Development of an Interoperability Solution Between BIM and a Structural Analysis Software: Application to the Global Seismic Analysis of the Chalet of the Countess of Edla

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Abstract

In the current state of the construction industry, the lack of interoperability is one of the major obstacles to the generalized BIM utilization as a centralized platform for modelling. This happens because it is a highly heterogenous industry, with hundreds of specialized software providers and users for whom it is extremely difficult to create a single way to exchange data. Because of this, the connection between Revit and *3Muri*, a seismic analysis program, is substantially more difficult than expected. However, by using the tools available in Revit, specifically Dynamo (a visual programming plugin), this problem can partially be solved.

To create the *3Muri* model a user uploads a simplified CAD floor plan for each of the levels which is used as a base to support the placement of walls and openings in the model. Using Dynamo, a program (R3AD) was developed to create, automatically, this floor plan and include in it as much information about the seismic analysis as possible and, in this way, facilitate the task of converting the BIM model into a *3Muri* model.

Lastly, this developed tool was used in a case study, the Chalet of the Countess of Edla in Sintra in it as-built configuration, to demonstrate its use and flexibility, and to support a discussion on the extent of the proposed automation.

With the developed *3Muri* model, the global seismic behaviour of the Chalet was assessed, and the results obtained were compared to a previous study developed to the building in its current state, i.e. including the structural strengthening elements added in 2009 in the buildings rehabilitation.

Keywords: BIM Interoperability, Dynamo BIM, Revit, *3Muri*, Non-linear Static Analysis (Pushover Analysis), Chalet of the Countess of Edla

1. Introduction

Building Information Modelling (BIM) is a process in which a construction model is created in a virtual environment containing all the information required for its construction, use and maintenance (Azhar and Asce, 2011). Currently, there are several BIM programs available in the market, with Autodesk Revit being one of the most used. Revit uses the concept of parametric design, which means that all 3D objects can be interconnected by logical rules allowing for a simpler replication and modelling (Autodesk Knowledge Network, n/d).

Dynamo is a visual programming tool that can be used to manipulate the parameters in Revit and give its user a wider range of possibilities when it comes to modelling and Revit operations. Visual programming is the concept of using two or more dimensions in programming creating a graph in which the functions (nodes) are connected by wires, contrary to traditional programming in which a single dimension is used (the compiler only reads a line of code at a time) (Myers, 1986). This programming concept is much easier to use, making it the ideal tool to create complicated geometries and to automate tasks in Revit (Kensek, 2015) even for those who don't have programming experience.

3Muri is a seismic analysis software for commercial use based on Tremuri, a program to perform non-linear evaluations of masonry buildings in an investigation setting. Both these programs use the same principles to model and evaluate but the commercial version uses a simpler interface and modelling process, allowing for a wider user base and making it ideal for use in the seismic evaluation of real (new or existing) buildings. *3Muri* modelling is based on the global analysis of 3D structures, although it can also perform a local analysis of the structure. In other words, the seismic analysis model is based on the principle that all the walls in the building work together and are properly connected to ensure the loads are transferred from one to another and only their in-plane capability is relevant. This software also can evaluate the out-of-plane response of the walls but, in the modelling sense, only the global response relevant because the principles used for the out of plane analysis are the same as for the global analysis.

Although both 3Muri and Revit have 3D modelling capabilities they use completely different models and data structures, which means a direct connection between the models is impossible.

The objective of this work is to use this programming tool to automate, as much as possible, the connection between Revit and 3Muri.

2. Global seismic analysis with 3Muri

2.1. Equivalent frame idealisation

To simulate the seismic global response of a structure, a three-dimensional equivalent frame modelling strategy is used to model the behaviour of the load-bearing masonry elements. This means the structure is defined as an arrangement of deformable elements, where the non-linear response is concentrated, and rigid nodes connect the deformable elements (Lagomarsino *et al.*, 2013). The deformable elements are further divided into vertical elements, piers, and horizontal elements, spandrels, as shown in Figure 1.

Piers carry the vertical and lateral loads, while spandrels are the parts of walls between two vertically aligned openings. This division of elements is based on the observation of the damage caused by earthquakes to masonry structures and validated by the performance of seismic testing of masonry structures, such as the work of Marques and Lourenço (2014), in which it is observed that cracks and failure are concentrated in these elements. As such, the location of the openings has a significant influence on the definition of each of these three possible elements, making it essential to get their size and location as precisely as possible in the model. This process is repeated for each wall and finally all walls are assembled, creating a 3D structure that can simulate the global structural behaviour.

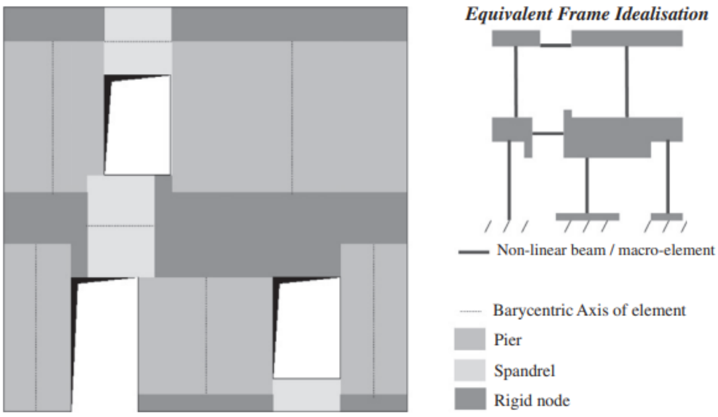

Figure 1. Example of an equivalent frame idealisation (Lagomarsino *et al.*, 2013)

2.2. Macroelement model

Once the assemblage of elements is defined, the overall behaviour of the structure is mainly dependent on the mechanical characteristics of the material that make up the elements. To simulate the non-linear behaviour of the materials several methods can be used, each with different simplifications and advantages:

A first possibility is to model every wall element as an interaction between units and mortar using finite elements, having as few simplifications as possible. This method, despite providing a highly accurate result, has several problems as an engineering solution: first of all, it requires a deep level of knowledge about the materials, their properties and their interactions, which is rarely possible in existing buildings; secondly, it is computationally heavy, making it only suitable to analyse simple structures, usually modelled in 2D.

Another possible approach, which is the one used by 3Muri, is the macroelement model. This approach is much simpler to apply in real-world situations and is used to model the non-linear behaviour of the deformable elements in an equivalent frame structure by homogenizing the material properties of the mortar and units. This means that the average properties are modelled in a single finite element based on the observation of experimental tests on masonry wall segments with different materials. Based on these tests an average properties table can be assembled and used with satisfactory results (Penna, Lagomarsino and Galasco, 2014). This method has the advantage of requiring less computational power and, due to its approximate nature, requires less detailed knowledge.

2.3. Methods of Analysis

According to Eurocode 8, Part 3 (European Committee for Standardization, 2005) the effects of a seismic action shall be evaluated by using one of the following methods:

- Lateral force analysis.
- Modal response spectrum analysis.
- Non-linear static analysis (pushover).
- Non-linear time history dynamic analysis.
- q-factor approach.

From the proposed methods, and according to Magenes and Penna (2009), the linear ones (lateral forces and modal response) are easier to use, but impracticable for the evaluation of masonry structures because they assume a linear elastic behaviour, brittle, which leads to a gross undervaluation of the structure's real ability to deform. Furthermore, because they presume a clear distinction between ductile and failure mechanisms, which is not feasible. The q-factor approach is also not a good solution as it does not apply to masonry structures, not even being presented in the national annex.

When it comes to seismic evaluation, non-linear methods have the significant advantage of giving a more accurate representation of the behaviour of the building and having a more generalized use (the conditions of applicability are not as tightly controlled as for the linear methods). Their major disadvantages are the complexity of the model and the need to compute displacements to simulate the non-linear behaviour, which implies a heavier computational burden.

From the specified non-linear methods, non-linear static analysis is the easiest to apply and also implies a low computational load when compared with an alternative non-linear time history dynamic analysis. Non-linear static analysis uses two lateral load distributions (a uniform distribution and either a modal or triangular load distribution, with some authors proposing a triangular distribution for masonry buildings with a flexible diaphragm, such as Simões (2018)) to predict the displacement capability at the top of the structure when is subjected to seismic action.

After reaching the yielding point, the lateral load is increased while keeping the same distribution and computing the shear force degradation as the non-linear elements collapse, obtaining a capacity curve (relation between the lateral load and the top displacement). These capacity curves represent the structure's capability to deform without collapsing. The maximum displacement (d_u) is then compared to the target displacement (d_t) obtained from the N2 method (Fajfar and Fischinger, 1988), according to Eurocode 8, Part 3, through the intersection of the capacity curve of a single degree of freedom equivalent structure and the response spectrum of the seismic action.

In 3Muri, this calculation is automatic, given the parameters of the seismic action.

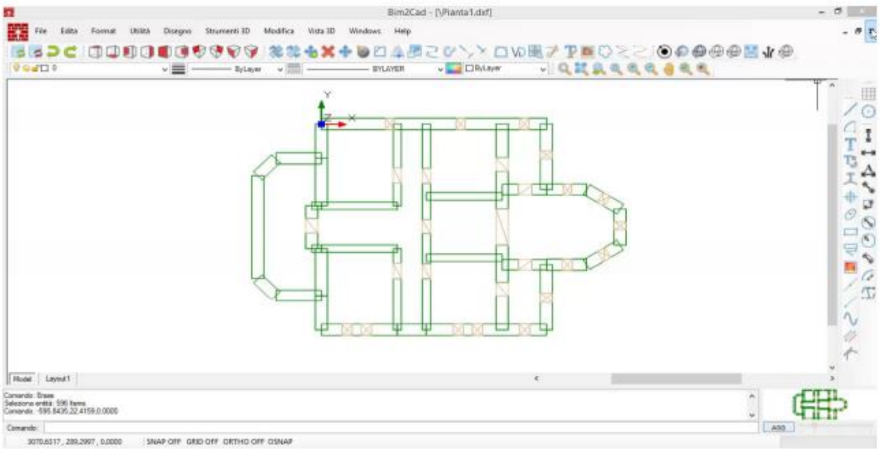

Figure 2 - Example of a floor plan obtained from the IFC-BIM module (S.T.A. DATA, n/d)

2.4. *3Muri* modelling

A *3Muri* model is made step by step by user input, meaning that user interaction is required in every stage.

The first step is to define the analysis parameters and the levels of the final model. Next, the user must generate the basic floor plan of the masonry walls (this is the stage that the present text aims to study). There are two ways to generate this plan: manually, with the user providing a CAD model, or by using the *S.T.A. DATA* supplied IFC-BIM module, an extra module that adds an interoperability feature to the 3Muri base software. This module uses IFC files, a neutral data format used by some BIM suppliers to allow limited interoperability capability, to create a CAD floor plan based on a BIM file (S.T.A. DATA, n/d).

The obtained CAD file has a representation of the walls and the placement of openings, making the task of assembling the structure easier (Figure 2). The major drawback is its inability to extract from the BIM model other relevant information, such as the thickness of walls, or the widths and heights of openings. Additionally, it must be acquired as it is not included in the main seismic analysis program.

After uploading the floor plan to *3Muri* and redrawing it to define the alignment of the walls, the materials of the walls must be defined, and the openings placed. Finally, the floors and roof are modelled, as well as any other required element. The only stage of this entire process that can be automated is the floor plan creation, as all others require input from the user.

3. Automation using Dynamo: the R3AD tool

To automatically generate a floor plan, with as much information as possible to help create a 3Muri model, a tool named *Revit to 3Muri Automated Drawing* (R3AD) was developed using the Dynamo visual programming plugin for Revit. The tool was developed using several packages (additional functions) made available by the user community under a free to use, edit and share licensing.

R3AD was developed using the following packages:

- Archi-lab.net, version 2020.23.3;
- Clockwork for Dynamo 1X, version 1.34.0;
- DynamoText, version 2.0.1;
- LinkDWG, version 0.3.82;
- LunchBox for Dynamo, version 2018.7.7;
- MeshToolkit, version 3.0.0.

R3AD is not aimed at allowing seamless interoperability between systems, as it simply converts the data stored in a Revit model into a format that 3Muri can receive, making it an automation tool. The process is described in Figure 3.

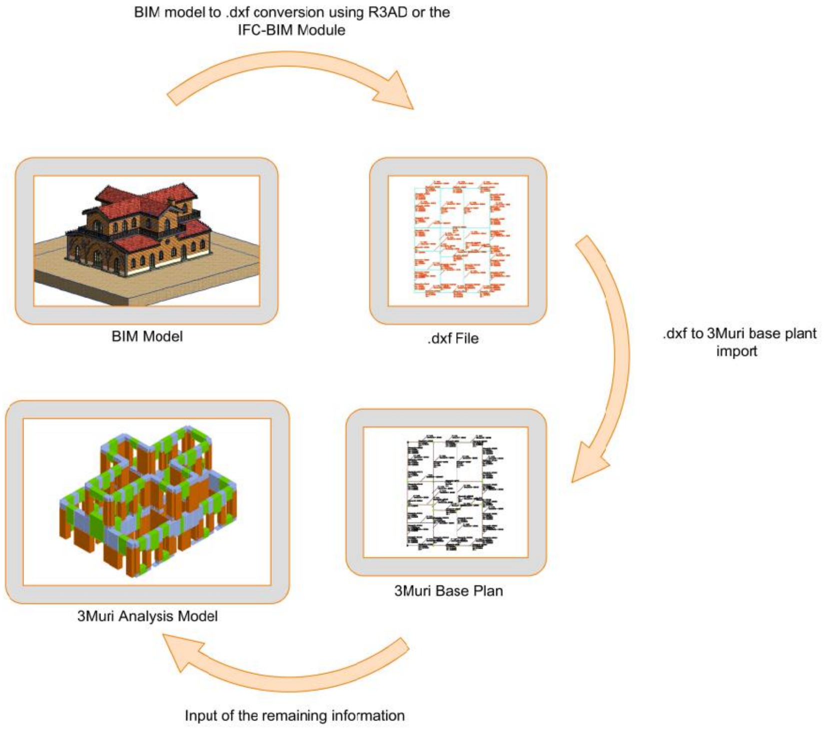

Figure 3 - Schematic representation of the proposed process

3.1. Dynamo visual programming

Dynamo's visual programming principles are simple: there are nodes, where a function is performed, and wires, that interconnect the nodes and allow for an information flow between them (Figure 4). These nodes can be customised using common programming languages, such as python, or downloaded from the program's website as free packages of nodes created by the community.

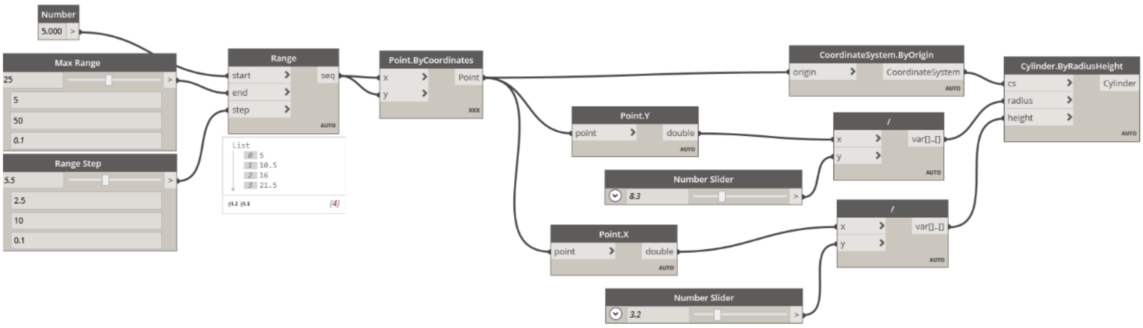

Figure 4 - Example of a Dynamo algorithm in which a series of evenly spaced cylinders are created with variable height and thickness based on their XY coordinates

3.2. Conditions to apply to the Revit Model

To allow the use of R3AD it is essential that it is capable to identify the information on the Revit model. To do so, there are some conditions that must be verified, because the Revit designer has a large influence on the way the different elements are modelled, making it difficult to create an automation routine that can work in any situation. These conditions are:

- The walls should be as tall as the height of the level they are in, and the starting and finishing points should be on that same floor. This is essential because 3Muri models each level individually, meaning that it requires a distinct floor plan for each floor. The developed tool cannot identify a continuous wall that spans multiple floors.

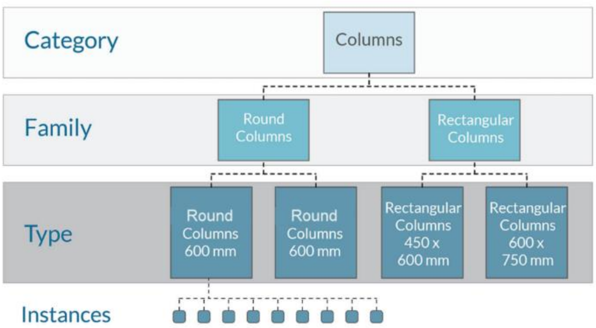

Figure 5 - Revit hierarchy (The Dynamo Primer, 2021)

- The model should be as simplified as possible. R3AD takes advantage of the Revit hierarchy (Figure 5) to filter all the necessary elements and extract the necessary parameters. One of the main drawbacks of visual programming is its inability to process large volumes of data, and in the case of R3AD, it must verify all elements of a given category or family in the Revit hierarchy to ensure it complies with the given conditions, meaning it must process a large number of elements from the Revit model.

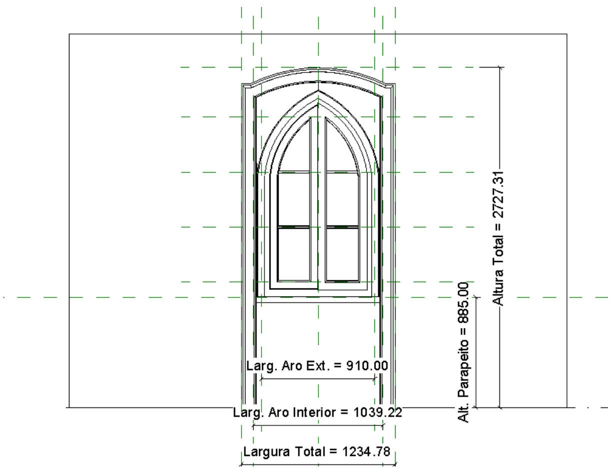

Figure 6 - Example of a parameterised opening in Revit

- All opening elements must be defined as a window or as a door family and never as a void. In Revit, voids are not elements, meaning Dynamo is not able to identify them.
- All opening elements must have the width, height, and sill height measures parameterised. Dynamo uses Revit's parametric design to measure the elements, and, as such, these elements must have them parameterised, as in the example of Figure 6.

3.3. R3AD Tool

The workflow of R3AD is shown in Figure 7. In the input nodes, the user must define the level from which the floor plan must be created.

Due to the *3Muri* requirement of a floor plan for each level (unless they can be duplicated), this means that the entire process must be repeated for each level of the building. In the input phase, the user must also define the parameters describing the opening (height, width, and sill height) and the colour for the output layers in the CAD file (captions, walls, and openings).

From this input, the program filters the load-bearing walls based on the level as well as the predefined minimum thickness and height. A material or structural parameter can also be defined as the predefined parameter to search for, depending on the level of detail of the model. The openings are in turn filtered by their host element (element in which they are implanted) by connecting them to the load-bearing wall's unique Revit ID. Based on the selected elements the relevant parameters (thickness for the walls and height, width, and sill height for the openings) are selected and stored.

After this, the elements are drawn in place as well as a caption with the elements unique ID and selected parameters.

Finally, each of the layers is drawn in a CAD file open in the background. This CAD file must then be saved as a .dxf (a drawing exchange format) and uploaded to 3Muri using the available tools in the program.

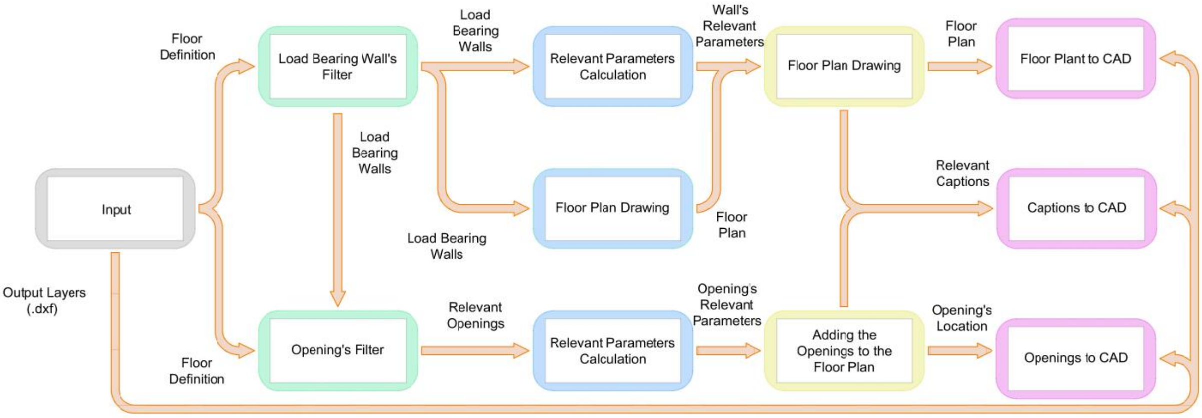

Figure 7 – Workflow of the R3AD program

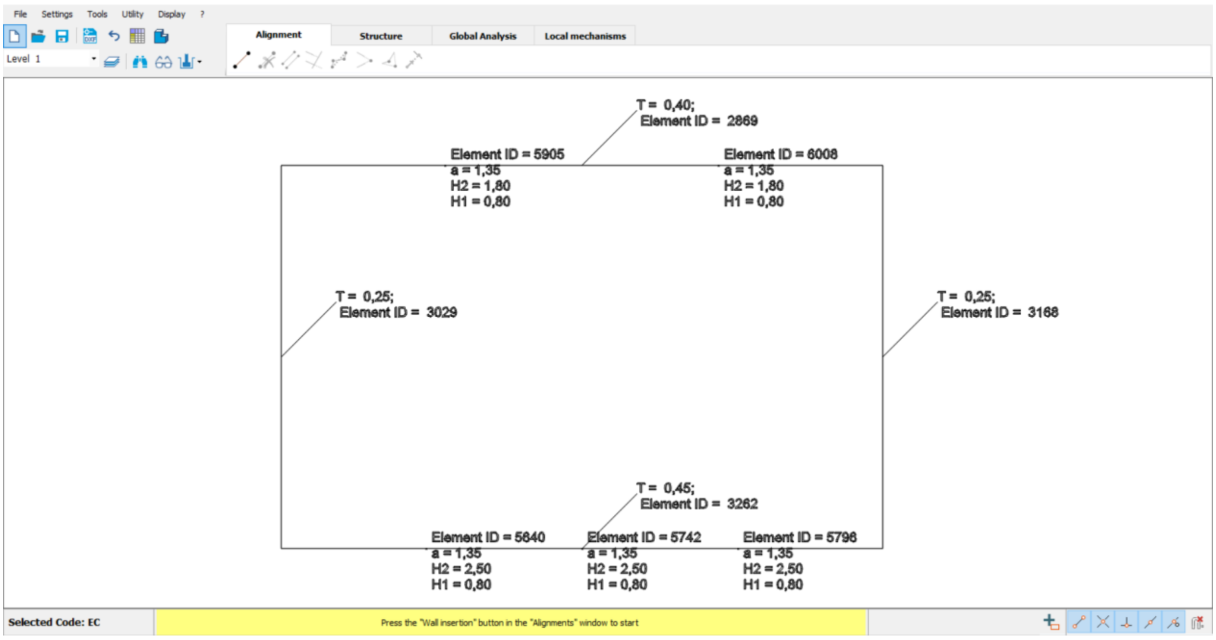

Figure 8 – Workspace of 3Muri with a floor plan created by R3AD

The result is a floor plan, as shown in Figure 8. This floor plan may need some adjustment to comply with the precision requirements of *3Muri*, such as:

- Alignment of the walls so they are perfectly straight and continuous amongst themselves.
- Placement of the insertion point (x,y = 0,0) in an intersection of walls (the bottom left corner of the floor plan is suggested). This happens because 3Muri requires a user-defined insertion point that keeps the walls perfectly aligned.

4. Case Study: The Chalet of the Countess of Edla

The Chalet of the Countess of Edla is a stone masonry building, located in the Pena Park near the Pena Palace, part of the Cultural Landscape of Sintra UNESCO World Heritage Site. It was built in the 1860s in the style of the swiss chalets of the time, although with a significant difference: instead of a wood structure it has a stone structure. The building itself is composed of two main floors: the ground floor with a rectangular shape and an upper floor with the shape of a cross. On the ground floor, the load-bearing wall is placed in the perimeter and around the stairs. On the upper floor, the load-bearing walls are in the perimeter, supported by masonry arches that unload at the bottom floor's perimeter walls.

Figure 9 shows the placement of the various walls: the load-bearing walls in pink, and non-structural walls in yellow, light blue, dark blue, green, and orange.

The load-bearing walls are in ordinary stone with varying thickness. The arches (Figure 10) are in stone as well. All masonry elements were modelled using values presented by the Italian standard (NTC, 2008; MIT, 2019) and are presented in Table 1.The wood floors properties are based on the Italian and New Zealand standards (UNI 11035-2, 2003; NZSEE, 2017) and are shown in Table 2. The vertical weight distribution is shown in Table 3.

Figure 9 - Placement of the walls, adapted from Neves da Silva (2020)

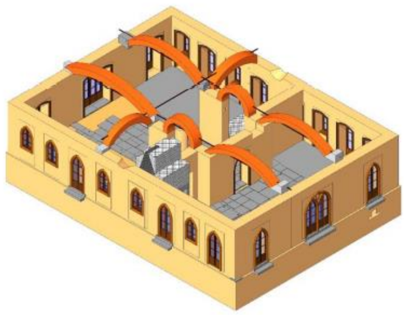

Figure 10 - Placement of the stone arches

The building was severely damaged by a fire in 1999. The thorough study of the constructive system for the reconstruction identified some vulnerabilities of the original building, mainly due to the fire and to the following years of abandonment. Thus, the chalet's structural strengthening project in 2007 focused on correcting these vulnerabilities, primarily targeting the general safety of the structure.

Table 1 - Masonry material properties (NTC, 2008; MIT, 2019)

Material	f_k (MPa)	τ_0 (MPa)	E (GPa)	G (GPa)	Υ (kN/m^3)
Masonry wall	1.00	0.018	0.69	0.23	19.0
Masonry arch	7.00	-	2.8	0.86	22.0

Table 2 - Wood floor properties (UNI 11035-2, 2003; NZSEE, 2017)

Material	f_k (MPa)	E_0 (GPa)	E_0 (GPa)	G (GPa)	Υ (kN/m^3)
Castanea sativa Mill	22.00	11.00	0.73	0.021	5.40

Table 3 - Vertical weight of the model elements and applied loads, adapted from Neves da Silva (2020)

Element		W (kN/m^2)	G_k (kN/m^2)	Q_k (kN/m^2)
Balconies		2.75	0.10	4.00
Roof		1.50	-	0.40
Wood Floors	Room with public access	0.50	-	5.00
	Room without public access	0.50	-	2.00
Ceiling	Lathed	0.40	-	-
	Stained	0.60	-	-

Performing the pushover analysis, as proposed in Eurocode 8 Part 3 (European Committee for Standardization, 2005) for the seismic assessment of existing buildings, the capacity curves, which represent de deformation capacity of the structure, are obtained. These curves must be calculated for both X and Y directions and both ways (positive and negative). The curves obtained for the Chalet are the ones shown in Figure 11.

From this image, it is possible to understand that the most conditioning load distributions are the uniform load in the X direction and the triangular load in the Y direction because they are the ones with the lowest deformation capability.

Both directions display a higher-than-expected ductility but, on the other hand, the structure's stiffness is lower when compared to similar evaluations on the current building (Neves da Silva, 2020). This can be, in part, attributed to the structural arches modelled, giving it a better-than expected behaviour, especially in the X direction.

To verify the structural safety the maximum displacement must be compared with the target displacement, obtained from the N2 method (Figure 12). Based on this calculation the global safety of the structure is not verified for any of the seismic actions (type 1.3 and 2.3) and for any limit states (Near Collapse and Significant Damage). It can also be seen that in the X direction, for the 2.3 seismic action and the Significant Damage for the 1.3 seismic action can the structure verify the safety criteria.

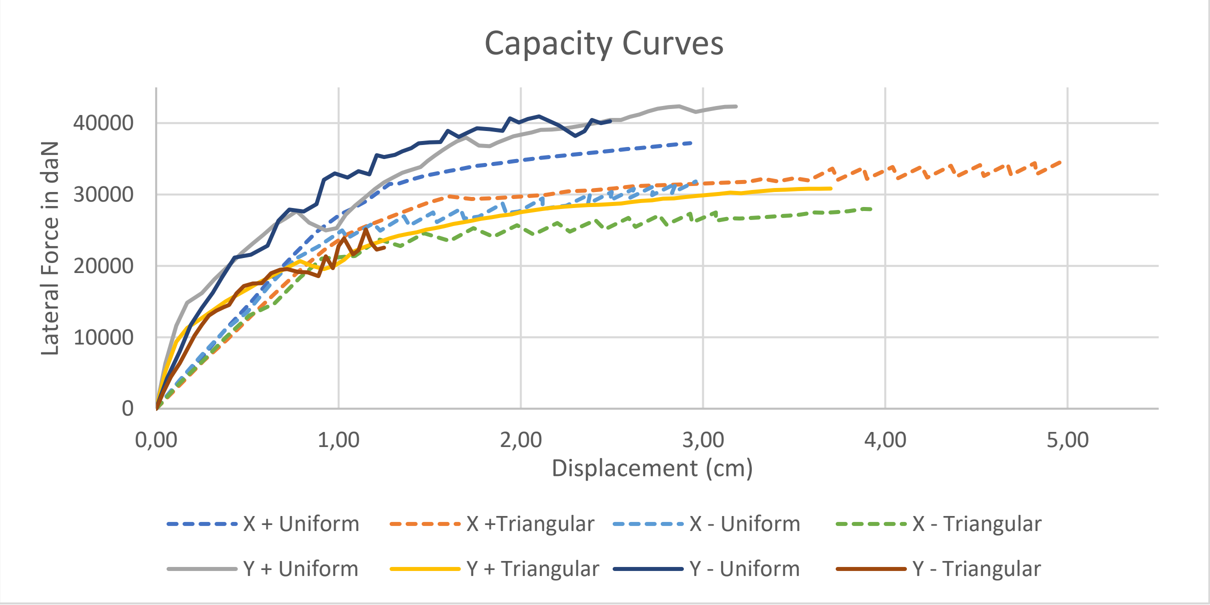

Figure 11 - Capacity curves for the chalet seismic analysis

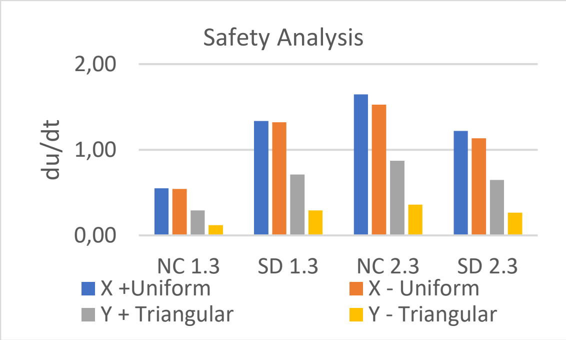

Figure 12 - Chalet safety analysis

By comparing the result of the analysis to the original building with the results of the post restauration building (Neves da Silva, 2020) it can be seen they are quite different, due to the modern building techniques used, but similar enough to conclude that the applied methodology was able to provide a good result for the evaluation.

In a broader sense, the developed tool to facilitate the transition from BIM to *3Muri* has successfully been able to allow a more straight forward integration of the BIM data into the seismic evaluation program. Its application to other buildings should give similarly satisfactory results.

5. Conclusions

The addressed BIM/3Muri interoperability problem hinders a seamless data migration between the two programs. The solutions proposed in the literature (S.T.A. DATA, n/d) were considered unsatisfactory due to the lack of useful information to build the 3Muri model it can provide. To facilitate the migration of data allowing BIM-based building models to be transformed into workable 3Muri floorplan models, a new solution, supporting the modelling phase and providing a flexible data transference, was proposed. The solution, named R3AD, was developed in the Dynamo visual programming interface and enables the conversion of Revit floorplans to 3Muri although with some limitations such as the inability to automatically align the wall's location lines or the need to proceed one floor at a time. Dynamo is still a rather recent programming platform that is growing thanks to the community made updates and some of R3AD's limitations can be overcome with custom made nodes.

With the most recent advances in technology and the digitalisation of the Architecture, Engineering and Construction industry, the required expertise required from engineers is changing and the ability to program and automate repetitive data processing tasks will become more and more valuable. In this context, Dynamo might become a very useful resource due to its ease of use, availability, flexibility, and community support, allowing users to create their own solutions to deal with the data processing and interoperability issues that arise from the use of distinct programs within the engineering activities.

The main objective of this work was to explore and propose a feasible methodology to use BIM data in a seismic analysis software, inspecting the level to which customized solutions must be developed, and demonstrate the usability of the converted model through a case study in 3Muri. The proposed solution, R3AD, is capable to convert the Revit model of a building into a usable 3Muri dataset, under some conditions. It does not constitute a fully integrated and general solution to the interoperability problem, which would, in the analysed case, provide an ideal and seamless transference of data between BIM and *3Muri*, as it requires user input in the parametrization. The proposed solution can simplify the modelling process with satisfactory results.

The seismic global seismic assessment of the as-built building was carried out when subjected to a code seismic action, according to non-linear static analyses. The safety verification is not verified when subjected to the seismic action, type 1 and type 2, for the longitudinal and transversal direction of the building.

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