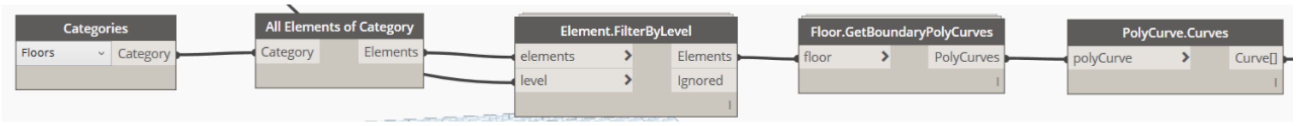


Figure 3.24 Getting polycurves of slabs of the selected level

“PolyCurve.Curves” gives the floor boundary curves with two sublists. The first sublist represents the top surface and the second represents the bottom surface of the floor. “Flatten” node is used to combine all the sublists to one list, and the first four items, which belong to the top surface boundary curves of the floor, are taken with the “List.TakeItems”. Finally, the required curves are obtained to create the safety nets for the selected floor. The safety net family should be selected under the node “Family Types”. Required inputs for the “FamilyInstance.ByCurve” must be matched with the suitable parameters (Figure 3.25).

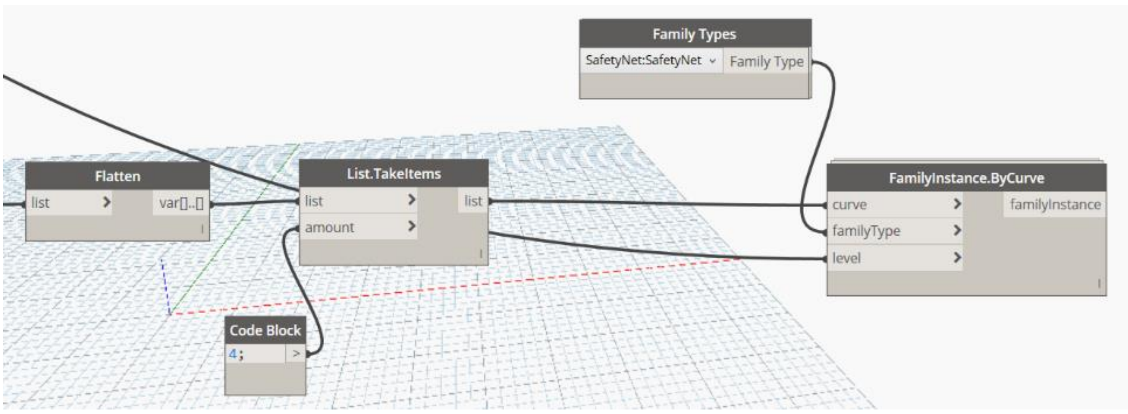


Figure 3.25 Creating safety nets to the locations of the slab edge

Detecting the shaft openings

As explained before, the shaft openings are also considered as hazardous locations in terms of falls. There are many uses of shaft openings such as to install elevators, to build stairs, to provide ventilation, and so on. Therefore, the area of the shaft openings vary based on the desired usage. AFSR tool suggests two fall safety measures for shaft openings in accordance with the area of the shaft opening, which are (1) shaft covers, and (2) guardrails. No specific threshold is used to determine the appropriate safety measure for shaft openings. In other words, the decision between the two options is up to the users, where the users can enter an area limit in mm^2. The below steps to check the area of the shaft openings are followed.

The “Shaft Openings” is selected from the “Categories” node. “All Elements of Category” is used to get all shafts in the model. Since AFSR perform the checks floor by floor, the “Element.FilterByLevel” node is used to filter the shaft openings which belong to requested floor. Moreover, boundaries of the shaft openings in Autodesk Revit have multiple curves due to the rectangular shape. Therefore, the “multipleCurves” is selected as the output (Figure 3.26).

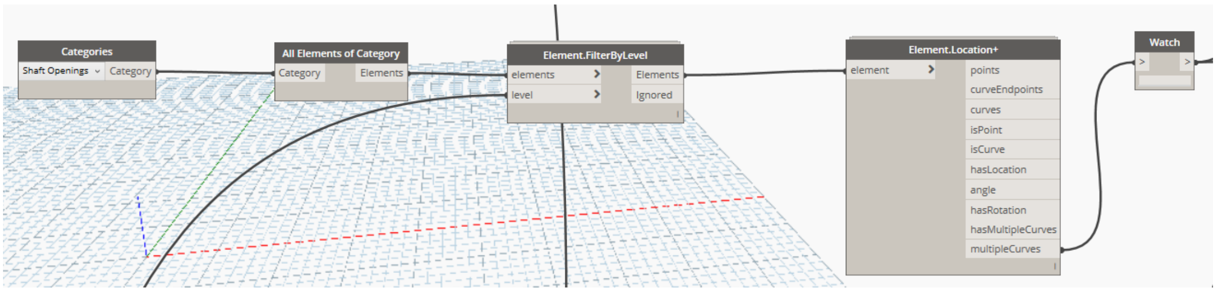


Figure 3.26 Getting multiple curves of shaft openings of the selected level in CM

The main purpose is to get the areas of each shaft opening. Thus, the necessary lengths should be obtained from the list. First of all, the “String.Split” node is used to filter the words from the multiple curves. Moreover, the “Flatten” cleans the subslists and creates one list (Figure 3.27).

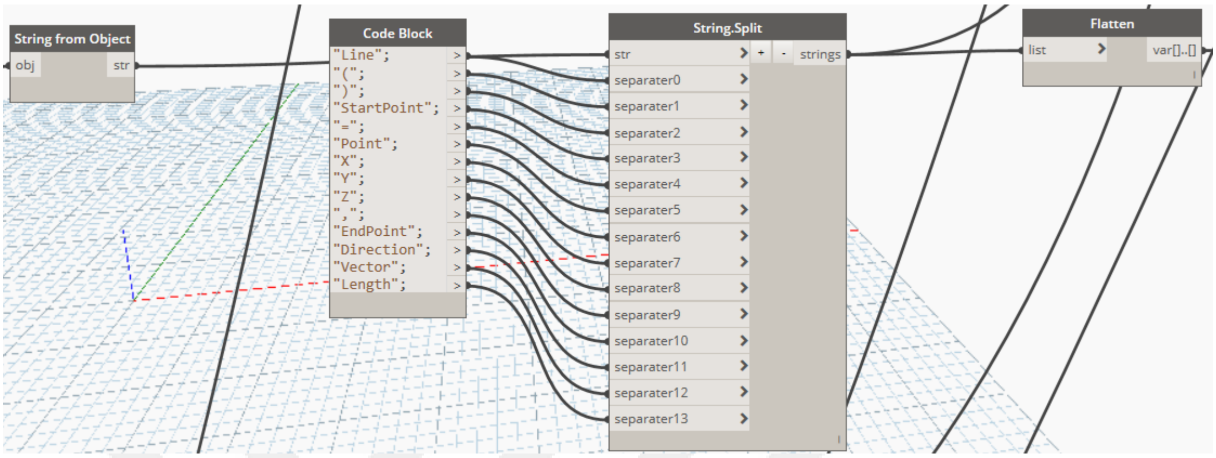


Figure 3.27 The part of getting the lengths of the boundaries of the shaft openings

Every 35th item is the value of the length of multiple curves of the shaft openings. The “List.Chop” creates the sublists, and every sublist represents the lengths of the boundaries of the shaft openings with the proper inputs which are shown in Figure 3.28.

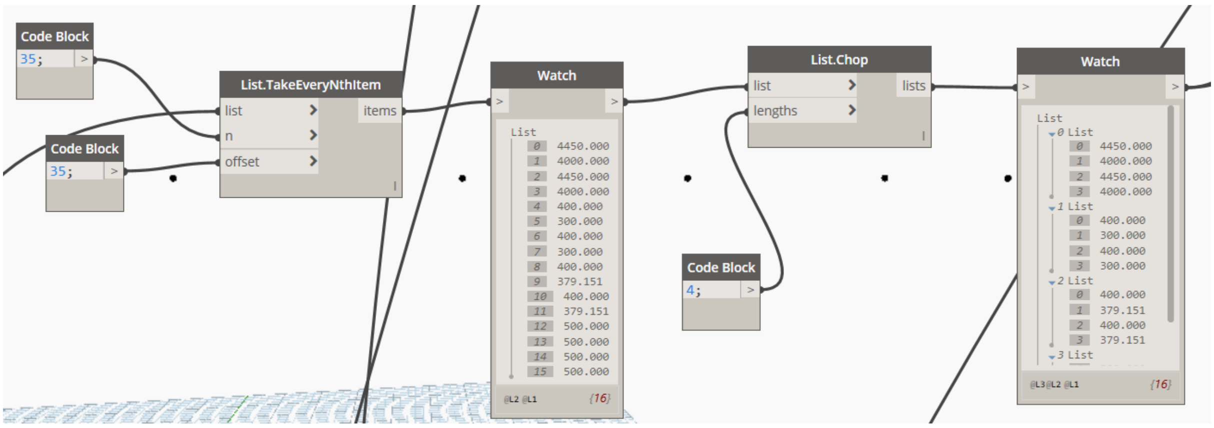


Figure 3.28 Getting the lengths of the boundaries of the shaft openings

The first two indexes of the sublists are enough to calculate the areas of the shaft openings. There is a special node to get the index from sublists that is called "Get from Sublists using One Index". The parameter type of the outputs are string. They have to be converted to number for performing mathematical operations. Two lengths are involved in the multiplication node that is shown with "*". Finally, the shaft opening areas of the floor being checked are obtained in terms of mm^2 (Figure 3.29).

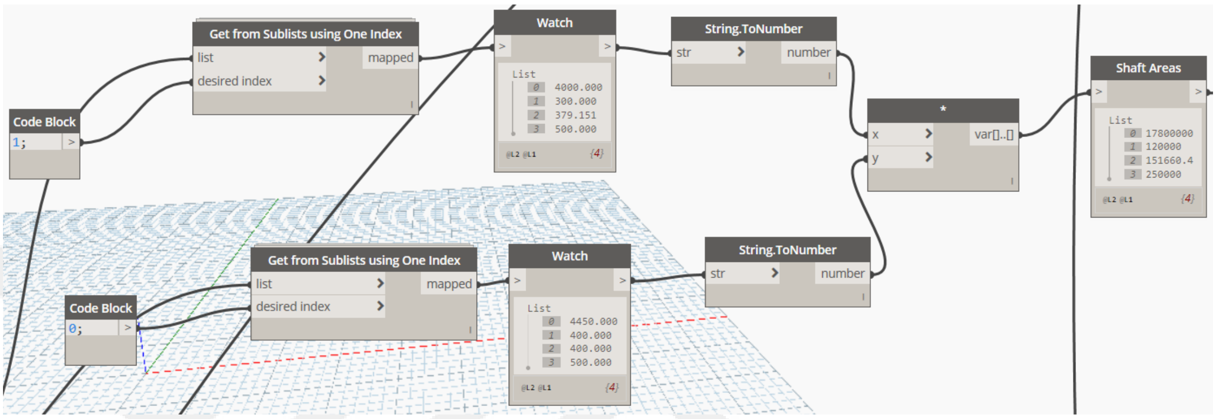


Figure 3.29 Calculating the areas of the shaft openings

The final step is the comparison with the desired threshold that was entered by the user. The default value for this threshold is set as 700,000 mm^2, however, there is not a specific value in any of the available standards. The "list" input of the "List.FilterByBoolMask" comes from the "Element.Location+" node from the first step and the "mask" input is obtained from the area comparison which is described in the fourth step.

Placing the safety measures around the shaft openings

If the outputs of the "in" of the "List.FilterByBoolMask" give that areas of these shafts as bigger than the threshold, they require guardrails as the proper safety measure around the shaft openings. Otherwise, covers are applied to the shaft openings for those that come from the "out" (Figure 3.30).

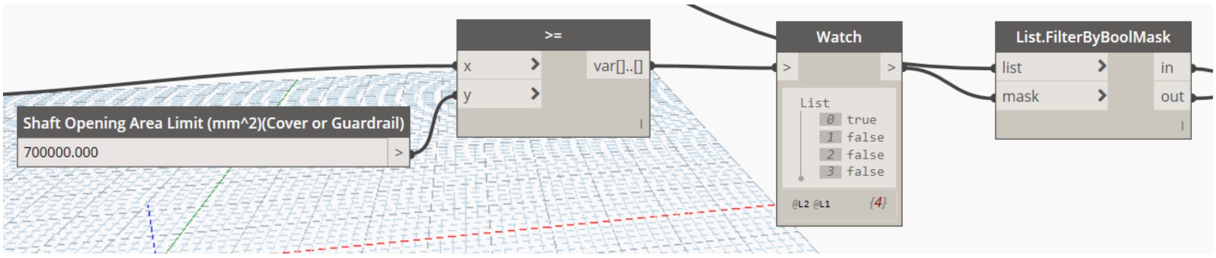


Figure 3.30 Comparing the areas of the shaft openings with the threshold

Figure 3.31 shows how the safety measures are created for shaft openings with smaller areas than the identified thresholds. Floor element is used as the safety measure for this kind of shaft openings to serve as a shaft cover. Moreover, the default floor type is set as the "Standard Timber-Wood Finish", and the user can change it.

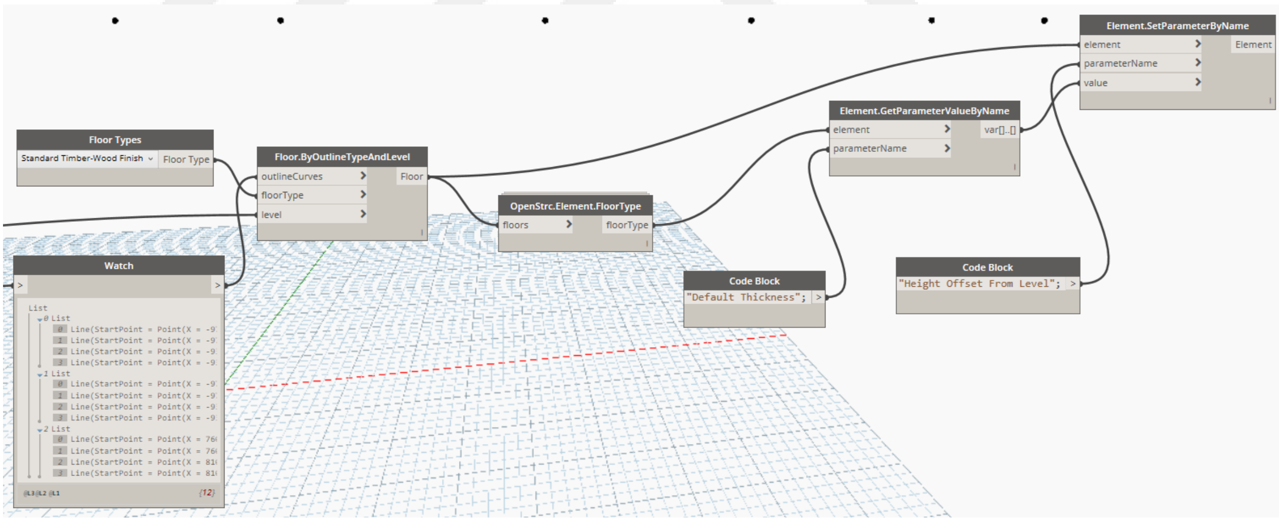


Figure 3.31 Creating shaft covers for the shaft openings which have smaller areas than the threshold

The "Floor.ByOutlineTypeAndLevel" node gets the "outlineCurves" from the "out" results of the "List.FilterByBoolMask" that is shown in Figure 3.26. To make these covers visible in the 3D view, their “Height Offset From Level” parameter is arranged to be equal to their “Default Thickness”.

Shaft openings with larger areas than the threshold are more complicated than the smaller ones since they might have shaft walls around them. Therefore, the locations of the shaft opening walls in both the CM and MM needs to be compared in order to prevent the overlapping of the walls and guardrails. In other words, AFSR checks if there are shaft opening walls in the CM, and if yes, does not place a guardrail at those locations.

The same steps of detecting the locations of the external walls are used to detect the locations of the shaft walls by filtering the keyword “Shafts” in the “Comments” parameter in this case. Figure 3.32 shows the difference between the detection of the locations of the exterior walls and the shaft walls.

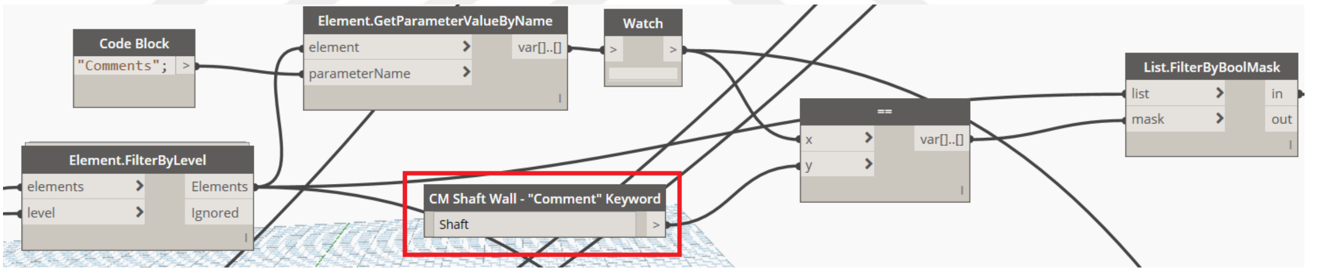
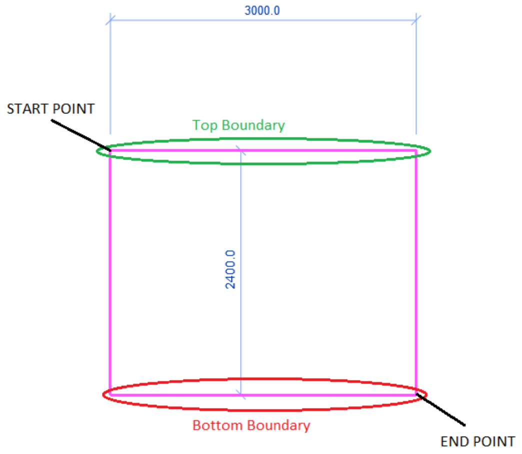
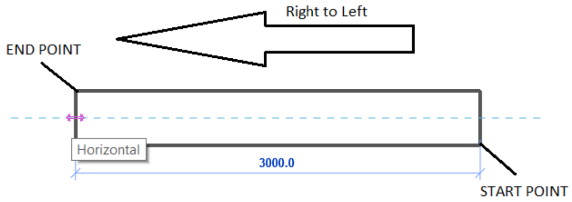


Figure 3.32 Filtering the shaft opening walls in CM and MM

Although shaft walls and shaft opening boundaries are located at the same location, their start and end points might be reversed since the users may model them by following different directions. For instance, a user can draw a shaft opening as shown in Figure 3.33(a). On the other hand, a shaft wall, which is located at the bottom boundary of that shaft opening, can be drawn as shown in Figure 3.33(b). Since the bottom boundary of the shaft opening is drawn from left to right, while the shaft wall from right to left; their curves will be different although their locations are the same.



(a)



(b)

Figure 3.33 (a) Drawing the shaft opening from left to right, and **(b)** drawing the shaft wall from right to left

The following steps explain how the AFSR tool handles this. The shaft walls in the CM, which are located at the shaft opening boundaries, are obtained as shown in Figure 3.32. AFSR obtains their curves by using the “Element.Location+” node, and then, converts them to string with the “String from Object”. The “String.Split” filters words from the curve list. The “Flatten” node bands the sublists together. Since items in the list are still in string format, they have to be converted to number in order to apply them the curve creation process by using the “String.ToNumber”. Finally, “null” values in the list are erased with the “List.Clean” node that is shown in Figure 3.34.

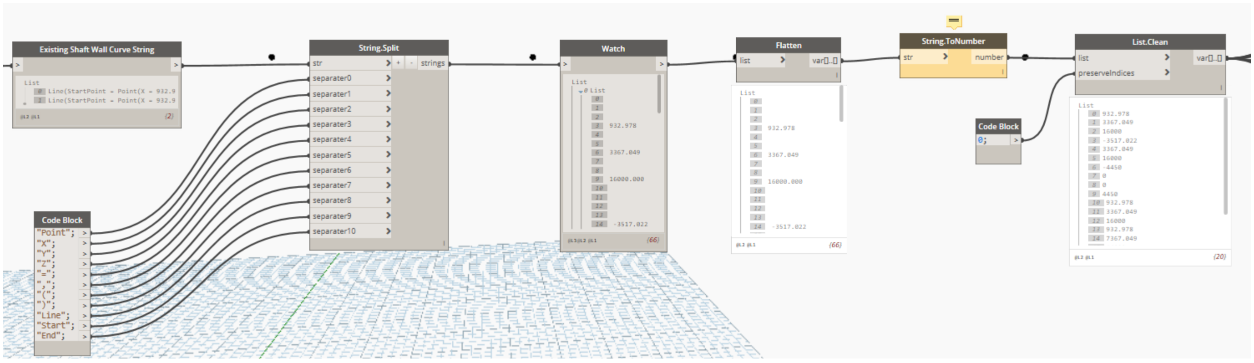


Figure 3.34 The code part of obtaining curves of existing shaft walls in CM

The key point is that there should be two different curves and these curves must indicate the same points. In other words, their start and end points should be swapped and vectors should be multiplied by -1 in order to obtain the same location. Each point and vector has a period on the list. Therefore, the “List.TakeEveryNthItem” is used to get the specific values for each point and vector. Furthermore, the points are created by using the “PointByCoordinates” and vectors are obtained by using the “Vector.ByCoordinates. Multiplication node “*” is used in order to reverse the vectors with the input “-1”. The coding process of this step is shown in Figure 3.35 and 3.36. The process in Figure 3.35 returns the same curves as the existing shaft walls. Moreover, the reverse curves of existing shaft walls, which refer to the same locations with the results of the process given in Figure 3.35, are obtained as shown in Figure 3.36.

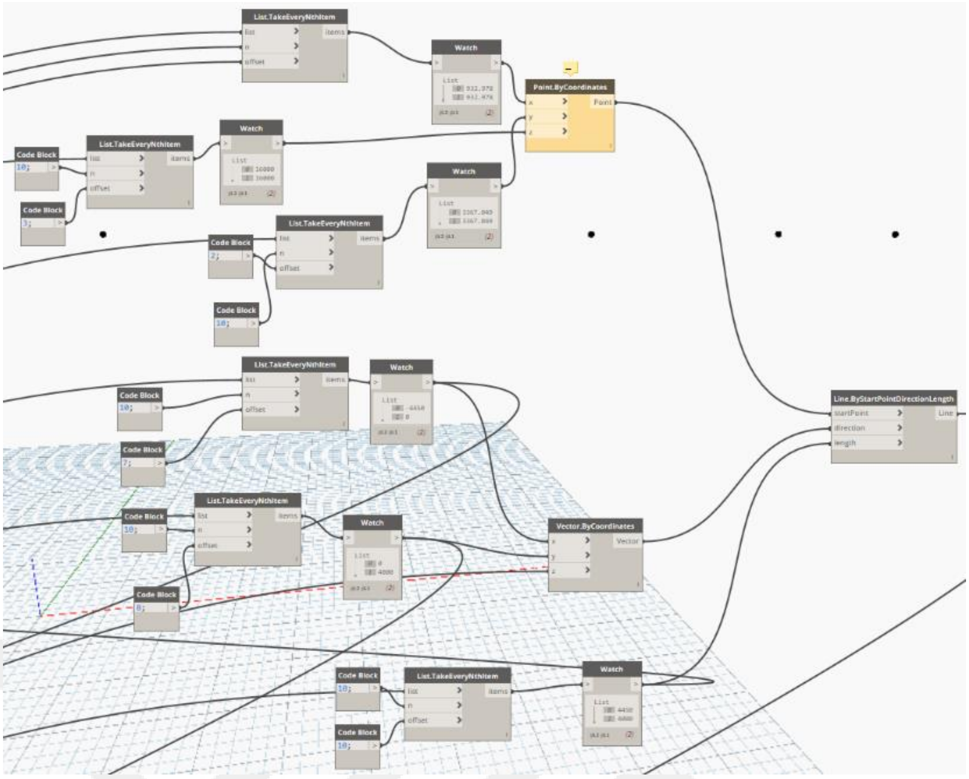


Figure 3.35 Obtaining the curves of existing shaft walls in the CM

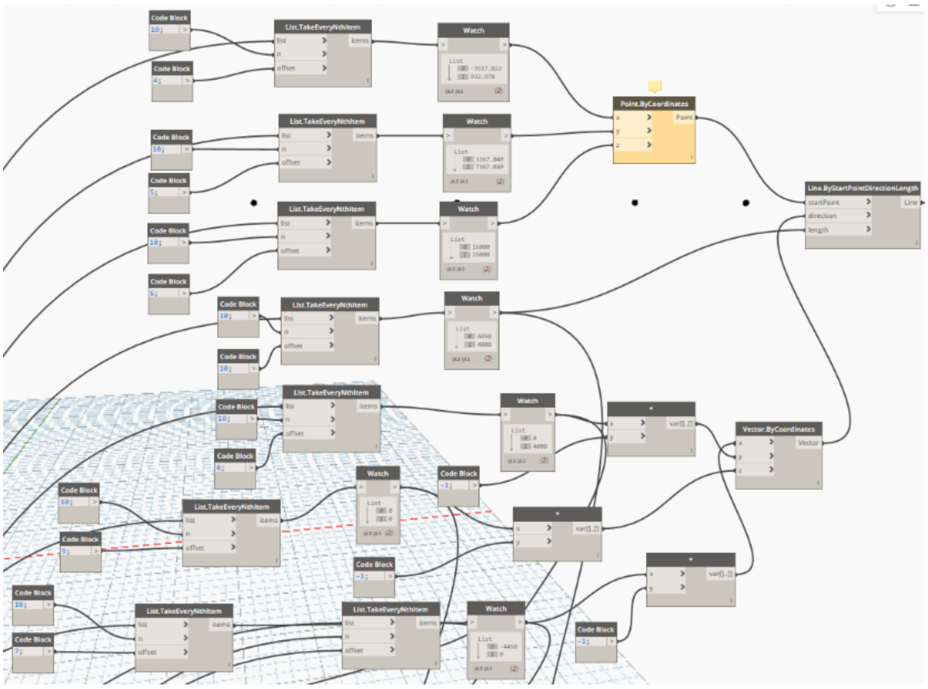


Figure 3.36 Reversing the curve of existing shaft walls in the CM

In this step, the “List.Create” node combines the lists obtained from the steps shown in Fig 3.35 and 3.36, and the result is sublists. The “Flatten” generates only one list from all items of the sublists. These curves are converted to string format in order to compare the list with the boundary curves of the shaft openings that have bigger areas than the threshold, and this comparison is done by the “SetDifference” node. The result is the curves of the location where the safety measure should be placed (Figure 3.37).

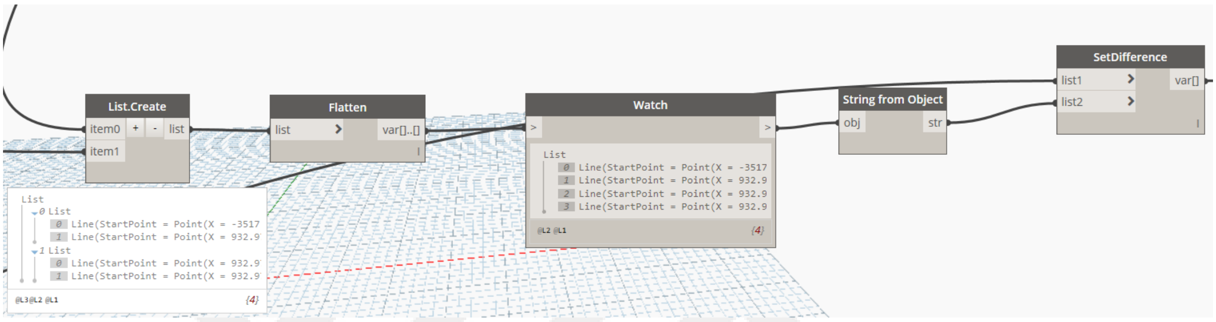


Figure 3.37 The curves of the locations of the missing shaft walls in CM

The “List.TakeEveryNthItem”, and then “Point.ByCoordinates” and the “Vector.ByCoordinates” nodes are used to create the start points and the vector of the curves as explained before. Finally, as shown in Figure 3.38, the final part of the shaft opening fall protection is performed, for the opening that has a bigger area than the threshold. This is the same as the exterior wall final process.

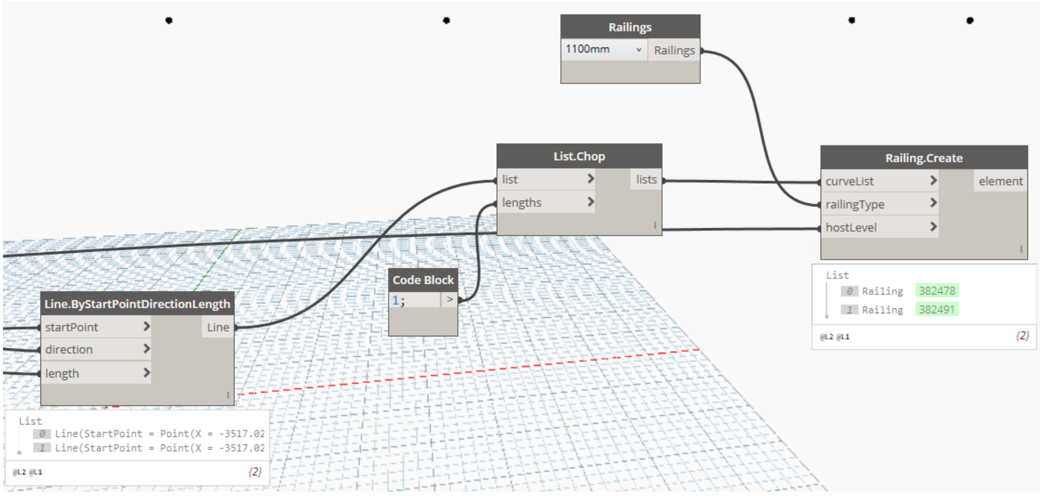


Figure 3.38 Placing guardrail to the locations of missing shaft walls in CM

Detecting the wall openings

AFSR also considers wall openings as hazardous locations for fall-related hazards. Below are the steps to detect these locations and to create guardrail as the necessary safety measure:

The “Opening” is selected from the options of the “Element Types”. The “All Elements of Type” gives all openings in the model that includes both the shaft openings and wall openings. Again, the AFSR tool perform checks for the hazardous locations floor by floor, it uses the “Element.FilterByLevel” to filter the openings of the requested floor. The “Base Offset” parameter is obtained by the “Element.GetParameterValueByName” node, and then, the openings with a negative offset (i.e., shaft openings), are filtered by the “List.FilterByBoolMask” as shown in Figure 3.39.

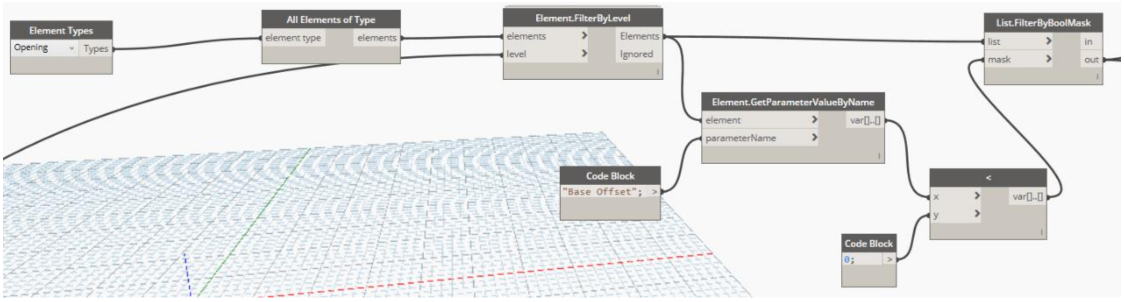


Figure 3.39 Filtering wall openings from all openings in the model

Railings in Autodesk Revit, which is used as a safety measure for the wall openings, cannot be viewed when located at the boundaries of the wall openings since the software perceives these locations as empty. Thus, the "Element.Geometry+" node from the "Clockwork" package is used to convert the wall openings to solids to handle this. Each wall opening has 8 vertices and they are obtained by the "Face.Vertices". Since this results in sublists for each wall opening, they are combined with the "Flatten" (Figure 3.40).

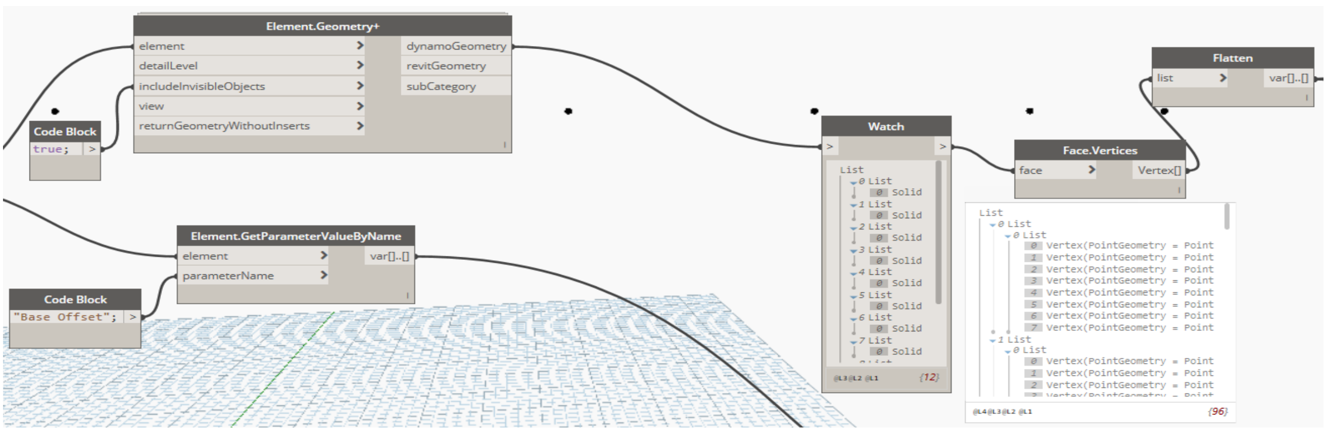


Figure 3.40 Obtaining vertices of the wall openings

The "List.TakeEveryNthItem" node gives the bottom external vertices points of the wall openings. Input "offset" is entered as "4" for the start point of the line and as "6" for the end point of the line. Moreover, input "n" value, which represents the period, is entered as "8" due to the eight vertices for each wall opening. The "Vertex.PointGeometry" converts the vertices to points. The lowest elevation point of the wall openings is obtained by the "Point.Z". Furthermore, since there is no specific suggestion made by OHSA for the base offset of the wall openings to be checked, a threshold given in OSHA was used . The threshold in OSHA for the wall openings is 1m (1000mm) (OSHA, 2015) from the level where they belong, it is necessary to check the elevation difference between the "Point.Z" and the level of elevation which is given by the "Level.Elevation". If a difference that is bigger than the 1000 mm threshold is identified, then it is filtered by the "List.FilterByBoolMask" (Figure 3.41).

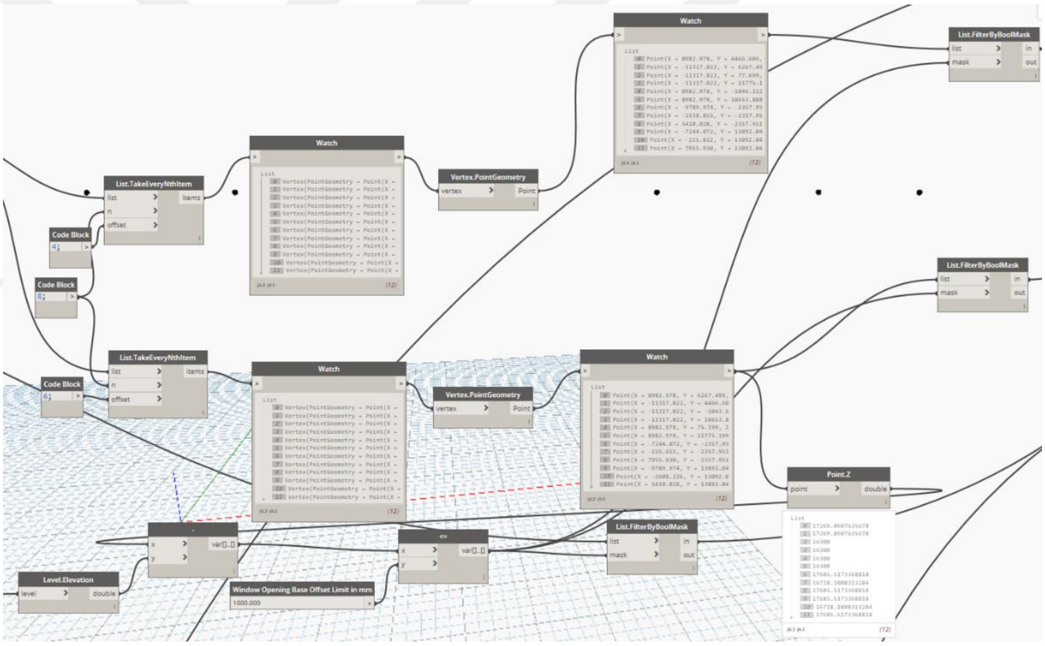


Figure 3.41 Creating curves to place guardrails for the wall openings to be checked

Placing the guardrails at the wall openings

The final step for creating the guardrail is almost the same with the exterior wall and the shaft opening final processes. Since the "Base Offset" of wall openings is bigger than 0, this parameter is arranged with using the "Element.SetParameterByName" node.

Input “value” of this node comes from the difference between the “Point.Z” and the “Level.Elevation”, which is shown in Figure 3.42, after applying the node “List.FilterByBoolMask” to check against the threshold.

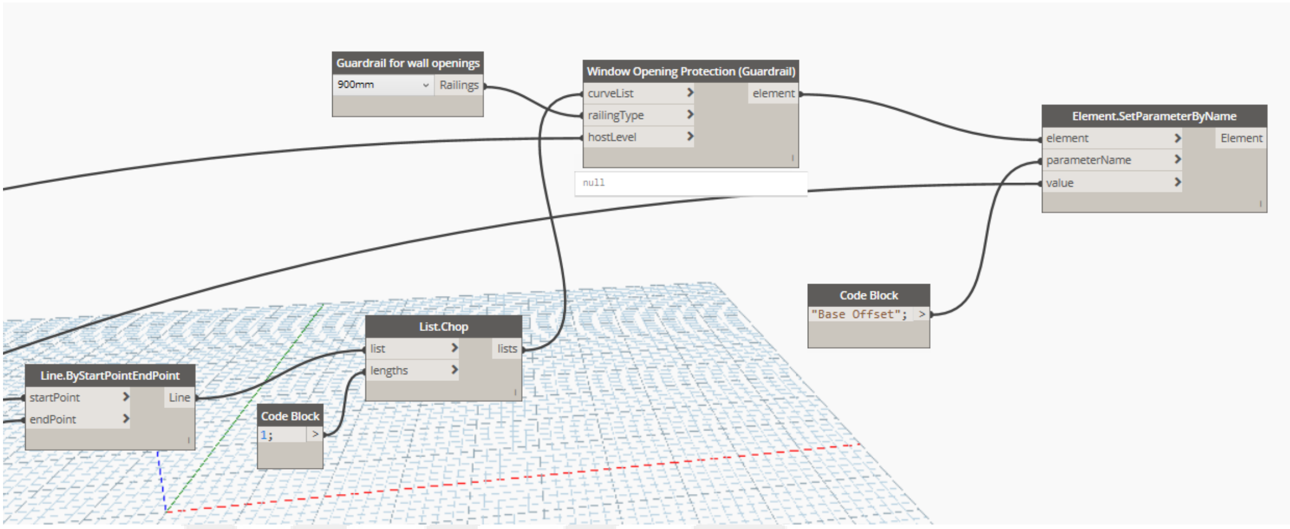


Figure 3.42 Placing guardrails to the wall openings to be checked

3.4. AFSR – Dynamo Player Manual

This section describes how the AFSR script could be run using the Dynamo Player once the MM and a CM is modeled as required by the AFSR tool as explained in Section 3.2.1. Each input of the AFSR tool in the Dynamo Player is given a number in Figure 3.43.

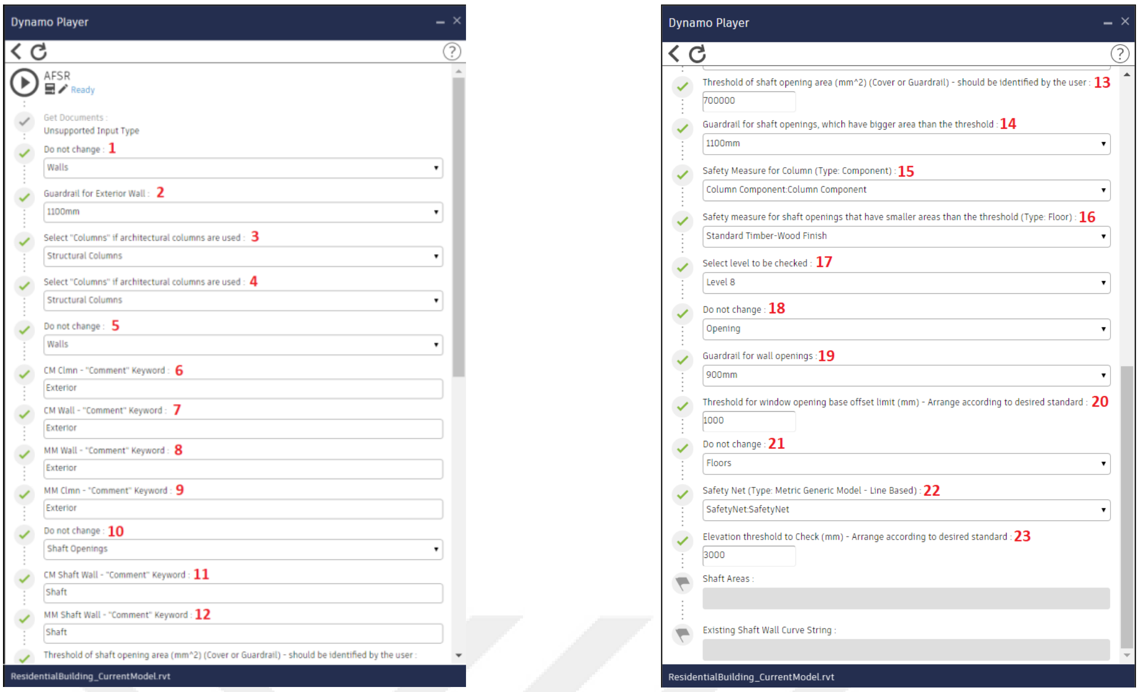


Figure 3.43 AFSR inputs as shown in the Dynamo Player

Input 1: This is determined by default, and therefore, the user should not change it and leave is as it is.

Input 2: Guardrail for the exterior wall. This input is used to select the desired railing type as a safety guardrail for the fall protection of the exterior walls (i.e., slab edges).

Input 3: Type of columns in the CM. This input identifies the default column type as “Structural Columns” for the CM. If columns are modeled as architectural, then the user should select “Columns”.

Input 4: Type of columns in the MM. This input identifies the default column type as “Structural Columns” for the MM. If columns are modeled as architectural, then the user should select “Columns”.

Input 5: This is a default input, and it should not be changed by the user.

Input 6: The “Comment” keyword for the exterior columns in CM, which are located at the slab edges, should be entered.

Input 7: The “Comment” keyword for the exterior walls in CM, which are located at the slab edges, should be entered.

Input 8: The “Comment” keyword for the exterior columns in MM, which are located at the slab edges, should be entered.

Input 9: The “Comment” keyword for the exterior walls in MM, which are located at the slab edges, should be entered.

Input 10: This is a default input, and it should not be changed by the user.

Input 11: The user enters the “Comment” keyword for the shaft walls in CM which are located at the shaft opening boundaries.

Input 12: The user enters the “Comment” keyword for the shaft walls in MM which are located at the shaft opening boundaries.

Input 13: The threshold for the shaft openings in terms of area is entered by the user in millimeters. Since there is not any specific threshold for this in the existing standards, it should be decided and entered by the user manually. If the area of a shaft opening is bigger than this value, a guardrail is used as a safety measure. Otherwise, the shaft opening cover is used.

Input 14: The desired railing type as a guardrail is selected for the shaft opening protection, which has a bigger area than the threshold.

Input 15: The name of the component is selected, which is prepared and loaded by the user manually, for the exterior columns that are located at the slab edge.

Input 16: The desired floor type is selected as a safety measure for the shaft opening protection, which has a smaller area than the threshold.

Input 17: The desired level is selected to be checked.

Input 18: This is a default input, and it should not be changed by the user.

Input 19: Railing type is selected as a guardrail for wall openings (window openings).

Input 20: The threshold for the amount of the base offset for the wall openings is arranged by the user in accordance with the desired standard. It is entered in millimeters.

Input 21: This is a default input, and it should not be changed by the user.

Input 22: The name of the component is selected, which is prepared by using Metric Generic Model line based family template and loaded by the user manually, for the slab edge protection.

Input 23: The elevation threshold is entered. If the level elevation is smaller than the threshold, AFSR does not check the hazardous places for this level. The default value is entered 3 meters (3,000 millimeters) in accordance with OHSA (OHSA, 2019). The user could change this value according to their standards.

Once all the inputs are entered according to the manual, the user can run the script by clicking the play button. The last step to run the AFSR script is shown in Figure 3.44.

Figure 3.44 AFSR run button in Dynamo Player

CHAPTER IV

CASE STUDY

A residential building was modeled in Autodesk Revit 2018 and used as the case study to verify the AFSR tool. The case study building has five floors. The Main Model (i.e., MM) of the building is given in Figure 4.1, that is the completed version of the project. MM has typical floors, and the floor layout is shown in Figure 4.2. At any stage of the project, another model of the building, called the Current Model (i.e., CM) (Figure 4.3), is used to compare it with the MM. Several models are created to reflect different stages of the case study building, and this allowed testing the capabilities of the AFSR tool from several perspectives. The AFSR tool compares the given CM with the MM, and identifies the hazards and the necessary safety measures for the building floor by floor, as mentioned in the previous section (Section 3.2).

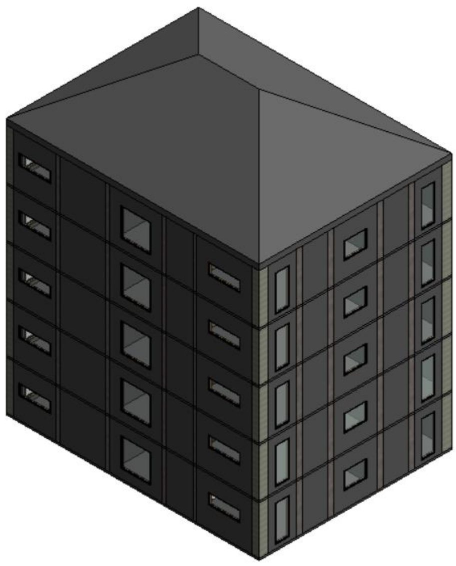


Figure 4.1 Main Model (i.e., completed project) of the building

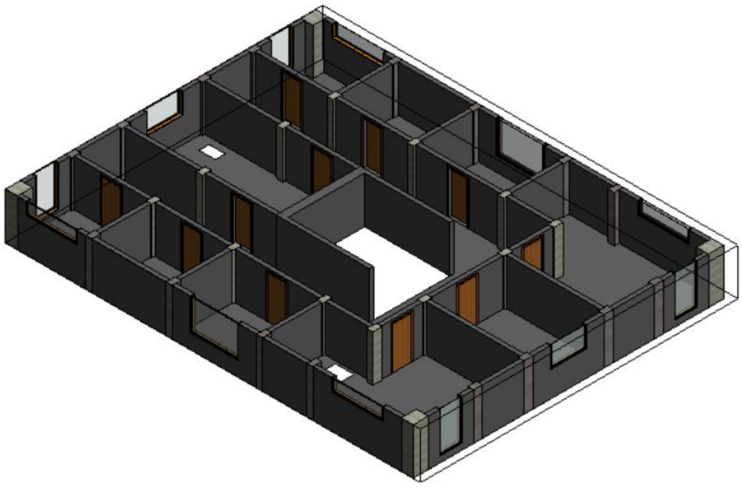


Figure 4.2 Typical MM floor layout in 3D

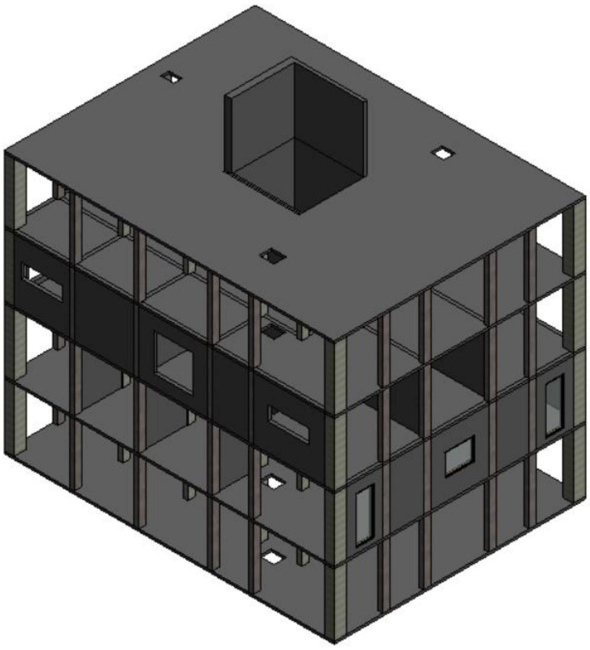


Figure 4.3 Current Model of the building (i.e., can be at any stage of project)

The following steps explain how the floors of the CM are modeled in a way to represent the different scenarios that create different fall-related safety hazards. All floor views are from the same direction (i.e., Northwest (NW)).

- **1st floor (Figure 4.4):** No exterior walls and no walls around the shaft opening were constructed in the 1st floor. Only the columns on the edge of the slab (i.e., exterior columns) were constructed.

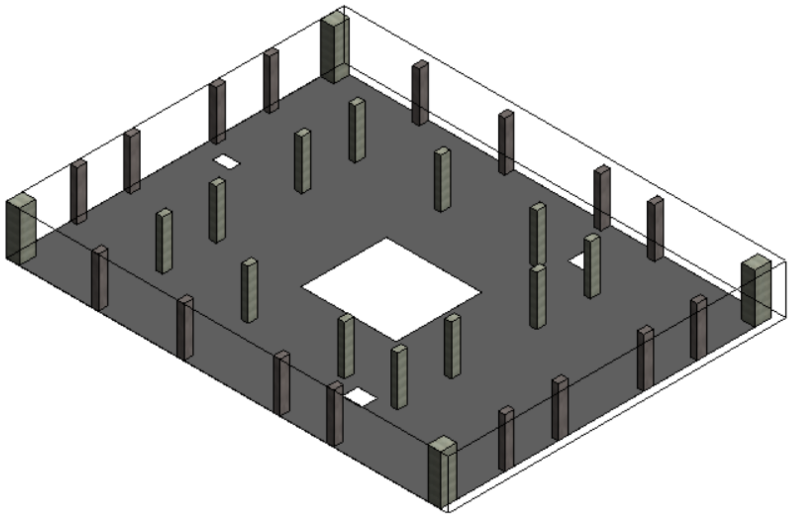


Figure 4.4 3D view of the 1st floor of the CM

- **2nd floor (Figure 4.5):** All of the exterior columns and shaft opening walls were constructed. A part of the exterior walls were constructed, and the windows were already installed on the completed walls.

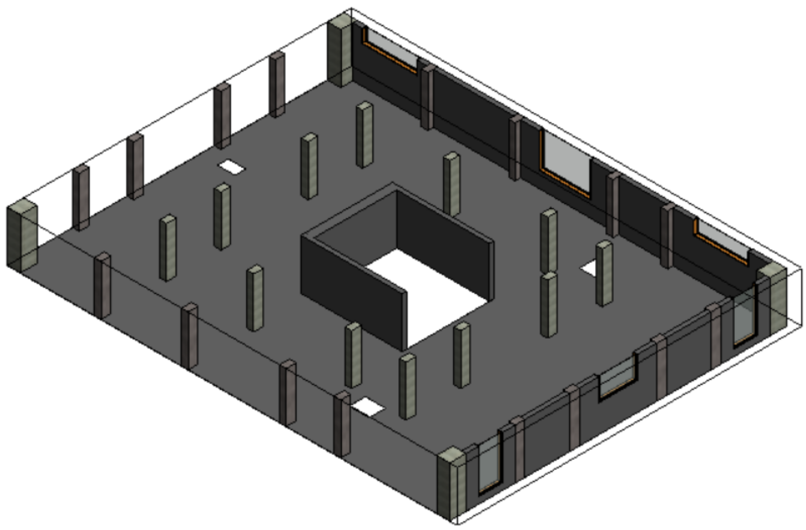


Figure 4.5 3D view of the 2nd floor of the CM

- **3rd floor (Figure 4.6):** All of the exterior columns and shaft opening walls were constructed. Some of the exterior walls were finished, on the opposite location of the exterior walls of the 2nd floor. Windows were not installed on the exterior walls, and therefore, exterior walls have wall openings without the windows.

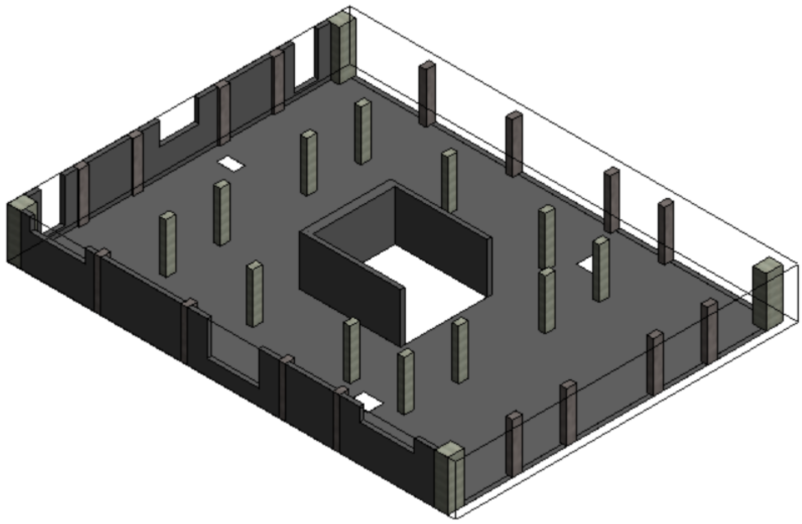


Figure 4.6 3D view of the 3rd floor of the CM

- **4th floor (Figure 4.7):** All of the exterior columns and shaft opening walls were constructed. Exterior wall work has not started at this floor.

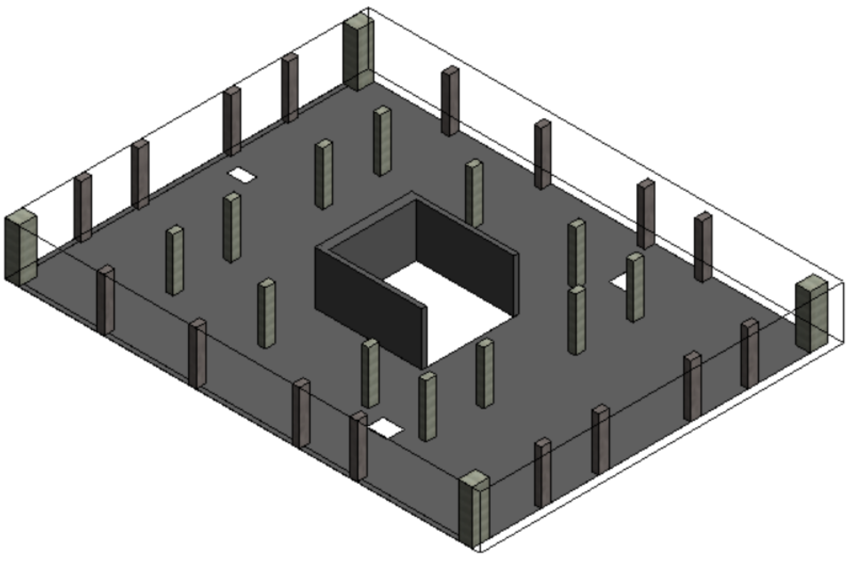


Figure 4.7 3D view of the 4th floor of the CM

- **5th floor (Figure 4.8):** Exterior walls and exterior columns were not constructed on the 5th floor. Moreover, shaft opening walls were partially constructed.

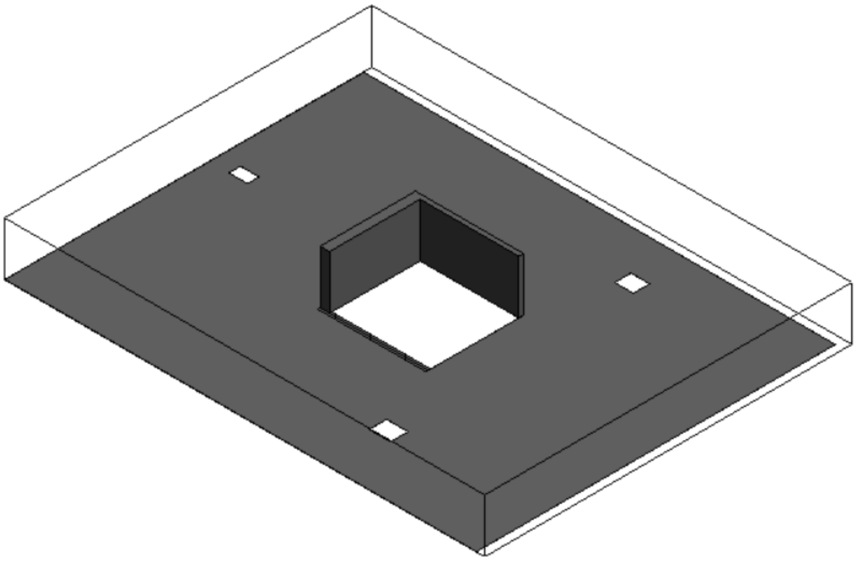


Figure 4.8 3D view of the 5th floor of the CM

4.1. AFSR Setup for the Case Study

This section first provides the characteristics of the case study (i.e., inputs of the case study for AFSR), and the thresholds applied. The analysis of the case study for the fall-related hazards are given in the next section.

Entering the thresholds

Using the Dynamo Player, the thresholds are entered to AFSR for the case study to determine where and when to use the safety measures. Table 4.1 summarizes the standards from which the safety measures are identified and included in the AFSR, and the related thresholds used in the case study.

Table 4.1 Safety measures and thresholds used in the AFSR tool

Hazard Location	Standard	Safety Measure	Threshold
Slab Edge	OHSA	Safety net and guardrail	Will be applied if level is at 3 meters or higher
Shaft Opening	OHSA	Guardrail or shaft cover	User defined based on the area of opening (e.g., 0.7 m^2)
Wall Opening	OSHA	Guardrail	Window openings located lower than 1 meter

Level thresholds: First of all, the height of a floor in the case study building is 4 m, as shown in Figure 4.9. Furthermore, Figure 4.10 shows that the elevation threshold is set to 3000 millimeters in the case study according to OHSA which is the default value in AFSR.

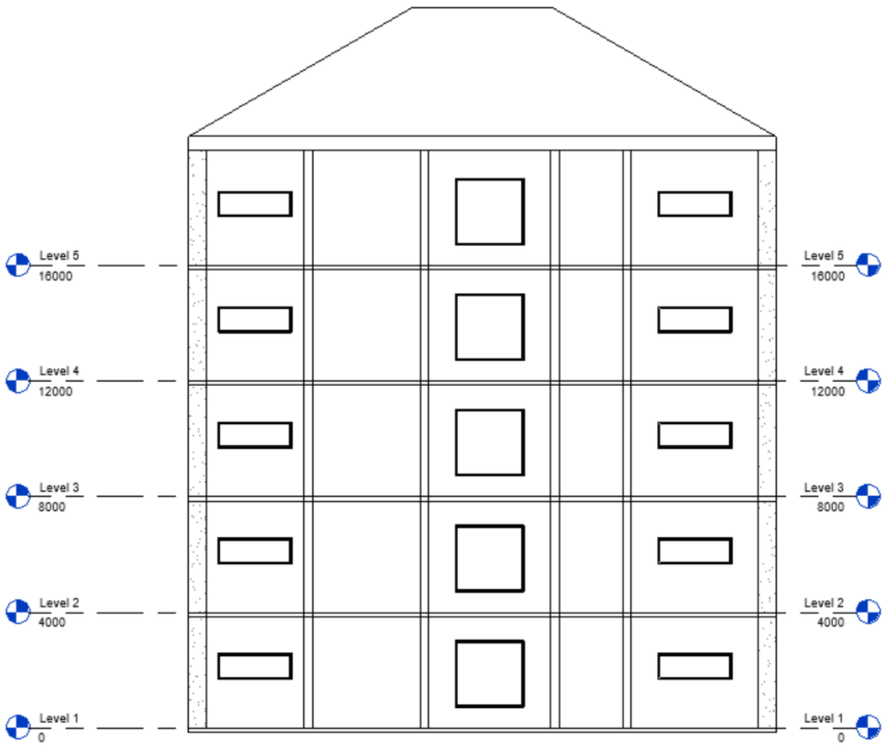


Figure 4.9 Floor elevations of the case study building

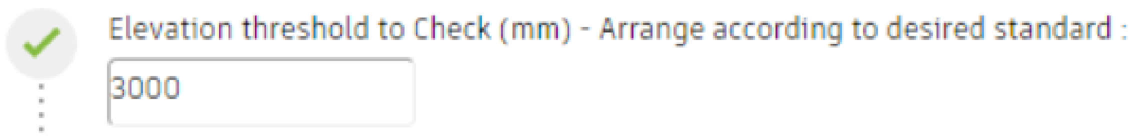


Figure 4.10 Elevation threshold for the case study

Shaft opening thresholds: There are four shaft openings for each floor and their areas are as shown in Figure 4.11. The desired threshold for the shaft opening areas is identified as 700,000 mm^2, which is available in Figure 4.12.

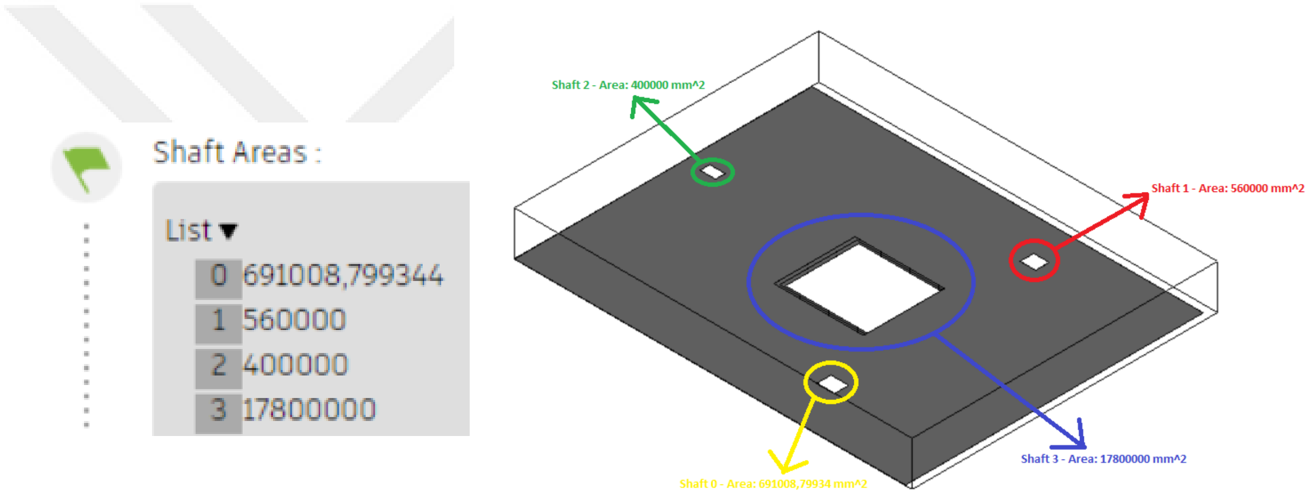


Figure 4.11 Areas of the shaft openings of each floor (mm^2)

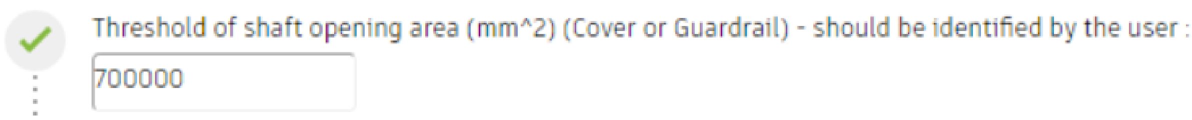


Figure 4.12 Default threshold for the shaft opening area

Wall opening base offsets: The base offsets of the wall openings are given in Figure 4.13. The opposing sides of these walls are the same. If windows are set up, then there is no need to check their locations in terms of fall. OSHA suggests that 1000 mm (1 m) should be used as the threshold for the base offset of wall openings, which is shown in Figure 4.14 below.

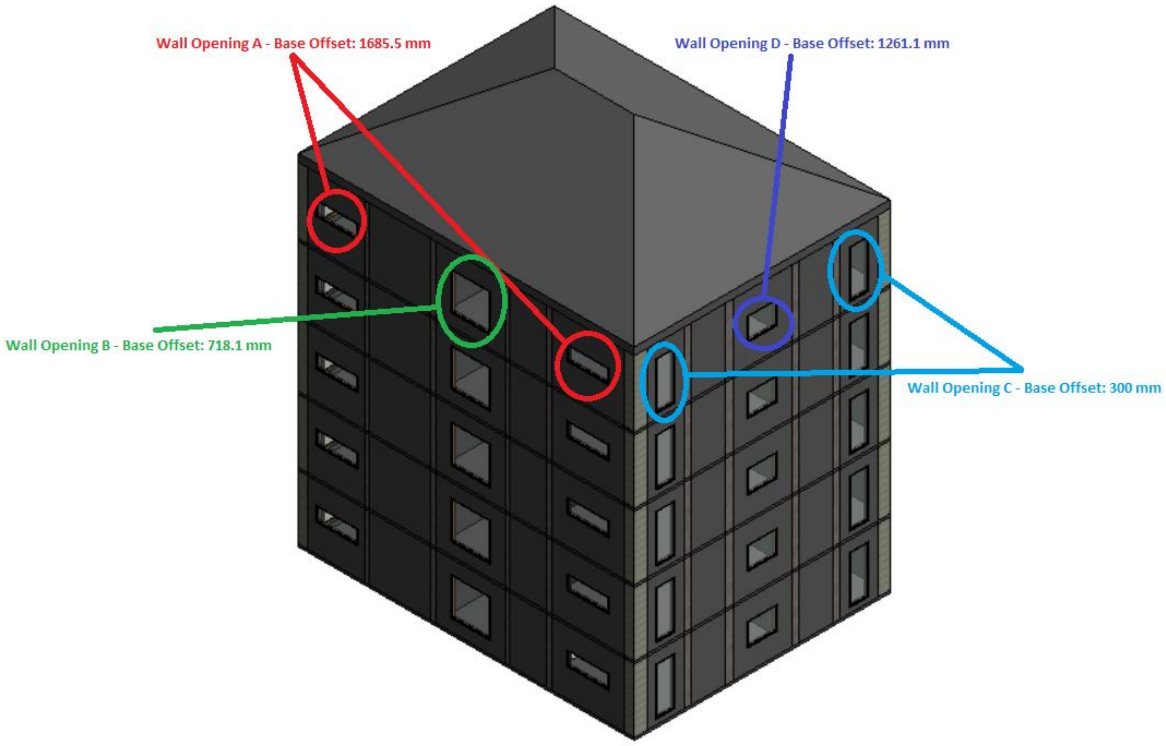


Figure 4.13 Base offsets of wall openings in the Main Model of the case study

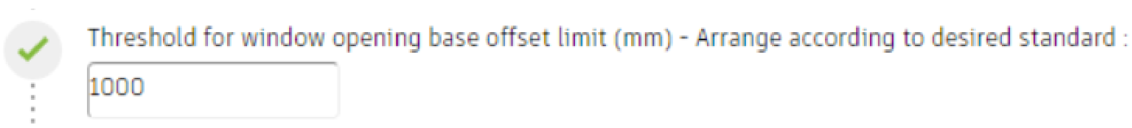


Figure 4.14 Threshold for the base offset of wall openings in the case study

In addition to these thresholds, the user should also load the Revit families for the safety measures (i.e., safety net and the columns used for placing guard rails) to the CM. Safety nets are placed at every floor as required, and the columns are used for placing the guardrails around the exterior walls. Once these are loaded, the user can select it from the AFSR input menu, as shown in Figure 4.15.

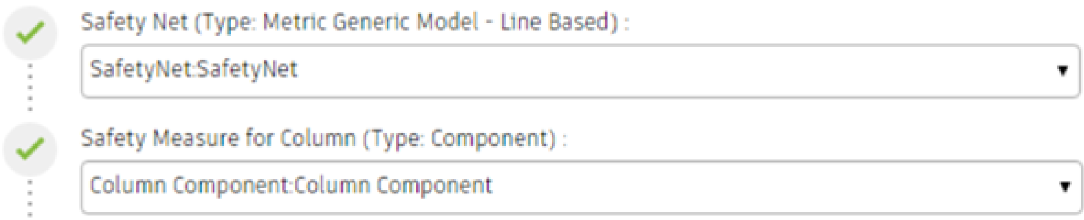


Figure 4.15 Selecting safety components in the AFSR

Two types of safety measures are used for the shaft openings in accordance with their areas, as shown in Figure 4.11. As explained before, if the area of a shaft opening is larger than the threshold, guardrails are placed on the edge of the shaft opening. Otherwise, the shaft opening cover is placed as a safety measure which should be selected as a floor type from the model. In this case study, "Standard Timber-Wood Finish" is used as the shaft opening cover and "1100mm" is used as the guardrail, which is shown in Figure 4.16.

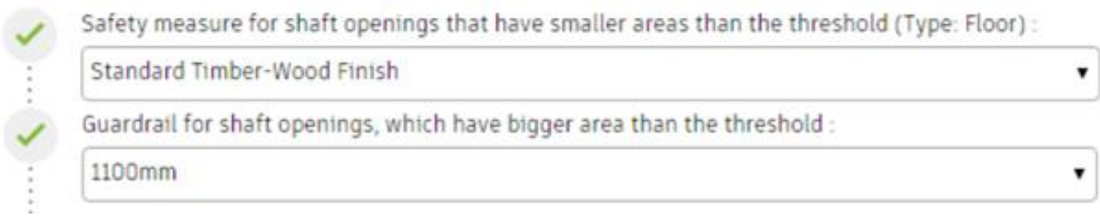


Figure 4.16 Selecting the safety measures for the shaft openings in the AFSR

Moreover, the type of guardrail should also be selected for the hazardous locations at slab edges and wall openings. OHSA suggests that the top of the guardrails should be located at least 900 mm but not more than 1100 mm (OHSA, 2019). Thus, "1100mm" was used for slab edges and “900mm” was used for wall openings in the case study, as shown in Figure 4.17.

Figure 4.17 Types of railings for the slab edges and the wall openings

4.2. AFSR Implementation and Results

This section explains how AFSR is utilized in the case study. The resulting model that includes the safety measures that are automatically applied to each floor by AFSR are shown in 3D. As mentioned before, AFSR performs safety review floor by floor (i.e., level by level). Therefore, after the setup of inputs, the last step is to select the level at which the safety review will be performed. As shown in Figure 4.18, AFSR lists all the existing levels in the CM.

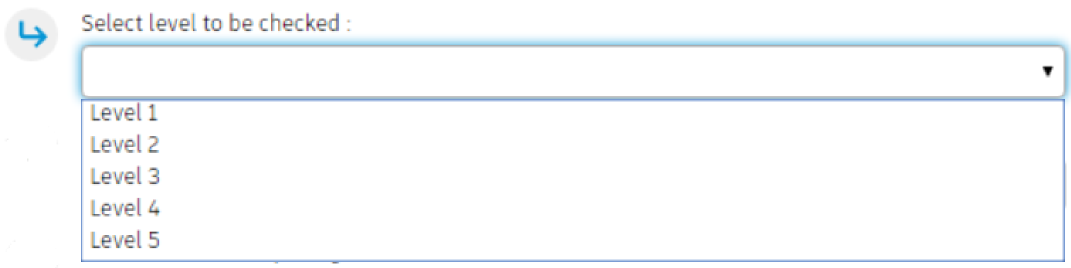


Figure 4.18 Level selection in Dynamo Player

The results of the case study are given below. The names of the shafts and wall openings are shown in Figure 4.11 and Figure 4.13.

- **1st floor results**

As explained before, there are no exterior walls and shaft opening walls constructed on the 1st floor. All of the shaft openings shown in Figure 5.10 are located at this floor. Since the elevation of this level is 0 m, this does not pose a hazard and these openings are ignored by AFSR. As described in Sec. 5.2, threshold for the elevation in order to check was arranged as 3,000 millimeters and this level's elevation is lower than the threshold. Therefore, written notification confirmed this condition with the expression "No safety check at this level according to selected standard". Moreover, there is no change at this level in terms of safety measures in 3D view. The process and results of AFSR for the 1st level is given in Figure 4.19.

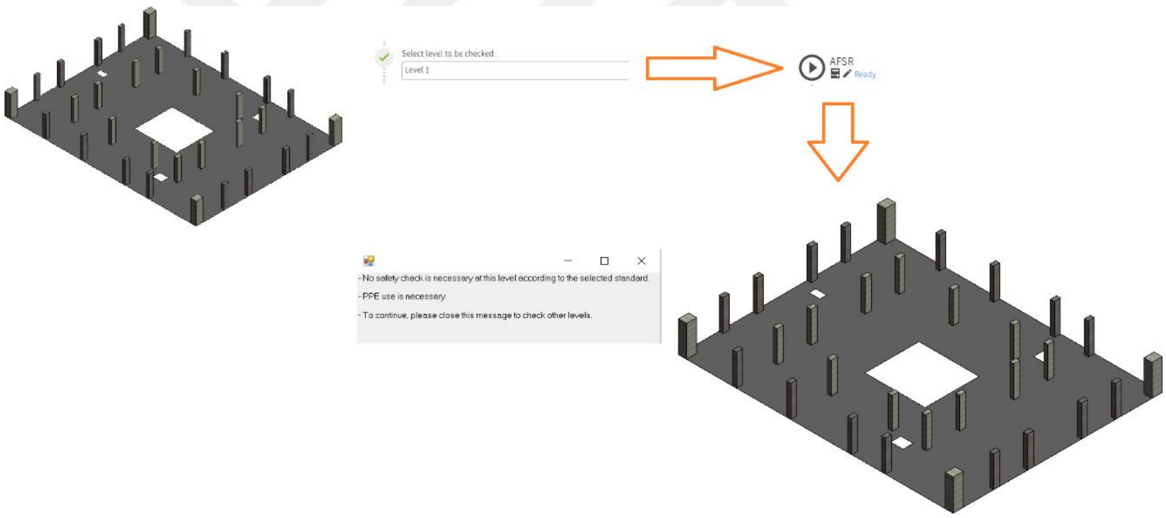


Figure 4.19 Process and results of the case study for the 1st floor

- **2nd floor results**

The elevation of this level is 4 m. Therefore, starting at this floor and on the upper floors, AFSR places safety nets.

In addition to the safety nets, shaft openings 0, 1 and 2 at the locations shown in

Fig 5.10, should be protected by shaft covers since their areas are smaller than the threshold 700,000 mm^2 (Figure 4.12). For the Shaft – 3 (Figure 4.11), guardrails should be placed where there is no wall around the shaft opening. AFSR places these safety measures to the 2nd floor.

Exterior walls of the 2nd floor are partially constructed, and therefore, AFSR places guardrails to the locations where there is no exterior wall and no shaft opening walls.

AFSR checks and confirms that windows are placed at all wall openings, and therefore, there is no safety hazard related to the wall openings.

For the 2nd floor and the higher floors, a message is communicated with the user: “Please refer to the 3D model for the necessary safety measures”. Figure 4.20 shows the safety measures that are automatically placed to the 2nd floor in terms of the fall-related hazards in 3D.

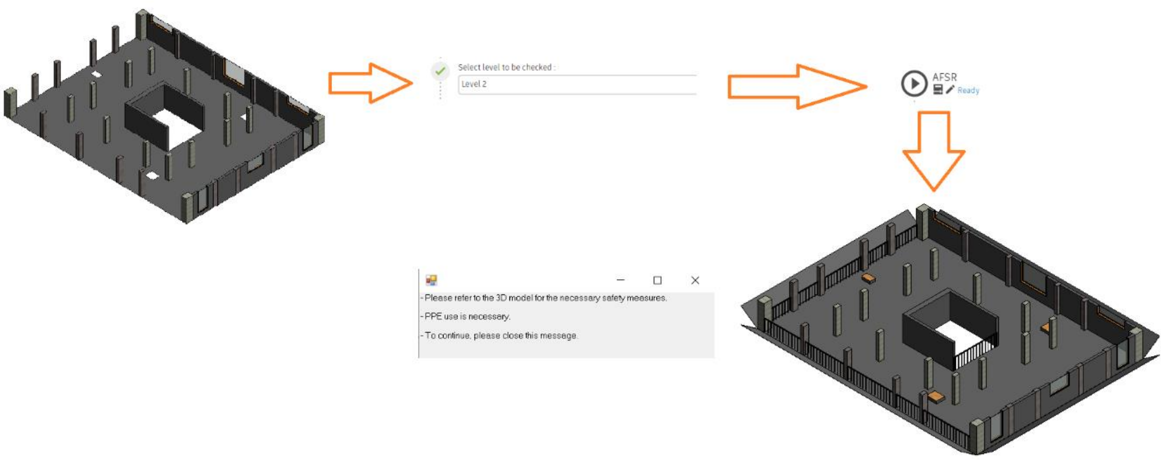


Figure 4.20 Process and results of the case study for the 2nd floor

- **3rd floor results**

Conditions of this floor are the same as 2nd floor, except the window placement and the exterior wall locations. Wall Opening B and Wall Opening C (Figure 4.13) are the hazardous locations since their base offsets are lower than 1000 mm which is the threshold defined in OSHA. Thus, guardrails are placed at these locations.

This part of the case study demonstrates how AFSR finds the locations of missing exterior walls of CM by comparing it to the MM. In other words, compares the exterior wall locations of the CM and MM, and then places the guardrails on the locations where the exterior walls are missing in the CM.

The process and results of AFSR implementation for the 3rd floor could be observed in Figure 4.21.

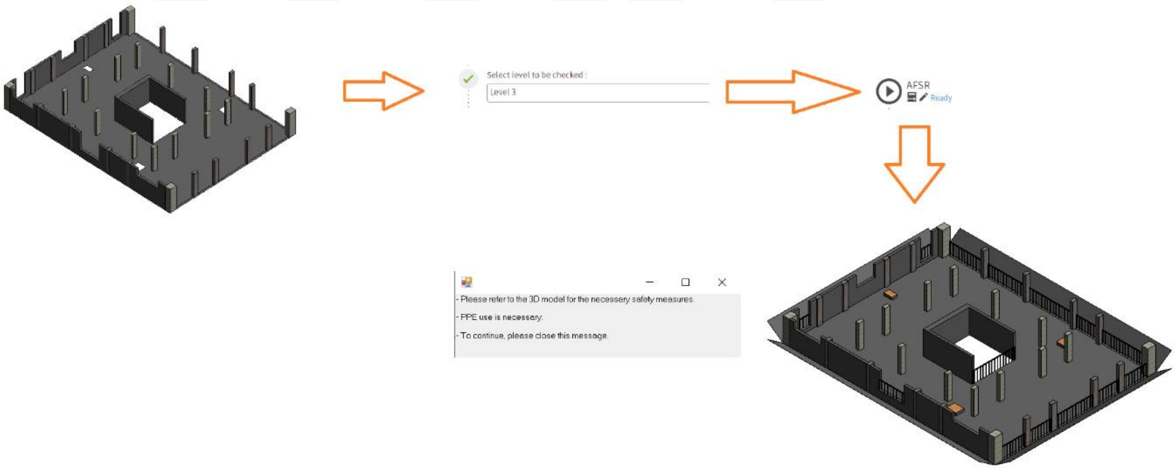


Figure 4.21 Process and results of the case study for the 3rd floor

- **4th floor results**

This floor is in the same construction stage with the 1st floor. However, it is required to check fall-related hazardous places at this floor since the elevation of this floor is higher than the defined threshold, which is 3 meters (Figure 4.10). Figure 4.22 shows the safety check results. The difference between 1st floor and 4th floor could be observed from Figure 4.19 and Figure 4.22.

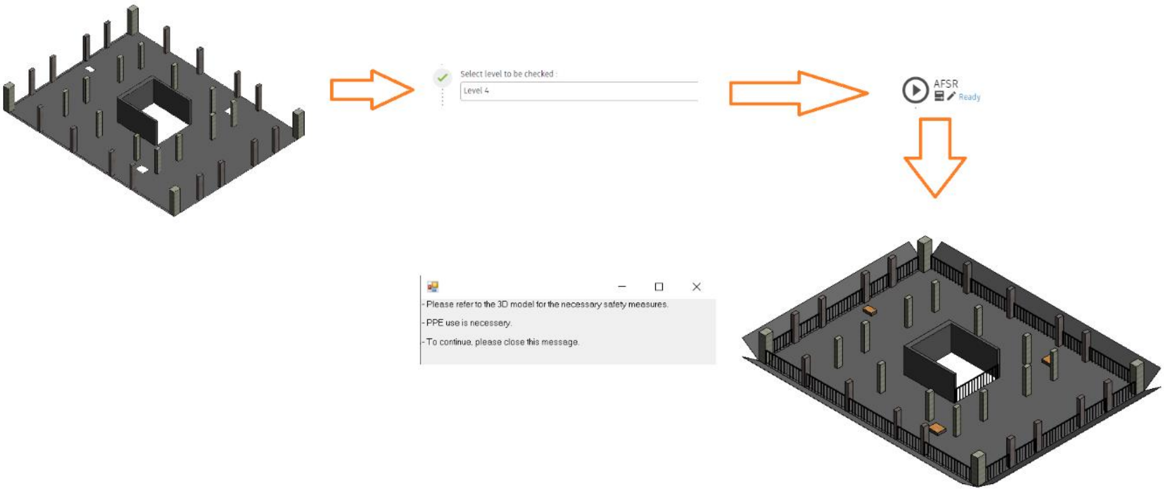


Figure 4.22 Process and results of the case study for the 4th floor

- **5th floor results**

No exterior walls and exterior columns are yet constructed at the 5th floor. The column component is used for assisting in placing the guardrails. Shaft opening walls for Shaft – 3 are partially set up at this floor. AFSR detects the location of the missing shaft opening wall in CM, and puts guardrails.

Figure 4.23 shows how AFSR updated the 5th floor with fall-related safety measures.

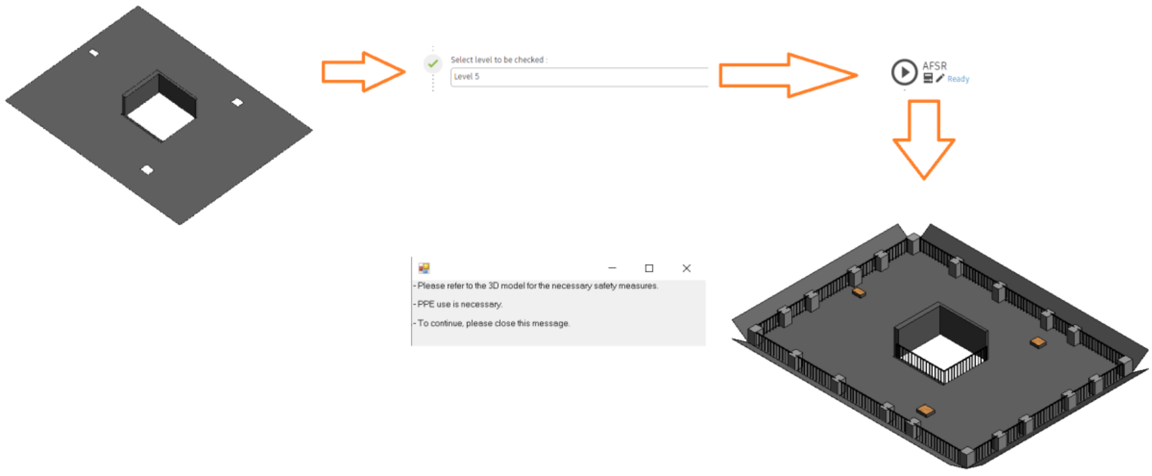


Figure 4.23 Process and results of the case study for the 5th floor

Each floor of the 3D case study model that is automatically modified with the fall-related safety measures, can be seen in Figure 4.24, and also the complete modified model can be seen in Figure 4.25.

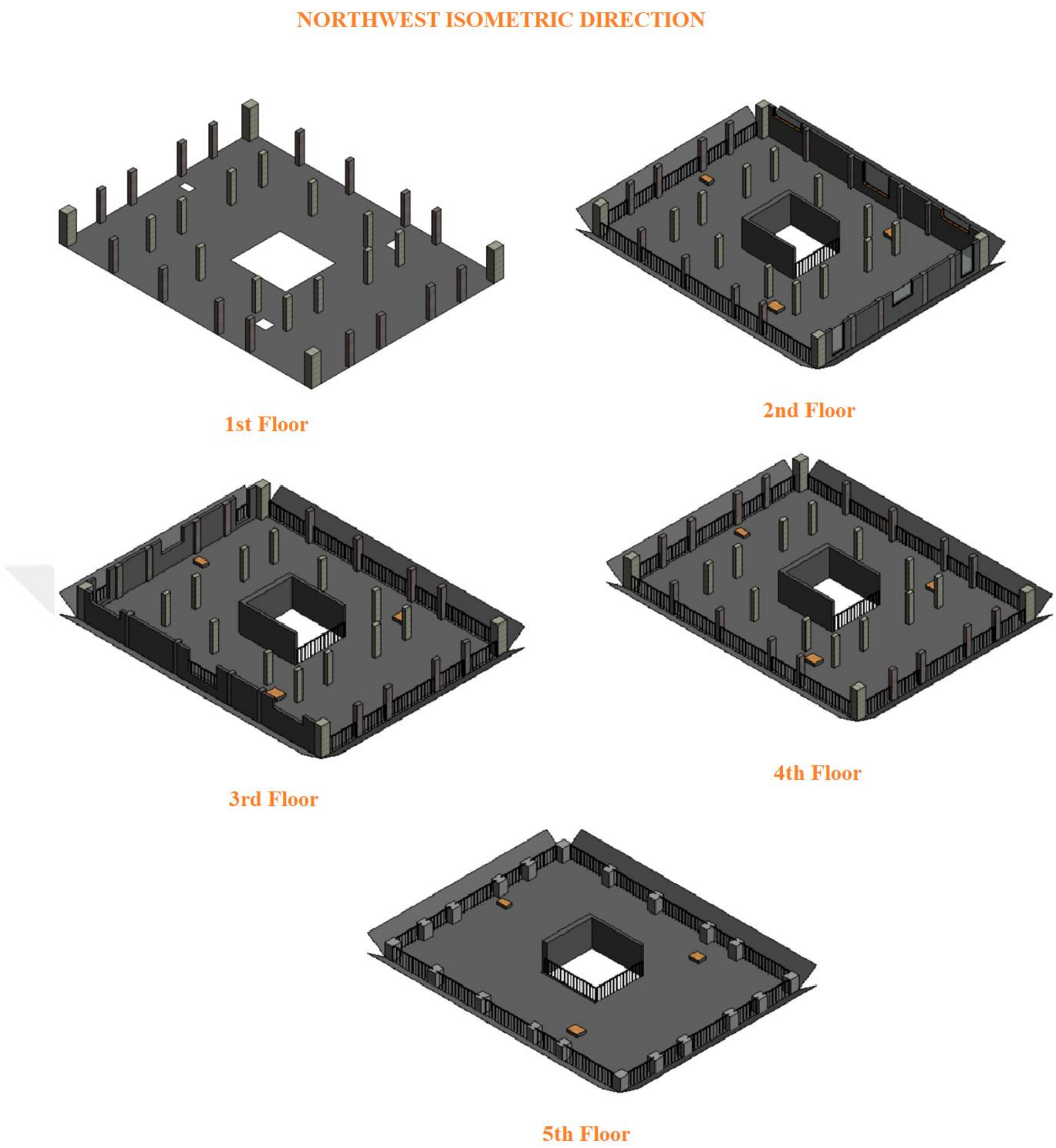


Figure 4.24 Case study model modified with fall-related safety measures shown floor by floor

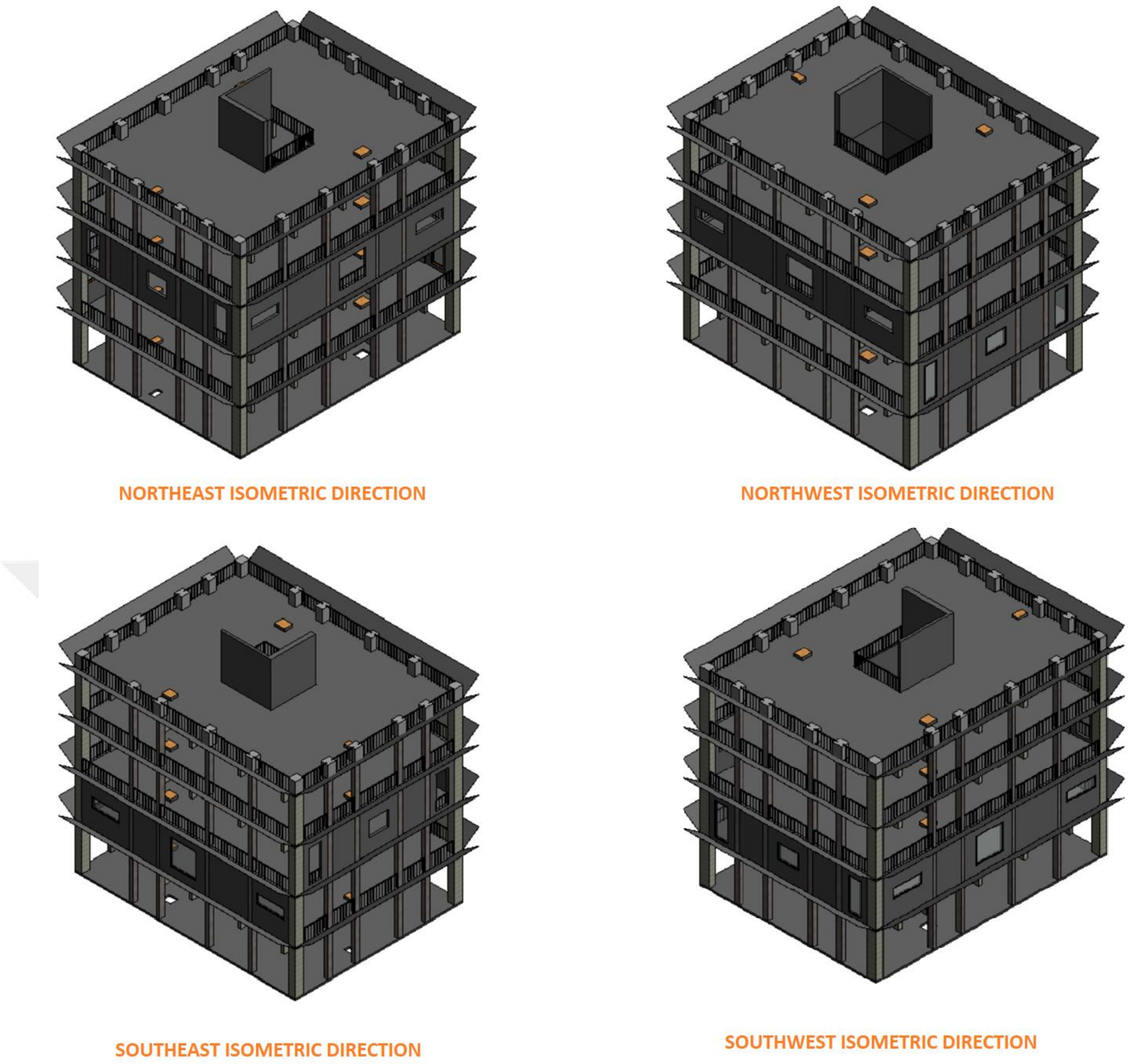


Figure 4.25 Case study model modified with fall-related safety measures shown in 3D

CHAPTER V

CONCLUSION

The construction industry is globally accepted as one the most of the hazardous industries. In the current practice, the efficiency of safety planning of a construction project depends on the experience of H&S experts although all the stakeholders should be involved in the safety design of a project. Moreover, the traditional safety planning method that relies on 2D drawings has the possibility to fail to pinpoint all the hazardous locations in a construction project. Building Information Modeling (BIM), with the enhanced 3D visualization capabilities it provides, can help performing an automatic safety planning and review on buildings, and also can apply the related safety measures on the 3D model and update the model. To demonstrate the application of BIM as a safety rule checking tool, an automated BIM-based review tool for fall safety, namely Automated Fall Safety Review (AFSR) tool, is developed in this thesis.

As falls from height and struck by objects are the most common types of accidents that occur at building projects, the focus of AFSR is on fall-related hazards. It checks the locations of the slab edges, external wall openings, and shaft openings, as these are the main locations in a building that create a fall hazard. It then places the related safety measures (i.e., guardrails, shaft covers, and safety nets) at these locations. The users manually select the safety measures that will be placed on the building before performing a safety review with AFSR. Identification of the hazardous locations are done based on the predefined thresholds that the users enter in the AFSR. Safety regulations and standards can be the source of these thresholds, or even the users can define a new threshold based on the needs of their own projects.

In this thesis, Autodesk Revit was used for performing the 3D modelling of a case study building. Also, Revit's open-source visual programming add-in Dynamo was used for coding the AFSR in order to perform the rule checking and to identify the related safety measures. Then the AFSR script was run using the Dynamo Player.

AFSR was performed on 5-storey residential building as presented in the case study section of the thesis. The presented building is designed to represent particular stages at each floor as different scenarios to test the AFSR tool under different circumstances. Thresholds were defined in accordance with OHSA and OSHA in Dynamo Player which are the default thresholds of AFSR. Since AFSR works floor by floor (i.e., level by level in Revit model), the 3D results of each scenario are presented separately in the chapter of the case study. Finally, the overall view of the updated model is shown as different isometric views.

Since Dynamo is an open-source tool, users can share and download the specific packages to find the necessary functions for their own studies. As previously mentioned, both researchers and construction industry professionals develop solutions to tackle several problems in construction. Dynamo and Phyton work coordinately, and therefore, knowing Phyton language is advantageous as scripting becomes easier where one Phyton code block can correspond to several node combinations in Dynamo.

This tool is particularly aimed to be used by site personnel that includes the contractors, designers who work at site offices, site engineers, as well as the on-site H&S staff. Also, other project participants who should have a general idea about the safety planning of a particular project can make use of this tool. However, it can be developed to serve advanced functions for the use of H&S experts, who should check every details of the safety design of a building in accordance with the standard being used or regulation that is in force.

5.1. Contributions

Fall-related hazards and the related safety measures are investigated as part of this thesis. The literature on safety in construction is reviewed, and the results of the accidents in construction, especially the fall-related accidents, are presented.

According to the Design for Safety approach, all project participants should be involved in the safety design of projects. With the use of BIM-based automated safety review tools, even the less experienced project participants can be involved in the responsibility of safety in a construction project. The developed tool in this thesis, AFSR, is mainly aimed to assist the on-site personnel working in site offices and site engineers by identifying hazardous places in buildings and placing the related safety measures automatically for fall-related hazards.

As reviewed in the literature, researchers have been studying on computer-aided safety in construction. Tools developed previously that are similar to AFSR mainly based on using the schedule of a project to perform a safety review, however, AFSR works regardless of the schedule of a project and its progress, and it can work at any given stage of a building. Moreover, since the previous tools were not created by using an open-source software, their modification by the users is limited. On the other hand, Dynamo that was used to create AFSR allows its users to modify the tool from the Dynamo interface if some changes are needed. Another advantage of AFSR is that the 3D model of the building is not converted to any format (e.g., IFC), and or it does not need to be imported to any other software to perform a safety review. All implementation is done within the Revit model, and this performs more efficiently and eliminates the use of other tools.

AFSR can potentially help increasing productivity in construction projects since it assist in preventing possible accidents that can result in penalties or delays. Moreover, related safety measures can be observed by the users thanks to automation even before the project starts, and thus, this can help save time. Automated safety review provided by the AFSR tool also helps saving time of the project teams in every phase of the project, when the safety review of the building needs to be performed. It also increases the quality of the safety review as the automated checks every part of the building design.

5.2. Constraints and Limitations

In the current version of AFSR, there are some limitations that can be overcome in the future versions. First of all, when identifying the hazardous locations on a building design, AFSR is limited to only identifying linear geometry. Other types of geometry, such as curvatures, cannot be identified. However, this is not a significant limitation as in the common construction practice, slab edges, shaft openings, and wall openings in buildings are typically designed linear rather than with a curved geometry.

AFSR currently does not check roofs where parapets and anchorages are generally used as safety measures to prevent fall from roofs (Behm, 2005). This function can be added to the future versions of AFSR. Also, to be able to use the current version when the user needs to check the hazardous places at a roof; the roof can be designed as a slab in Revit, and guardrails and safety nets can then be recommended by AFSR as the related safety measures.

The safety measures included in the AFSR are limited to the availability of the Revit families. It was possible to create a new family from scratch to represent the safety net in the AFSR tool, however, other fall-related measures, such as wind panels, are not included in the tool as a wind panel family is not currently available for Revit.

Finally, AFSR could check only one building model at a time. Therefore, if there is a project that includes more than one building in one Revit file, each building should be saved separately as individual files.

5.3. Future works

There are some further improvements and future work related to the developed AFSR tool. For instance, calculation of the amount of the safety measures that are automatically added to the 3D model can be included in AFSR. This can be done by creating schedules (i.e., material take offs) in Revit. The total amount of length of guardrails and safety nets, and the total area of the shaft covers could be provided to the user, and this can also be used to calculate the cost of the required safety measures practically.

The scope of the AFSR tool is buildings, and it is aimed to be used during the design and construction stages, especially during the structural works. However, it can easily be adapted to different types of projects other than buildings. The scope of the thesis currently considers slab edges, wall openings and shaft openings as hazardous locations in buildings. Although falls from roof are also common,, this is not currently included in the AFSR. Future work includes exploring the application of the AFSR tool on the roof construction.

Traditional fall-related safety measures (i.e., guardrail, safety net, and shaft cover) are used in AFSR, however, wind panels could be added as an option to prevent fall-related hazards. The tool would check the floor boundary locations, then, install the wind panels at those places automatically.

Currently AFSR does not consider re-using the safety nets every two or three floors. For a more cost efficient approach that can also help preventing waste, the tool can be modified in the future versions to install the safety nets for every 10 m.

The tool in this thesis only reviews fall-related hazards in buildings. However, it can be modified and applied to other types of hazards in the future. For instance, the materials used in the design could be automatically checked by the tool to classify them in terms of inflammable and non-flammable. In this method, available material types in the model should be categorized in Dynamo according to their flammability, then all the elements in the model can be examined by the tool automatically. Consequently, the users will be allowed to get a final report that gives the information about the risky elements in terms of fire. Moreover, these risky elements could be also highlighted in 3D view of the project in Revit. These research ideas for future significantly demonstrate the generalizability of the developed approach.

REFERENCES

Arslan, M., Cruz, C., & Ginhac, D. (2019). Semantic trajectory insights for worker safety in dynamic environments. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2019.102854

Autodesk. (2018). No Title. Retrieved from https://knowledge.autodesk.com/support/revit-products/getting-started/caas/CloudHelp/cloudhelp/2018/ENU/Revit-GetStarted/files/GUID-D8835F8E-1330-4DBC-8A55-AF5941056C58-htm.html

Autodesk. (2019a). No Title. Retrieved from https://knowledge.autodesk.com/support/revit-products/troubleshooting/caas/CloudHelp/cloudhelp/2019/ENU/Revit-Customize/files/GUID-F45641B0-830B-4FF8-A75C-693846E3513B-htm.html

Autodesk. (2019b). No Title. Retrieved from https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-AddIns/files/GUID-BFCE20D2-86D4-4591-8CF3-5405D26DB825-htm.html

Behm, M. (2005). Linking construction fatalities to the design for construction safety concept. *Safety Science*. https://doi.org/10.1016/j.ssci.2005.04.002

Bilir, S., & Gurcanli, G. E. (2018). A Method For Determination of Accident Probability in Construction Industry. *Teknik Dergi*. https://doi.org/10.18400/tekderg.363613

Bilir, S., & Gurcanli, G. E. (2018). A Method For Determination of Accident Probability in Construction Industry. *Teknik Dergi*. https://doi.org/10.18400/tekderg.363613

Camino López, M. A., Ritzel, D. O., Fontaneda, I., & González Alcantara, O. J. (2008). Construction industry accidents in Spain. *Journal of Safety Research*. https://doi.org/10.1016/j.jsr.2008.07.006

Chantawit, D., Hadikusumo, B. H. w, Charoenngam, C., & Rowlinson, S. (2005). 4DCAD Safety: Visualizing project scheduling and safety planning. *Construction Innovation*. https://doi.org/10.1108/14714170510815203

Cheng, C. W., Leu, S. Sen, Lin, C. C., & Fan, C. (2010). Characteristic analysis of occupational accidents at small construction enterprises. *Safety Science*. https://doi.org/10.1016/j.ssci.2010.02.001

Cheng, T., & Teizer, J. (2014). Modeling tower crane operator visibility to minimize the risk of limited situational awareness. *Journal of Computing in Civil Engineering*. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000282

Choi, S. D., Guo, L., Kim, J., & Xiong, S. (2019). Comparison of fatal occupational injuries in construction industry in the United States, South Korea, and China. *International Journal of Industrial Ergonomics*. https://doi.org/10.1016/j.ergon.2019.02.011

Chong, H. Y., & Low, T. S. (2014). Accidents in Malaysian construction industry: Statistical data and court cases. *International Journal of Occupational Safety and Ergonomics*. https://doi.org/10.1080/10803548.2014.11077064

Feng, C. W., & Lu, S. W. (2017). Using BIM to automate scaffolding planning for risk analysis at construction sites. *ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction*. https://doi.org/10.22260/isarc2017/0085

Gambatese, J. A., Hinze, J. W., & Haas, C. T. (1997). Tool to design for construction worker safety. *Journal of Architectural Engineering*. https://doi.org/10.1061/(ASCE)1076-0431(1997)3:1(32)

Gurcanli, G. E., & Mungen, U. (2009). An occupational safety risk analysis method at construction sites using fuzzy sets. *International Journal of Industrial Ergonomics*. https://doi.org/10.1016/j.ergon.2008.10.006

Hadikusumo, B. H. W., & Rowlinson, S. (2002). Integration of virtually real construction model and design-for-safety-process database. *Automation in Construction*. https://doi.org/10.1016/S0926-5805(01)00061-9

Harrell, R., & Mathews, M. (2018). *Could Autodesk Revit Be Automated for Code Compliance Checking and Demonstration with A Focus on Fire Safety Regulations? Footer Logo*. Retrieved from https://arrow.dit.ie/bescharcrep

Hongling, G., Yantao, Y., Weisheng, Z., & Yan, L. (2016). BIM and Safety Rules Based Automated Identification of Unsafe Design Factors in Construction. *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2016.11.646

Islam, M. S., Razwanul, I., & Mahmud, M. T. (2017). Safety Practices and Causes of Fatality in Building Construction Projects: A Case Study for Bangladesh. *Jordan Journal of Civil Engineering*.

Janicak, C. A. (1998). Fall-Related Deaths in the Construction Industry. *Journal of Safety Research*. https://doi.org/10.1016/S0022-4375(97)00027-3

Kang, Y., Siddiqui, S., Suk, S. J., Chi, S., & Kim, C. (2017a). Trends of Fall Accidents in the U.S. Construction Industry. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001332

Kang, Y., Siddiqui, S., Suk, S. J., Chi, S., & Kim, C. (2017b). Trends of Fall Accidents in the U.S. Construction Industry. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001332

Khan, N., Ali, A. K., Skibniewski, M. J., Lee, D. Y., & Park, C. (2019). Excavation Safety Modeling Approach Using BIM and VPL. *Advances in Civil Engineering*. https://doi.org/10.1155/2019/1515808

Leigh, J. P., Marcin, J. P., & Miller, T. R. (2004). An Estimate of the U.S. Government's Undercount of Nonfatal Occupational Injuries. *Journal of Occupational and Environmental Medicine*. https://doi.org/10.1097/01.jom.0000105909.66435.53

Li, M., Yu, H., & Liu, P. (2018). An automated safety risk recognition mechanism for underground construction at the pre-construction stage based on BIM. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2018.03.013

Lin, J. R., Zhang, J. P., Zhang, X. Y., & Hu, Z. Z. (2019). Automating closed-loop structural safety management for bridge construction through multisource data integration. *Advances in Engineering Software*. https://doi.org/10.1016/j.advengsoft.2018.11.013

Malekitabar, H., Ardeshir, A., Sebt, M. H., & Stouffs, R. (2016). Construction safety risk drivers: A BIM approach. *Safety Science*. https://doi.org/10.1016/j.ssci.2015.11.002

Meliá, J. L., Mearns, K., Silva, S. A., & Lima, M. L. (2008). Safety climate responses and the perceived risk of accidents in the construction industry. *Safety Science*. https://doi.org/10.1016/j.ssci.2007.11.004

Ministry of Labour, O. (2013). *Health & Safety at Work: Prevention Starts Here: Worker Health and Safety Awareness in 4 Steps*. Retrieved from http://www.e-laws.gov.on.ca/html/statutes/english/elaws_statutes_90o01_e.htm

Mneymneh, B. E., Abbas, M., & Khoury, H. (2017). Automated Hardhat Detection for Construction Safety Applications. *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2017.08.022

OHSA. (2019). No Title. Retrieved from https://www.ontario.ca/laws/regulation/910213

OSHA. (2015). *Fall Protection in Construction (OSHA 3146-05R 2015)*. 48.

Perlman, A., Sacks, R., & Barak, R. (2014). Hazard recognition and risk perception in construction. *Safety Science*. https://doi.org/10.1016/j.ssci.2013.11.019

Pradhananga, N., & Teizer, J. (2013). Automatic spatio-temporal analysis of construction site equipment operations using GPS data. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2012.09.004

Saunders, L. W., Kleiner, B. M., McCoy, A. P., Ellis, K. P., Smith-Jackson, T., & Wernz, C. (2017). Developing an inter-organizational safety climate instrument for the construction industry. *Safety Science*. https://doi.org/10.1016/j.ssci.2017.04.003

Suraji, A., Duff, A. R., & Peckitt, S. J. (2001). Development of causal model of construction accident causation. *Journal of Construction Engineering and Management*. https://doi.org/10.1061/(ASCE)0733-9364(2001)127:4(337)

Talat Birgonul, M., Dikmen, I., Budayan, C., & Demirel, T. (2016). An expert system for the quantification of fault rates in construction fall accidents. *International*

Journal of Occupational Safety and Ergonomics. https://doi.org/10.1080/10803548.2015.1123516

Vermeulen, D. (2017). No Title. Retrieved from https://revitbeyondbim.wordpress.com/2017/01/03/fire-exit-risk-assessment-with-revit-and-dynamo/

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*. https://doi.org/10.1016/j.ssci.2014.08.001

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Publications:

1. Tekbas, G. and Guven, G. (2019). BIM-based Automated Safety Review for Fall Prevention. Eurasian BIM Forum (EBF 2019). Istanbul/Turkey.