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IMMERSIVE MULTI-PERFORMANCE PARAMETRIC FRAMEWORK TO ENHANCE LOW-DAMAGE TIMBER BUILDINGS DESIGN

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Abstract: *In order to face the increasing challenges resulting from climate change and catastrophic events, the built environment has to deal with multi-performance requirements. The well-recognised dependency between seismic performance and environmental footprint calls for advanced technological solutions together with integrated (multi-)decision-making approaches, able to handle multiple and sometimes conflicting domains in building design.*

Combining sustainability with high seismic performance, the use of timber low-damage post-tensioned structural system, also known as Pres-Lam, represents a viable strategy to design highly resilient buildings. The components modularity enables also a valuable adaptive capacity to meet changes in user demands over time. Nevertheless, to address the multiple potentials of this technology and to guide decision-makers towards the optimal solution, an integrated building design methodology is needed. Such an approach inherently leads to Multi-Objective Optimization (MOO) problems due to the (partly) conflictual nature of the goals involved.

This paper proposes a parametric framework for the multi-performance optimization and evaluation of adaptive Pres-Lam buildings, through a comprehensive model within the Rhino-Grasshopper platform. The aim is to reduce embodied and operational carbon emissions while ensuring high performance of the post-tensioned timber frames and maximum flexibility of the internal space. The effective seismic performance of the selected optimal solutions is then assessed through a probabilistic approach. Two different scenarios are considered, locating the building in Italy and in New Zealand, whose different seismic hazard and climate provide intriguing perspectives on the (multi-)performance of Pres-Lam buildings.

Besides the use of a holistic and easy-to-handle model, visualization plays an important role in building design. In this respect, architectural modelling radically evolved over the last decades towards increasing use of Virtual Reality (VR) along the design process. Despite this, VR is mostly used for the end visualization of 3-dimensional software-based models. This study aims to address the challenge of bringing the parametric modelling capability of Grasshopper within the immersive environment. The designer has thereby the chance to directly modify the input variables in VR and to have real-time feedback of the generated model.

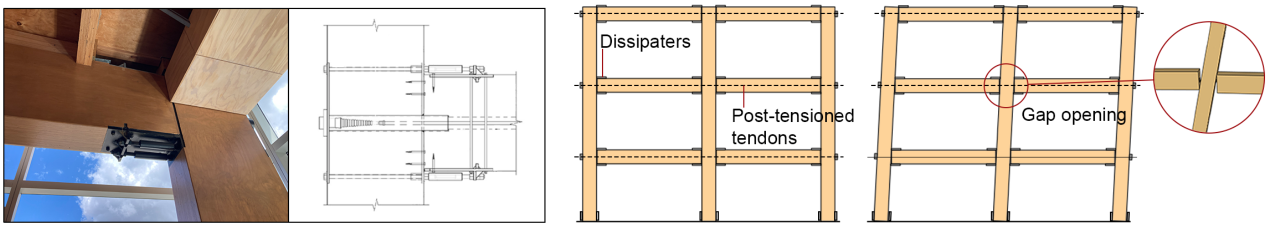
1. Introduction

The built environment plays an important role in the achievement of the Sustainable Development Goals specified in the United Nations Agenda 2030 (United Nations, 2015). On the other hand, the construction sector is the largest contributor to Greenhouse Gases (GHGs) emissions and energy consumption, making these goals harder to achieve (IEA, 2019). In addition, the buildings safety and that of their occupants are severely compromised by the consequences of the ever-increasing climate change's catastrophic events and devastating earthquakes. For these reasons, it is necessary to implement new advanced technologies and design approaches for innovative sustainable and resilient buildings. In fact, in line with the current code-based seismic design approach (typically targeting Life-Safety), even modern structures may be affected by substantial damage after major earthquakes and can be deemed as not cost-effective to repair (Pampanin, 2012, 2015), resulting also in a significant environmental impact (e.g., Belleri and Marini, 2016).

To overcome this issue, research effort has been devoted in developing innovative high-performance technologies to move towards a more appropriate damage-control design objective. Specifically, low-damage solutions based on post-tensioned rocking and dissipative mechanisms for concrete (PREcast Seismic Structural System – PRESSS – Priestley, 1991; Priestley et al., 1999) or timber (Prestressed Laminated Timber – Pres-Lam – Palermo et al., 2005, 2006) have attracted increasing interest. These structural systems combine self-centring capacity with energy dissipation through, respectively, internal post-tensioned tendons and internal mild-steel bar or external replaceable "Plug&Play" dissipaters (Pampanin, 2005; Sarti et al., 2016), as shown in Figure 1a. During the earthquake, a controlled rocking mechanism is expected between the dry-jointed structural members (Figure 1b), whereas at the end of the shaking, the unbonded post-tensioned reinforcement ensures a re-centering action, with the pre-existing gap closure between members and negligible residual displacements/deformations. Combining a low-carbon material with the abovementioned high seismic performance, the Pres-Lam technology represents a competitive choice in a lifecycle thinking approach. It potentially provides structures able to withstand major earthquakes with negligible damage during their nominal life, while matching the requirements in terms of standardization, demountability, reparability, and reusability. This represents a fundamental step towards circularity in constructions, keeping products in use as long as possible and re-using them eventually. Furthermore, a resilient attitude can be pursued since the system allows for different levels of flexibility, from the reversibility of internal spaces to the modifiability of structural and non-structural building components (Smith et al., 2011). Despite being relatively new, the Pres-Lam technology has proven to be effective by extensive testing in the past twenty years (Newcombe et al., 2010; Iqbal et al., 2010; Sarti et al., 2016; Moroder et al., 2018), and when subjected to real earthquakes (Smith et al., 2012; Holden et al., 2016; Granello et al., 2020). Pres-Lam constructions worldwide have demonstrated that this technology allows for the creation of high-quality buildings with large open spaces, and excellent living and working environments.

Besides the technology and material choice, the design approach plays a key role in achieving sustainability and resilience in construction. To date, many design/assessment tools have been employed and developed in the decision-making processes for the evaluation of the life cycle environmental impacts of buildings, the most common being the Life-Cycle Assessment (LCA) regulated by ISO (2006). Nevertheless, they are typically used as a stand-alone procedure, rarely considering all the building performance simultaneously. Yet, to design a proper resilient building, designers need to handle several interrelated performance objectives from the early design stage, whose trade-off often leads to multi-objective problems. This paper proposes a parametric framework for low-damage Pres-Lam buildings able to simultaneously account for all the relevant decision variables affecting the definition of sustainable construction, i.e., environmental footprint, energy efficiency, seismic performance, and architectural flexibility. Because of the conflicting nature of the goals involved, a Multi-Objective Optimization (MOO) technique is applied, enabling the exploration of alternative options and the assessment of the trade-off between the performance. The parametric nature of Rhino+Grasshopper software (McNeel, 2010), enable the automated calculation of the objectives and the compliance with the imposed constraints. Such an approach might also represent a step towards an increased collaboration between disciplines in the early design stage (Shen et al., 2018).

The collaboration and communication between the multidisciplinary stakeholders can be improved also adopting Virtual Reality (VR) in the decision-making process. VR is a powerful tool, whose use as an advanced visualization platform in the building industry cannot be called emerging any longer. Yet, its potential as a collaborative environment where decisions can be made is far from being fully exploited. To date, only a few studies discussed the possibility of combining parametric design and VR, e.g., Coppens and Mens (2018), Moubile (2018), Podkosova et al. (2022). The proposed study aims to stream the parametric modelling to the immersive environment, developing an automated process and connection between Rhino+Grasshopper software and the Virtual Reality engine, Unity3D. In this way, the users can manipulate the model input while exploring the building in the virtual environment getting real-time feedback of the design choice and fully appreciating the scale of construction.



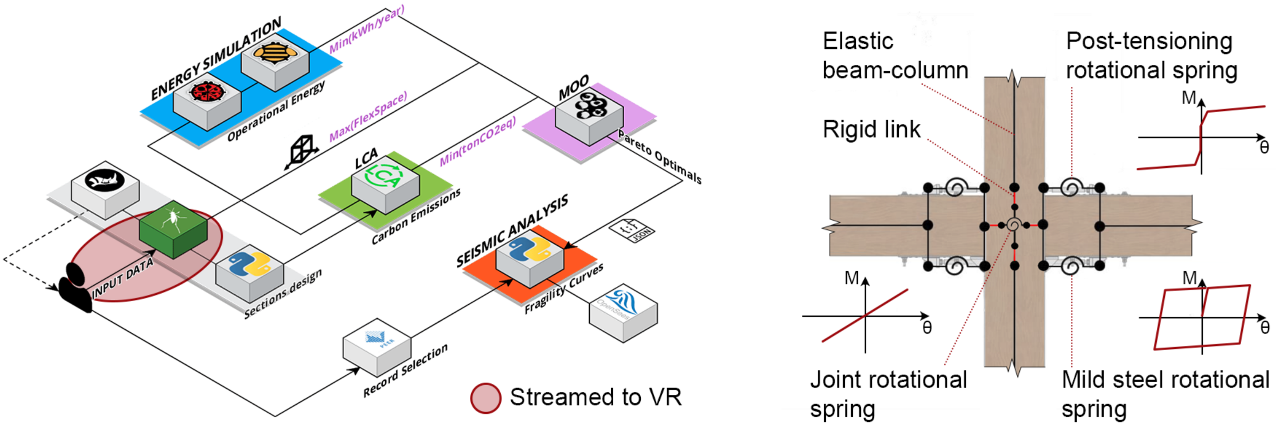
a) b)

Figure 1. a) Pres-Lam beam-to-column connection detail with Plug&Pay dissipaters on top and bottom of the beam, Merritt building (modified after Miliziano et al., 2020); a) Pres-Lam frame and its peculiar rocking mechanism.

2. Methodology

The workflow of the developed Grasshopper-based holistic parametric framework is shown in Figure 2a. Through independently developed software packages and Python-based modules, a series of automated algorithms generate the outputs defining the building components and performance. Geometry, material properties, seismic hazard and climatic zone are set as input, as well as the non-structural attributes (i.e., fa cades). A wide range of solutions can be assessed by varying the input sliders, which are automatically modified by the MOO package to calculate all the possible parameters combinations and the corresponding building configurations and performance in the search for the optimal solutions. Specifically, an evolutionary approach based on genetic algorithm is used (Holland, 1975).

A summary of the main workflow activities is provided below.



a) b)

Figure 2. a) Workflow of the multi-performance parametric framework; b) Lumped plasticity modelling of a hybrid (rocking-dissipative) Pres-Lam beam-column joint.

2.1 Structural seismic design

The Direct Displacement-Based Design methodology (Priestley, 2002; Priestley et al., 2007), is implemented for the lateral force-resisting frames through the Python programming language within Grasshopper. Once the target/design displacement/drift is selected, the secant-to-target displacement of the equivalent SDOF (single degree of freedom) system is derived and so the effective period and the required Base Shear, To distribute the internal actions throughout the frame, an equilibrium approach is used following Priestley et al. (2007). The structural members are then dimensioned first at the serviceability limit state (SLS) and then designed in detail and verified at the ultimate limit state (ULS), following the procedure described in the Pres-Lam Design Guidelines (Pampanin et al., 2013). The size of timber elements and the amount of post-tensioning are in fact usually governed by the SLS in Pres-Lam structures (Miliziano et al., 2020), while the number and dimensions of Plug&Play dissipaters are returned from the ULS design.

2.2. Life-Cycle Assessment (LCA)

Using the output, in terms of material quantities, from the previous module as well as the 3D building model generated from the user-defined input, a Life-Cycle Assessment is performed. In this study the analysis is carried out from cradle-to-gate, i.e., from the extraction to the raw-materials to the factory supply (BS EN, 2011). From the extensive database of One Click LCA (Apellániz et al., 2021), the Environmental Product Declarations (EPDs) of the project's components are collected, using either manufacturer-specific data or country-specific average data. The resultant building Embodied Carbon, expressed as equivalent tons of Carbon Dioxide (tonCO_{2eq}), is calculated by multiplying the embodied carbon factors from the EPDs relative to each material by the mass or volume of the elements parametrically mapped in Grasshopper.

2.3. Dynamic energy simulations

The building energy model is generated by assigning material thermal properties (conductivity, density, and heat capacity) and boundary conditions to all the building components using Ladybug's Honeybee Grasshopper plug-in (Roudsari and Pak, 2013). The building is subdivided into parametrically defined internal thermal zones, characterized by different occupancy loads, equipment, lightning, and internal mass (i.e., furniture). Natural ventilation is provided where possible. Windows opening and closing are controlled by temperature setpoints. The HVAC is assigned using a simplified Ideal Load System, which does not factor in any inefficiency of the system but does enable a precise estimation of the building's operational energy consumption, as validated in Bianchi et al. (2022). To account for the real effects of heating and cooling systems, thus any evaluation of actual energy use, a detailed HVAC should be modeled using a coefficient of performance as input. The external thermal load is characterized by the climatic zone where the building is located, provided by the data contained in EnergyPlus Weather (EPW) files imported through Ladybug, which also allows for interactive climate graphics, e.g., sun path visualization. Dynamic hourly energy simulations are implemented through the EnergyPlus or OpenStudio software integrated within Honeybee, returning the total (normalized) thermal annual load as the energy needed from cooling, heating, lights, and electric equipment to maintain a comfortable environment within the building (expressed as kWh/sqm/year). Results can be shown also in terms of average inner surface temperature or surface heat transfer.

2.4. Multi-Objective Optimization (MOO)

Multi-Objective Optimization is carried out using the SPEA-2 algorithm (Strength-Pareto Evolutionary Algorithm – Zitzler et al., 2001) contained in the Octopus plug-in for Grasshopper. SPEA uses a regular population and an archive (external set) of a fixed size. The archive is populated iteratively by non-dominated solutions, evaluated through a fitness (objective) value which considers the Pareto-strength and the sparsity of the solutions. To maintain a constant archive size, clustering techniques are applied preserving the characteristics of the non-dominated front. The population is made of individuals which are newly bred, using crossover and mutation strategies, and evaluated at each generation. The objectives of the MOO in the framework are:

- Minimize the embodied carbon (tonCO_{2eq}).
- Minimize the energy consumption (kWh/sqm/year)
- Maximize the internal space flexibility (expressed as the maximum free span between vertical structural members).

To fulfil the objectives, input parameters (or "genomes") are iteratively changed, building the population of the evolutionary algorithm. These genomes are represented in this framework by geometric measures of the building configuration along with design targets, as will be explained further. To guarantee the feasibility of the explored solutions, e.g., compliance with materials strength limits, hard constraints are also given in the MOO, represented by Boolean true/false statements in the Grasshopper model.

2.5. Structural modelling and seismic analyses

To model the seismic response of the Pres-Lam frames, a lumped plasticity approach, as shown in Figure 2b, is implemented using the OpenSees software (McKenna, 2011; Zhu et al., 2018) through an external Python script. The input data related to the frame and sections configuration are stored in a JSON file from the Grasshopper model, then broadcasted to the script. Two rotational springs are inserted at the end section of the structural members in the beam-column joint and column base: one to simulate the energy dissipation of the mild-steel external damping devices through a Giuffrè-Menegotto-Pinto (GMP) hysteretic behaviour, the other to account for the post-tensioning tendons using a multi-linear elastic link. The joint panel deformation is also modelled, using a linear elastic link whose stiffness is derived from the formulations proposed by Pampanin et al. (2013) for external and internal joints. To define the parameters of the dissipaters and the post-tensioned tendons, the monolithic beam analogy originally developed by Pampanin et al. (2001) and adapted to Pres-Lam by Newcombe et al. (2008) is adopted.

To assess the seismic performance of the Pres-Lam frames relative to the optimal solutions found by the previous module, a probabilistic approach is applied using fragility curves to obtain the Mean Annual Frequency of Exceedance (MAFE) of a number of limit states. The fragility curves are derived through Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell, 2002) scaling progressively a suite of ground motions until the desired limit state is achieved. In this study, the 44 ground motions (22 recordings times 2 directions) provided by FEMA P-695 are used (FEMA, 2009). The limit states (LS) for the Pres-Lam frames are the following:

- DS1: failure of the external mild steel dissipaters, considered as the gap opening that induces a 6% axial deformation in the fuse-shaped devices.
- DS2: timber yielding in compression parallel to the grain.
- DS3: yielding of the post-tensioning tendons in the beams.

The limit state is considered achieved when at least one section in the frame reaches it. The Demand Capacity Ratio (DCR) is used as the Engineering Demand Parameters (EDP) in the analysis, computed as the ratio between the maximum gap opening occurring during the Non-Linear Time-History Analyses (NLTHA) and the one corresponding to the onset of the considered limit state in the specific connection. The global DCR is the maximum between all the connections. The chosen Intensity Measure (IM) is the spectral acceleration, $S_a(T_1)$ at the first mode period. Following the performance-based earthquake engineering principles, the MAFE is computed integrating the fragility curves with the hazard curve relative to the building site and its first mode period. The hazard curve is derived analytically using the second-order hazard approximation proposed by Vamvatsikos (2012). The MAFE is then defined as follows, considering a probability of occurrence of the damage state equal to 1 for return periods (T_R) higher than 10^5 (Iervolino et al., 2018):

$$\lambda_{LS} = \int_0^{IM_{T^*_R}} P\left[DCR_{LS} \geq 1 \mid IM = x\right] \cdot \left|\mathrm{d}\lambda_{IM}(x)\right| + 10^{-5} \tag{1}$$

2.6. Streaming to Virtual Reality (VR)

The real-time link between the parametric model and the VR engine, Unity3D, happens through a series of C#-based components in the Grasshopper model. The first one can locate and collect all the input sliders within the Grasshopper canvas and send them to the Unity3D User Interface (UI). The second component is based on the work of Horikawa (2021) using “Rhino.Inside” (McNeel, 2020) to send all the geometry meshes to Unity. On the VR engine side, a scene able to initialize and open Grasshopper is created. Once the parametric model is open, a series of scripts and components in the Unity project talk with the C# scripts in the Grasshopper model and stream all the information in the VR display. At this point, the user can change the input sliders from Grasshopper and visualize real-time geometry changes in Unity, or most importantly, manipulate the sliders directly within the VR environment.

3. Pres-Lam case-study building

The proposed methodology is applied on a three-storey office building (Figure 3), featuring post-tensioned timber frames in the longitudinal direction and post-tensioned timber walls in the transversal one. The optimization and the seismic analyses are carried out only for the longitudinal direction, i.e., for the Pres-Lam frames. However, the environmental footprint and energy simulations are performed on the whole building. In the frame direction, CLT-based cladding panels with insulation are used, connected by low-damage connections to the load-bearing structure (Baird et al., 2013; Pampanin, 2015), while in the wall direction the building is coated with a spider-glazing curtain wall. The flooring system is made by timber-concrete composite

(TCC) floors. For timber beams and columns, Laminated Veneer Lumber (LVL) has been chosen with a flexural strength of 44 MPa and a parallel-to-grain modulus of elasticity of 14000 MPa for Italy, Steico (2017), while LVL13 (modulus of elasticity of 13200 MPa and bending strength of 48 MPa) has been adopted for New Zealand, Nelson Pine (2016). Unbonded 7-wire strands, characterized by a yielding tensile strength of 1670 MPa, are used for the post-tensioning. The cables run all the way through the hollow beams at mid-height. The beam-column joint configuration features external mild-steel fuse-shaped "Plug&Play" dissipaters at the top and the bottom of the beams, with a yielding strength of 355 MPa. To prevent crushing perpendicular to the grain in the connections, columns are reinforced with internal steel rods. The number and diameters of the Plug&Play dissipaters and the number of post-tensioned tendons are determined by the DDBD procedure as explained above.

Two different locations have been considered for the building, namely, L'Aquila in central Italy, characterized by high seismicity and type C soil, and Auckland in New Zealand, located in the lowest seismic area of the country, for which a type C soil has been considered as well. The building is designed considering an Importance Level 3, following the NTC 2018 for the case of Italy and NZS 1170.5:2004 for New Zealand. Accordingly, the EPDs for the Life-Cycle Assessment have been chosen considering the two different countries of origin. For the energy simulations, the weather data of both cities are collected. Specifically, the subtropical climate of Auckland, whose small temperature variation across the year is about 10°C with an average maximum temperature of around 25°C, highly differs from the sub-continental climate of L'Aquila. The latter, in fact, exhibits an average minimum temperature slightly below 0°C while the maximum is comparable to that of Auckland.

In the Multi-Objective Optimization (MOO), structural input parameters are changed at each iteration. In evolutionary algorithms, they are called "genomes"; in this work, the genomes of the MOO are the following:

- Beams and columns section height.
- Post-tensioned (longitudinal) frames span length.
- Gravity (transversal) frames span length.
- Target design drift for the DDBD procedure.

The beams and columns width are fixed at 405 mm for LVL production consideration, made of nine 45 mm thick laminations glued together. To comply with materials strength and deformation limits, as well as to guarantee the adequate re-centering of the structural system during the design process, hard constraints are assigned. This means that all the solutions not meeting these limits and characterized by a global ratio between re-centering and dissipative contribution, λ, lower than 1.15 are rejected from the evaluation.

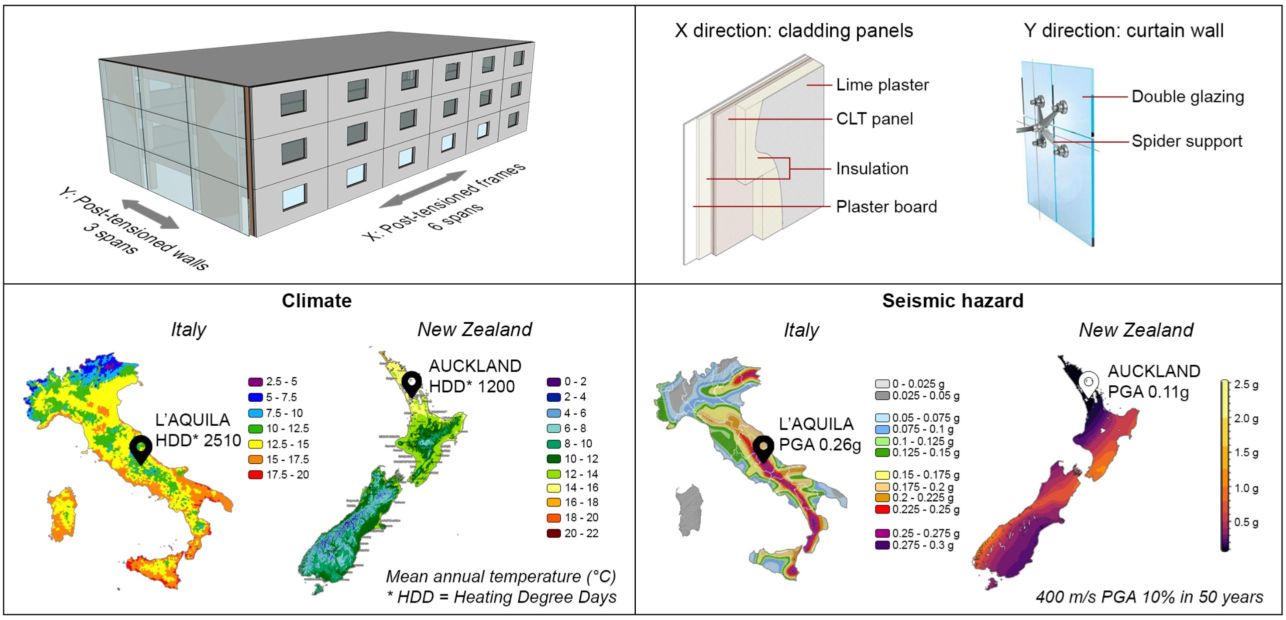


Figure 3. Pres-Lam case-study building, its non-structural attributes, and the seismic and climate characteristics of its different locations.

4. Optimization results

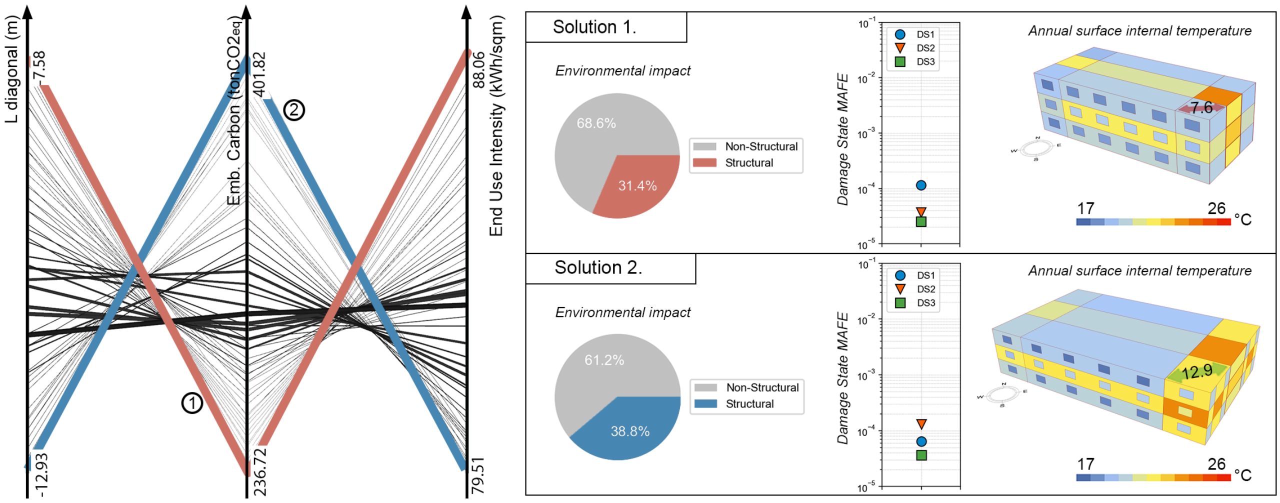
Two Pareto-optimal solutions have been selected for each site. Specifically, the two most different configurations for both L'Aquila and Auckland have been chosen, in order to investigate the influence of the design variables (i.e., the genomes) on the performance (i.e., the objectives). The input and the corresponding outcomes generated by the optimization are shown in Table 1.

Table 1. Optimization design variables and objective values for the 4 selected solutions.

	1st solution L'Aquila	**2nd solution L'Aquila**	**1st solution Auckland**	**2nd solution Auckland**
Design drift (%)	1.9	1.5	1.6	2
Seismic span (m)	5.7	8.2	8.6	9.4
Gravity span (m)	5	10	6	10
h_{beam} *(mm)*	610	900	520	640
h_{column} *(mm)*	520	710	880	690
$n_{diss.beam}$ *(level 1 to 3)*	2, 2, 2	3, 2, 2	2, 2, 2	2, 2, 2
$d_{diss.beam}$ *(mm) (level 1 to 3)*	14, 14, 14	16, 16, 14	14, 14, 14	14, 14, 14
$n_{tendons\ beam}$ *(level 1 to 3)*	4, 3, 2	6, 5, 2	3, 2, 1	3, 3, 2
$n_{diss.column}$ *(level 1 to 3)*	3	3	2	2
$d_{diss.column}$ *(mm) (level 1 to 3)*	14	22	14	14
Embodied carbon (tCO2eq)	237	402	384	540
Window-to-wall ratio (frames direction)	0.2	0.11	0.13	0.12
*Window-to-wall ratio (walls direction)**	0.04	0.52	0.2	0.52
Energy usage (kWh/m^2/year)	88	79	70	70

*The value refers just to those spans where the walls are present.

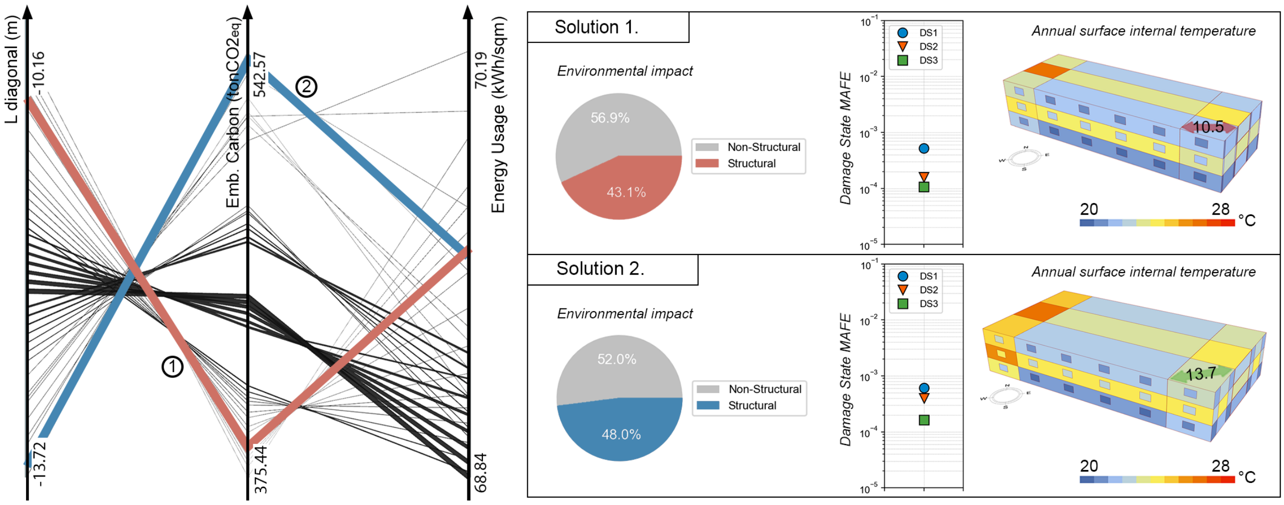
As presented in Figure 4, the least and the most flexible solutions have been chosen for L'Aquila case-study. As expected, the smaller building is the one characterized by the lowest embodied carbon, which becomes almost twice when doubling the frames spans. However, it is worth noting that the greatest amount of CO_2 equivalent is due to the non-structural components, possibly because of the use of glass in the curtain walls on the transversal direction. This trend occurs for all the selected configurations. As far as the seismic performance is concerned, the lateral loads are resisted by four post-tensioned timber frames in the longitudinal direction. The increase of building spans for both seismic and gravity frames in the second configuration comes with the insurgence of Damage State 2 (i.e., timber yielding in compression) before Damage State 1 (i.e., failure of external dissipaters). This is due to the higher axial load in the sections, especially at the base of the columns. Despite that, the values of the MAFE can be considered relatively low, with the Damage State 3 (i.e., post-tensioning tendons yielding) close to the value of 10^{-5}, which corresponds to ground-motions with a return period T_R=100000 years. The second building configuration is not characterized by higher energy consumption, as it would be expected from the larger internal spaces. In fact, the high temperature range of L'Aquila between summer and winter, as well as night and day, makes the use of HVAC necessary to ensure the internal thermal comfort, which is better maintained by the low window-to-wall ratio (i.e., a smaller amount of dispersant surfaces) in the longitudinal direction of the longer span solution.



a) b)

Figure 4. a) Solution space visualization with the selected optimal solutions for Auckland case-study. Each solution is represented by a polyline and its objectives values, i.e., performance, by the intersection with the relative axis; b) Relative environmental impact of structural and non-structural components, seismic performance as the mean annual frequency of exceedance of the limit states, and a representation of the average surface internal temperature of the two selected buildings.

On the contrary, Auckland case-studies (Figure 5) show all the same value of energy intensity. The mild weather of the northernmost big city of New Zealand allows to meet the internal comfort almost entirely by natural ventilation. When compared to the Italian case-studies, both the solutions in Auckland are characterized by higher values of embodied carbon, as well a higher rate of environmental impact related to the structural components. This is possibly due to the different EPDs used for the two countries, with New Zealand being the one with the highest materials' embodied carbon factors. This underlines the importance of products selection within the chosen database for Life-Cycle Assessment, which considerably influences the results. The lower seismic demand here enables the use of just two seismic-resistant post-tensioned frames in the longitudinal direction. Moreover, the solutions show a higher level of flexibility compared to L'Aquila, without compromising the desired hierarchy of limit states, which is characterized by the onset of DS1 before DS2 even for the larger building configuration, albeit slightly.



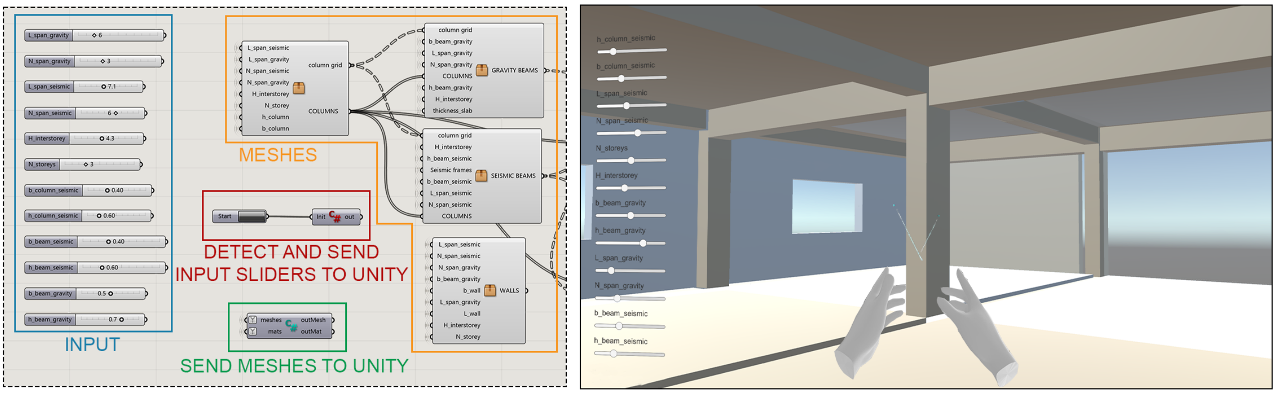
a) b)

Figure 5. a) Solution space visualization with the selected optimal solutions for Auckland case-study; b) Relative environmental impact of structural and non-structural components, seismic performance, and average surface internal temperature of the two selected buildings.

However, despite the lower seismic hazard of Auckland, the optimization of the post-tensioned frames to meet the design requirements with as little material, thus embodied carbon, as possible is achieved at the expenses of higher MAFE for all the damage states. It is also worth noting that a second level of optimization should be carried out to reflect the most efficient element sizes and thus reduce the residual material in the manufacturing process.

5. Model manipulation in Virtual Reality

VR enhances our ability to visualize full-scale models and gain a better understanding of what the final product will look like. While existing VR integration generally requires a set of actions from the user to export a model to the virtual environment, the proposed methodology enables a real-time synchronization between the modelling software and Unity3D application. The Grasshopper interface with the components designated to connect the two software is shown in Figure 6a. The dialogue takes place through so-called “callback” functions entrusted with specific methods, such as detecting the input sliders and values. Calling these functions in both the Grasshopper and Unity scripts allows to pass all the necessary information from the model to the VR environment, as well as the real-time modification from both ends. Although the bidirectional link and interaction have been set up, this part of the study is still ongoing, especially concerning improvements in the building VR visualization and the input sliders in-game display. The actual user’s VR view of the simplified building and its editable dimensional variables is presented in Figure 6b. The designer can easily navigate in the building space and intuitively interact with the model editing the imported input sliders through the controllers. The project has been tested with Meta Quest v.2 as head-mounted display, which can be connected to the Windows pc either through Link cable or wireless with AirLink, resulting in a greater freedom of movement.



a) b)

Figure 6. a) Grasshopper canvas with input sliders, the algorithms defining all the building elements meshes, and the C# boxes designated to link the model definition to Unity3D engine with a real-time connection; b) Visualization of the building model in the virtual environment using Unity3D application and Oculus Quest v.2, with the Grasshopper corresponding input sliders; any slider’s changes made in Unity are automatically transmitted to Grasshopper, and vice versa.

To better evaluate the advantages of immersive modelling and design compared to the more traditional desktop-based processes, a pilot evaluation study is suggested and will be possibly undertaken in the future.

6. Conclusions

This paper presented an integrated parametric framework for the multi-performance optimal design and evaluation of flexible low-damage post-tensioned laminated timber (Pres-Lam) buildings. Specifically, the Grasshopper-based framework allows to perform simultaneously environmental Life-Cycle Assessment (LCA) and energy simulations of the building designed through an automated Displacement-Based Design procedure and assess its seismic performance through a fragility-based probabilistic approach. The trade-off between these sometimes-conflicting performance happens through a Multi-Objective Optimization (MOO) able to iteratively change the design variables in the search for those building configurations which minimise the embodied carbon from-cradle-to-gate and operational energy consumption, and maximise the internal space flexibility. The framework is applied to a three-storey case-study building located in L'Aquila (Italy) and Auckland (New Zealand). The selected Pareto-optimal solutions for the two locations show how such an approach can capture results that might not be self-explanatory, enhancing the decision-making process in the early-stage design phase. The framework application also highlights the great potential of Pres-Lam buildings in delivering sustainable and adaptive buildings with high seismic performance, as it is demonstrated by the low Mean Annual Frequency of Exceedance (MAFE) of the damage states even in the cases of the most flexible building configurations.

As a further improvement towards an increased engagement and collaboration between multi-disciplinary actors in the design process, a real-time link and interaction between the Grasshopper model and the Virtual Reality (VR) environment is developed. Even if the building realistic visualization and a proper in-game menu for design input manipulation is still under development, it is already possible to experience the advantages of a direct design exploration in the immersive environment. Leveraging this innovative technology, which use in the AEC industry is rapidly increasing, the design process could be streamlined and enhanced by providing essential building information in virtual reality and simulating the actual conditions to which the building will be exposed in the future.

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