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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

An overview of the efficiency of anti-graffiti products in the context of climate change

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Abstract

Especially in urban environments, existing buildings are prone to anthropic hazards, such as unauthorized graffiti. Anti-graffiti products may protect surfaces against unwanted paints by acting as sacrificial, semi-permanent or permanent coatings. In addition, under the current climate change scenario, the preservation of the existing buildings is seeking sustainability and reducing maintenance energy and efforts. Therefore, the present study aims to discuss how anti-graffiti products and their related efficiency may be affected by the changing climate and how their performance and durability can present different scenarios. An overview is reported based on existing literature. Concerning the application of protective coatings on polluted environments, distinct anti-graffiti products can be differently affected by atmospheric pollutants, and the cleaning effectiveness of paints may be harmed. Furthermore, the cleaning and protective efficacy of anti-graffiti products may be affected by ageing, highlighting the importance of practical maintenance. The protective solutions' choice is also fundamental within sustainable practices, pointing to the relevance of environmentally sustainable and low-invasive removal methods. The environmental and economic impacts of anti-graffiti products are closely related to their number of required cleaning cycles.

Keywords: Anti-graffiti; Climate change; Efficiency; Durability

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1. Introduction

Graffiti is a commonly seen source of damage (Rossi et al., 2016), especially in urban areas (Moura et al., 2016), which affects not only recent buildings with low significance but also façades with historical and artistic value (Pozo-Antonio et al., 2016). In fact, as reported by Lettieri et al. (2019), although graffiti writings might be observed more frequently as an art expression, mainly their presence in historical buildings is still understood as vandalism.

Typically, spray paints are used for graffiti applications; the spray paints are composed of a pigment, a binding medium, and a solvent (Sanmartín et al., 2014). Regarding the removal of graffiti applications, it seeks to recover the former esthetical properties of the affected surfaces and reduce physical-chemical consequences on the substrate arising from the graffiti paint (Feltes et al., 2023). However, graffiti removal may be challenging concerning the high costs involved (Pozo-Antonio et al., 2016) and the adherence of the paint to the surface (Feltes et al., 2023), which can even prevent its total extraction, further than altering the surface characteristics (Pozo-Antonio et al., 2016). Although unauthorized graffiti, as an anthropic hazard, can be painted over, this may not be the best approach (Sanmartín et al., 2014) aiming to solve the problem durably, especially in case of historic buildings. Therefore, prevention is regarded as a promising approach (Carmona-Quiroga et al., 2010a).

Thus, to protect the building surfaces against unwanted vandalism, anti-graffiti products can be applied; the protective products are available as sacrificial, semi-permanent or permanent coatings, which, respectively, are eliminated during graffiti cleaning, can withstand two or three cleaning cycles, or, finally, may resist to more than ten cleaning cycles (García and Malaga, 2012). Generally, anti-graffiti coatings act as protective barriers, which prevent the penetration of the paint within the substrate (Moura et al., 2014) and facilitate its cleaning due to the resulting energy of the surface (Lettieri and Masieri, 2014; Rabea et al., 2012).

Moura et al. (2017) investigated sacrificial anti-graffiti products composed of SiO_2 nanoparticles or water-based organoxiloxane emulsions with special additives; the studied permanent products were water-based fluoroalkylsiloxane and an aqueous nanostructured emulsion of silicon-based molecules. In fact, the majority of commercial anti-graffiti products are siloxane/silicone-based, as they can repel most water-based paints and markers; however, they may not be able to protect the surfaces against oil-based paints, which require the protective solutions to be oleophobic or superomniphobic (Bayer, 2017).

Hence, to avoid paint penetration, the anti-graffiti products should ideally be hydrophobic and oleophobic, with low surface energy (García and Malaga, 2012). In addition, anti-graffiti coatings should be transparent (Rossi et al., 2019). Moreover, the efficiency of the anti-graffiti actions depends on the staining agent, the cleaning procedure, and the affected substrate (Lettieri et al., 2019). Regarding metallic substrates, for instance, smooth surfaces are more favorable for graffiti removal (Rossi et al., 2016).

There may be a compromise between the protection provided by the anti-graffiti solutions to the underneath surface, favoring the prolonged service life of paintings and façades, and their effects on the substrate properties. Gil et al. (2023) reported impacts on the surface gloss, hydrophobicity, drying capacity, and water absorption by capillarity of External Thermal Insulation Composite Systems (ETICS) when applied with anti-graffiti products. Moura et al. (2016) verified physical alterations on Portuguese limestone and painted and unpainted lime-based mortars, including water absorption, drying behavior, and water vapor permeability; the porous and capillary structure of the substrates may affect the impregnation of the anti-graffiti products, and, therefore, the capillary water absorption (Moura et al., 2016).

Currently, the long-term performance of building materials is emphasized within the sustainability context: durability and resilience of the materials can be affected by the existing scenario of a changing climate (Lacasse et al., 2020), whose impacts are surrounded by significant uncertainty (Wallace et al., 2021). García and Malaga (2012) have already referred to the need for anti-graffiti products to be friendly considering building users and the environment. The importance of the topic actually relies on global warming as one of the major current challenges (Yassaghi et al., 2019) and the need to investigate preservation strategies under climate change (Blavier et al., 2023; Xiao et al., 2021).

The application of anti-graffiti products may impact the maintenance economy (Carmona-Quiroga et al., 2010b); successful building maintenance cost estimation plays a role in the circular economy, so as strategies to deal with construction waste (Mahpour, 2023). Furthermore, preserving the existing buildings, seeking sustainability, and reducing maintenance energy and efforts is essential. In this context, the present study aims to discuss, based on the available literature, how anti-graffiti products and their efficiency may be affected by the changing climate and, on the other hand, how their performance and durability can represent different scenarios.

2. Methods

Initially, an advanced search in the Scopus database with the query string "anti-graffiti AND climate chang*" within the title, abstract, and keywords of scientific papers in English was carried out. Solely one result (Carmona-Quiroga et al., 2017a) was retrieved, ensuring the relevance of discussions on the topic and pointing to the need for a broadened search.

Therefore, an overview is reported substantiated by the state-of-the-art referring to anti-graffiti products, firstly addressing their application in polluted environments. The subsequent section was focused on their efficiency and durability, for which the search query "anti-graffiti AND durab*" regarding title, abstract, and keywords retrieved 16 journal papers in English from the Scopus database. Lastly, also in the field of sustainability, the choice of anti-graffiti products considering the related cleaning methods is discussed along with the environmental and economic impacts throughout their service life, following topics retrieved from existing research.

3. Results

3.1. Application of anti-graffiti products in polluted environments

Air pollution is a decisive variable regarding health and climate change; sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter lead to massive impacts on the air quality and are mainly resulting from fossil fuels combustion (Kumar et al., 2023).

In this context, Carmona-Quiroga et al. (2010b), for example, investigated anti-graffiti solutions as potential pollutant deterrents to be applied to construction materials, considering an SO_2-polluted environment. An organic-inorganic hybrid anti-graffiti product was effective in deterring pollutants when applied to carbonate-based materials, while it was not efficient in preventing SO_2 absorption by cement mortar and brick; on the other hand, another anti-graffiti product, water-based fluoroalkylsiloxane, did not influence the SO_2 uptake of any studied substrate (Carmona-Quiroga et al., 2010b). Regarding the protected substrates, roughness parameters may, besides impacting graffiti access, affect as well the access of pollutants (Carmona-Quiroga et al., 2017a). Although further studies may be suggested on the performance of anti-graffiti products exposed to other air contaminants, the available information indicates that distinct anti-graffiti products may respond differently to a polluted atmosphere.

Furthermore, Gomes et al. (2018) approached the exposure of graffiti paints with different compositions to an SO_2-rich environment, aiming to study its influence as an ageing cause on the effectiveness and harmfulness of graffiti chemical cleaning procedures since the external environment may affect the graffiti paints. Without applying anti-graffiti products, the graffiti paints were cleaned with a potassium hydroxide (KOH) solution and a solution of n-butyl acetate, xylene and alcohol isobutyl. Alkyd-based and polyethylene-based graffiti paints had a different behavior when exposed to the SO_2 and moisture-rich environment; the SO_2 ageing of the painted specimens influenced the chemical cleaning efficiency by requiring a higher number of cleaner solution applications in order to reach similar results as on the unaged specimens (Gomes et al., 2018). Therefore, the cleaning effectiveness of graffiti paints may be harmed by continuous exposure to air pollutants, highlighting the importance of prevention measures.

3.2. Efficiency and durability of anti-graffiti products

The long-term performance of permanent and sacrificial coatings is considered scarcely known, which is problematic since they are affected by environmental factors and, often, by aggressive cleaning procedures (Carmona-Quiroga et al., 2017b). Thus, additional knowledge is needed regarding the behavior of anti-graffiti products under natural exposure in the long run (Gil et al., 2023). The anti-graffiti coatings must be able to keep their effectiveness throughout time, allowing graffiti removal with the lowest possible resulting color and gloss changes within the substrate due to the cleaning actions; furthermore, resistance to solar radiation and chemical and thermal stability are required from the protective products, in addition to environmental and economic compatibility (Rossi et al., 2016).

In stone substrates, two anti-graffiti treatments, one composed of a water dispersion of polyurethane with a perfluoropolyether backbone and the other of a water-based crystalline microwax, lost their cleaning efficiency after artificial ageing during 2,000 hours in a chamber with UVB radiation and natural ageing trials in a temperate maritime climate for 12 months (Carmona-Quiroga et al., 2017a). Concerning ETICS protected with anti-graffiti products and submitted to accelerated ageing with hygrothermal cycles, they showed a slight darkening, a gloss increase, a partial erosion of the material, and a general reduction of the water absorption by capillarity and drying kinetics, which can affect their cleaning efficacy over time (Gil et al., 2023).

In metallic substrates, weathering through UVB and condensation led to an increase in the hydrophilicity of specimens protected with anti-graffiti products based on a polyester resin, and, although color variation was considered acceptable after graffiti removal with xylene and methylethylketone, the gloss increase was excessive (Rossi et al., 2016). In concrete slabs, a permanent anti-graffiti coating composed of a fluorinated polyurethane was weathered after 500 h of ageing in a chamber with UVB radiation and after six months of exposure in the south of England, getting yellower and dark and, in some cases, losing its adhesion from the substrate, besides being partially removed by pressurized water spray; sacrificial coatings composed of a crystalline microwax were also degraded in the natural environment, becoming darker and less water-repellent due to cracking (Carmona-Quiroga et al., 2017b).

Rabea et al. (2012) prepared polyurethane coatings with anti-graffiti properties with a silicone acrylic additive and, through ageing under UV irradiation, the degradation of the additive was registered; thus, the improvement of the UV resistance of the films was suggested to achieve durable protective products. In this context, Amrutkar et al. (2022) suggested the addition of silica nanoparticles to improve anti-graffiti coatings durability, especially regarding UV radiation and weathering resistance. Gao et al. (2021) produced a protective coating by cross-linking two kinds of siloxane regarding the need for durability; the anti-graffiti performance of the coating, applied to a glass surface, was considered excellent facing both water and oil-based paints and, additionally, it was not affected by harsh environments, including ultraviolet irradiation, sunlight, and corrosion.

Regarding the nature of anti-graffiti products to be used, especially sacrificial systems, generally based on waxes and silicones, may have their durability affected by intense environmental conditions (Gardei et al., 2008; Gomes et al., 2017), while semi-permanent and permanent products can provide a more efficient graffiti removal (Gil et al., 2023). Cocco et al. (2015) evaluated one semi-permanent anti-graffiti product's durability through cleaning tests and verified that, although the technical data sheet stated the resistance of the product to three to four cleaning cycles with dichloromethane, only one cycle partially compromised the coating, leading to vulnerability of the substrate against graffiti paints. On the other hand, Lettieri and Masieri (2014) applied sacrificial water-based anti-graffiti emulsions to a highly porous stone, observing that limited areas still presented residual anti-graffiti after cleaning. Therefore, compatibility problems or harmful accumulations could arise from maintenance activities with further treatments, besides impacts on the surface characteristics (Lettieri and Masieri, 2014).

García and Malaga (2012) proposed a series of durability tests to assess anti-graffiti products for use in the protection of historical porous substrates, including acid rain ageing, UV and condensation ageing, salt crystallization, and natural weathering tests; cleaning efficiency was proposed to be assessed through an absolute cleaning measure, for which classes of fulfilment were presented.

In the context of climate change, climate loads such as wind-driven rain events are expected to be longer and more frequent, therefore imposing a risk of premature degradation on building elements, including walls (Lacasse et al., 2020). Hence, the acknowledged need for improvement on anti-graffiti products to protect building façades can eventually be considered enlarged. Similar to self-cleaning façades technology (Chew et al., 2017; Fernandes et al., 2020), applying anti-graffiti products to building envelopes could contribute to their maintainability. Therefore, investigating anti-graffiti products could be interesting within green maintainability performance indicators, seeking to minimize adverse environmental impacts and maximize functional, safety, energy efficiency and financial performance (Asmone et al., 2019).

3.3. Environmental and economic impacts of anti-graffiti products throughout the service life

Low-invasive and eco-friendly graffiti removal techniques should be preferred instead of conventional chemical-mechanical removal methods, drawing upon highly acid or basic products or high-pressure water jet; for instance, combined manual and mechanical brushing with low-pressure water steam jet, which achieved satisfactory graffiti removal mainly in ETICS with acrylic-finishing coats and EPS as thermal insulation, according to previous studies (Gil et al., 2023). On the other hand, there are, among others, paint strippers for use in substrates protected with sacrificial anti-graffiti products or even unprotected, and organic solvents recommended for slightly painted surfaces, which may be applied seeking to remove graffiti over permanent protective products (Moura et al., 2017). By studying the available methods for graffiti removal, Sanmartín et al. (2014) identified that typical chemical substances may penetrate the substrate, damaging it irreversibly, further than causing environmental and health hazards; thus, new environmentally safe methods should be developed for graffiti removal from porous materials, including bioremediation (Sanmartín et al., 2014).

Thus, further than the essential need for an adequate choice of anti-graffiti products (Rossi et al., 2016), investigating the cleaning procedures required to remove the graffiti paint is fundamental regarding the expected environmental impacts from the coatings. If removal products will actually be used, the ideal is to clean graffiti with less aggressive solutions, like mixtures of aliphatic and aromatic organic solvents or xylene; if, unfortunately, the achieved results are not acceptable, more aggressive removers, including methylethylketone, may be a solution (Rossi et al., 2016).

Roviello et al. (2022) studied two commercial anti-graffiti products, one of which was permanent, nano-based and considered environmentally sustainable, and the other was semi-permanent. As graffiti removal method, solely cleaning cycles with hot water at 60 °C were carried out; the removal method could effectively clean the surface of porous materials, including tuff, protected with the permanent product, which proved more effective than the semi-permanent anti-graffiti (Roviello et al., 2022).

Pedroso et al. (2022) quantified the environmental and economic impacts of protection solutions to be applied on ETICS; regarding anti-graffiti products, their environmental impacts were reported to depend highly on the number of cleaning cycles required to remove the graffiti application, even more than in the service life of the protective solutions. Therefore, the application of sacrificial products in buildings highly prone to vandalism can lead to very high environmental and economic impacts (Pedroso et al., 2022). However, especially considering the protection of cultural heritage, Roviello et al. (2022) emphasized the need for new anti-graffiti formulations comprising not only hydrophobicity but also sacrificial properties, besides environmental sustainability, focused on ecologic aspects and human health. Moreover, complexities arise from each specific case and should be considered according to the building façade to be protected.

4. Conclusions

The present study discussed the efficiency of anti-graffiti products in the context of climate change and the arising impacts and scenarios resulting from the performance and durability of the protective solutions. The topic's relevance is emphasized by the recurrent application of unauthorized graffiti paints in urban areas, understood as vandalism mainly in historical buildings, and the challenges posed by climate change upon the durability and resilience of buildings and construction materials.

About polluted environments, further studies should include diverse air pollutants since varied anti-graffiti products may respond differently to the imposed air quality, and graffiti paints themselves are also affected by the interaction with air pollution throughout time, impacting cleaning needs. Concerning the existing effects caused by environmental factors on anti-graffiti products, understanding their long-term behavior is essential, mainly due to the involved maintainability, energy, costs, and impacts. Different scenarios of study must be taken into account, considering not only the nature of the anti-graffiti products but also the substrates to be protected and their cultural value; maintenance strategies should be planned within the specific application context. Further attention should be dedicated to the life cycle assessment and life cycle costing of anti-graffiti products, and more research should address the search for environmentally friendly protective solutions and cleaning methods.

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Application of a retrofit system to improve the seismic and energy performances of RC framed buildings

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Abstract

The need to renovate the existing building stock in earthquake-prone countries is now widely recognized. In this framework, this paper aims at investigating an innovative technology for the seismic, energy and architectural renovation of RC framed buildings. This technology combines the seismic resistance provided by steel trusses with the thermal performance of wood-based panels, which are both applied to the outer building envelope.
In this paper, the proposed system is applied to a pilot building located in the city of Bucharest, in Romania, to examine its effectiveness and replicability. The pilot building is a five-storey apartment block located in a suburban neighborhood of the city and representative of many coeval buildings in Bucharest that are energy-intensive and earthquakes-prone since they were built before the enforcement of effective seismic and energy efficiency standards.
The proposed retrofit methodology involves designing wood-based prefabricated panels and steel trusses according to criteria of structural strengthening and energy efficiency, standardization in manufacturing process, fast installation, and architectural integration. Furthermore, the parametric modeling in BIM environment of the above-mentioned components enables controlling their size, quantity, manufacturing, cost, and arrangement on the building façade to optimize the construction and installation processes.

Keywords: energy efficiency; seismic performance; prefabricated wood-based panels; architectural integration; BIM methodology;

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1. Introduction

In the past, little attention has been paid to the issues of environmental sustainability and structural safety in the building construction sector. Indeed, most of the building stock in the European seismic countries is highly energy-intensive and earthquake-prone since it was built before the enforcement of effective energy and seismic codes. It is also often characterized by low architectural quality and relevant construction weaknesses. This is mainly caused by the natural decay of the materials over the years, but also by the originally use of poor-quality materials by construction companies whose intent was to minimize costs and maximize profits. Hence, building renovation is today a major priority to achieve the main EU targets of environmental sustainability and structural safety. The most frequent approach for anti-seismic and energy-efficient renovation involves combining the traditional retrofit techniques in an additive way. Nevertheless, these traditional techniques have relevant limits, which are mostly related to seismic upgrading interventions, such as: i) high costs; ii) long time for implementation; iii) high occupants' disturbance; iv) significant demolition and reconstruction interventions; v) large quantities of demolition waste.

In this framework, a recent research topic concerns the potential use of external steel braced structures, commonly named exoskeletons, as holistic renovation strategy for the concurrent energy and architectural renovation of the buildings (Takeuchi et al., 2006), (Labò et al., 2016), (Ferrante et al., 2016), (Marini et al., 2017), (D'Urso et al., 2019). Indeed, the addition of steel exoskeleton is an effective technique for the seismic upgrading of RC framed buildings (Rahimi et al., 2020), which has the advantages of reducing cost and time for implementation as well as occupants' disturbance thanks to the application from the outside of the building and the high level of prefabrication.

To this research context belongs the Horizon 2020 project e-SAFE (Energy and Seismic AFfordable rEnovation solutions) that aims at developing innovative, low-invasive, environmental-friendly technological solutions for seismic, energy, and architectural renovation of RC framed buildings. One of the e-SAFE solutions provides to combine a 3D steel exoskeleton (named e-EXOS) with prefabricated insulating panels (named e-PANEL) to be applied to the external envelope of the building.

The combined use of these two components has several advantages. On the one hand, the e-EXOS allows to force a uniform distribution of the storey drifts along the height of the building and avoid the formation of soft storey collapse mechanisms (Fig. 1a). Hence, it reduces the drift demand of the existing structure caused by earthquakes, thus preventing its collapse. Additionally, the trusses can be also provided with Buckling Restrained Braces (BRBs) at the base, which supply an increase of the dissipation capacity of the structure. On the other hand, in terms of energy performance, the e-PANEL aims at increasing the thermal resistance of the walls, and thus the energy efficiency of the building (Fig. 1b). Moreover, its new cladding layer contributes to renovate the new building's architectural image (Bosco et al., 2023).

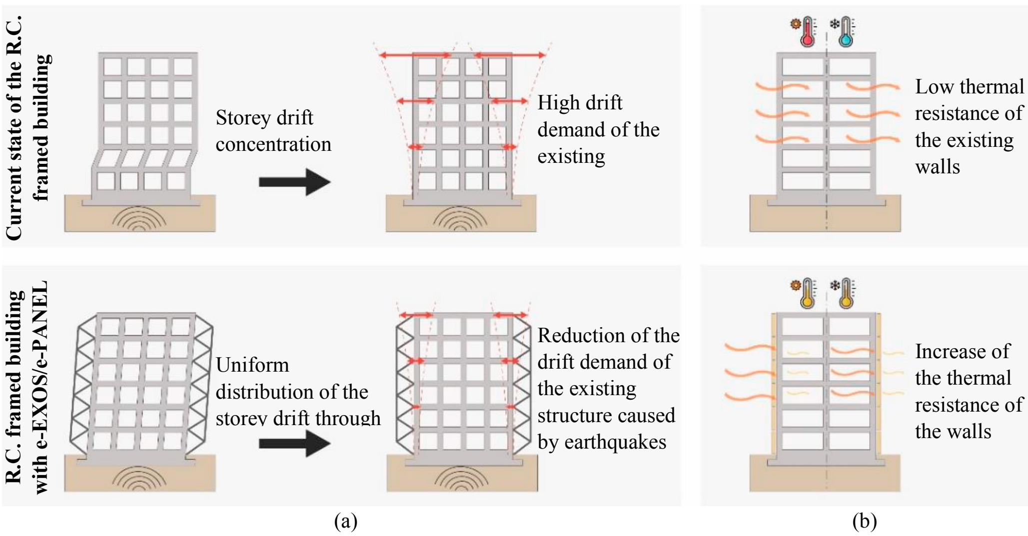


Fig. 1 Concept of the e-EXOS/e-PANEL system: (a) seismic performance of the e-EXOS; (b) energy performance of the e-PANEL.

Given the multidisciplinary nature of the e-SAFE technological system, an integrated management is fundamental to control the architectural, constructive, mechanical electrical plumbing (MEP), sustainability-related and economic aspects. Therefore, it was decided to use a Building Information Modelling (BIM) approach, which allows to control all the phases of the project, reducing dissimilarities and incongruities between the various design stages. In this context, this paper describes the e-EXOS/e-PANEL system and its validation through the retrofitting design of a pilot building.

2. Methods

The proposed methodology is divided in 9 phases (Fig. 2). The first four steps (yellow and blue portions in Fig. 2) take place simultaneously. Specifically, the phases 1 and 3 provide analyzing the current state of the building, by involving firstly the laser scanner survey of the building façades and the data transfer to BIM, and then filtering the information required for the specific intervention, e.g. the wall finishing data, since the components are applied from the outside. On the other hand, the phases 2 and 4 provide designing the e-SAFE components and their BIM parameterization (see Section 3.1). Indeed, one of the primary objectives of the e-SAFE system is the replicability of the retrofit intervention to different boundary conditions (geometric, climatic, structural, etc.). Consequently, the building components of the system need to be parametrically modelled to easily vary their characteristics. Therefore, a BIM methodology is employed to create a set of *parametric families* for both e-PANEL and e-EXOS and for each of the metalwork elements of the e-EXOS wall connection. Each family parameter needs to be a *shared parameter* so that is not associated to one *family* but can be accessed by different files and users. Moreover, the phases concerning the application of the e-SAFE building components in the BIM model (phase 5) and the construction details (phase 6) are highlighted in green (see Section 3.2). Finally, the methodology includes the last three more steps: the production of the e-SAFE building components (phase 7), their installation (phase 8) and follow-up maintenance (phase 9).

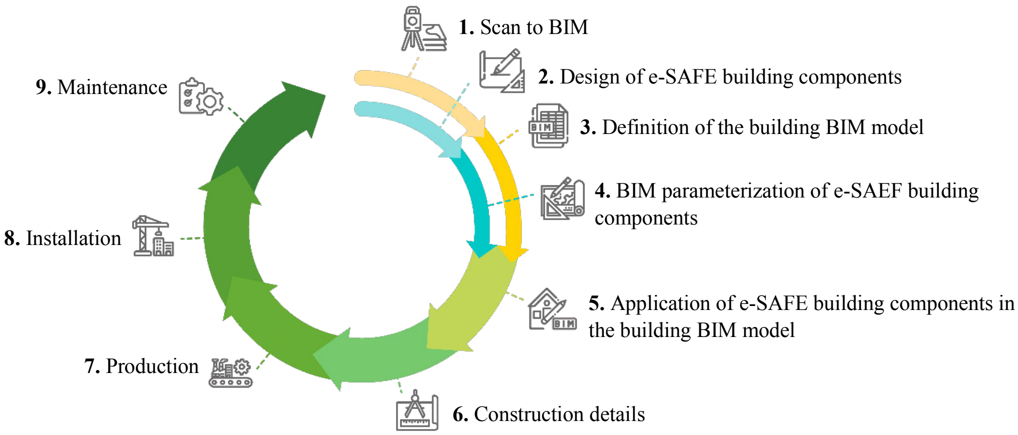


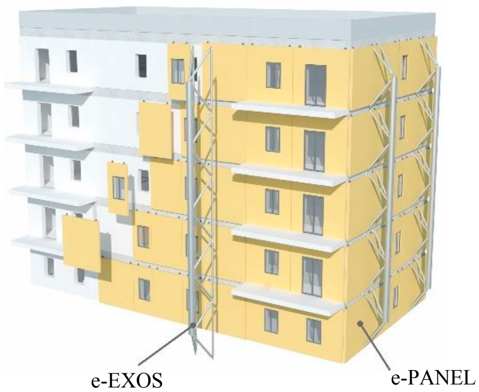
Fig. 2 Stages of the proposed retrofit methodology.

3. Results

3.1. Design and BIM parameterization of e-SAFE building components

Along with the building renovation "Scan to BIM" and "Definition of the BIM level of information needed" phases, the proposed methodology focuses on the "Design of e-SAFE building components". As already mentioned in Section 1, the building components described in this paper are the e-PANEL and e-EXOS developed within the e-SAFE project (Fig. 3a). The e-PANEL is a prefabricated and insulating wood-based panel to be applied to the existing outer walls of the building. This new building skin integrates a thermal-acoustic insulation layer and, if needed, also new high-performing windows and sun shading devices. In addition, it can integrate many cladding materials that contribute to the restyling of the building's architectural image. Fig. 3b shows the main e-PANEL stratification, which is an update of the preliminary configuration that has been designed within the project and reported in (Barbagallo et al., 2018). This new stratification can guarantee: i) adequate mechanical performance; ii) thermal transmittance compliant with limits imposed by law; iii) watertightness and airtightness; iv) vapor permeability and moisture resistance; v) fire-protection; vi) quick installation. Essentially, the e-PANEL is made of a lightweight wooden frame that integrates thermal-acoustic insulation. On the internal face, it is confined by marine plywood boards. On the external face, it is confined by a non-combustible cement-based board to ensure the panel adequate fire protection. The e-PANEL also includes a waterproof vapor-open membrane to avoid condensation issues and rainwater leakage. The panel is completed by a cladding layer, separated from the watertight layer by a ventilated air cavity. The e-PANEL is connected to the existing RC beams at the top through commercial angle steel brackets. Specific sliding connectors are provided at the bottom; in case of earthquakes, these connectors allow the panel to slide together with the upper RC beam, avoiding or reducing the panel damage.

Instead, the e-EXOS steel truss has a structural role. It provides for a dry installation and is a reversible seismic upgrading technique that does not interrupt the building operativity during its installation.



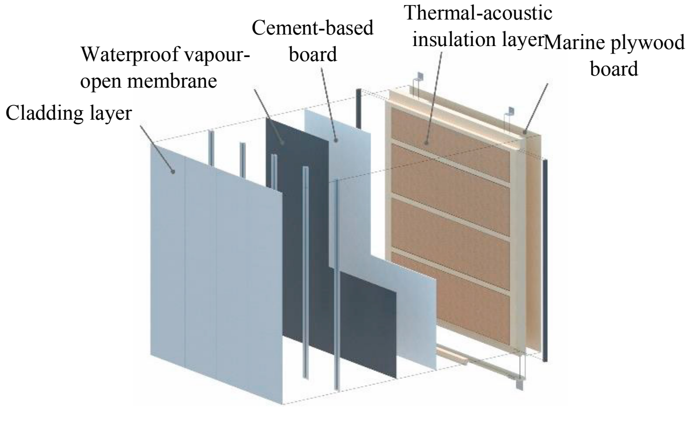


Fig. 3 (a) The e-EXOS system in combination with the e-PANEL solution; (b) e-PANEL stratification.

During the development phase, critical points have been detected at the connection node between e-EXOS, e-PANEL, and the existing RC beams as well as in the space between two panels of consecutive storeys (Fig. 4a). Specifically, the main issues that occur were referred to: i) the different sliding movements of the components during earthquake; ii) the thermal bridges at the beam level; iii) the watertightness of the components.

The sliding movements of the components differ due to the different sliding of the building decks during earthquakes. This issue is solved by configuring the connection node as shown in Fig. 4b: all the elements highlighted in orange will oscillate together with the beam to which they are fixed. To this extent, the sliding movement of the upper panel does not interfere with the e-EXOS wall connection. However, this solution creates a thermal bridge at the level of the RC beam. This issue is solved by designing a horizontal joint cover with an insulation layer, as shown in Fig. 5a-5b. The main wooden frame panel of the joint cover is prefabricated, while the following other layers are assembled on-site: i) a fiber-reinforced concrete panel; ii) a waterproof membrane; iii) a finishing layer separated from the watertight layer by a ventilated air cavity (to dry rainwater infiltrations and winter moisture). Additionally, the joint cover is connected to the bottom panel, while shaped strips made possible the sliding movements on the upper panel connection. To protect the panel from rainwater, the proposed solutions include a ventilated air gap behind the finishing layer (Fig.5c) and the folding of a waterproof membrane towards the edge of the panel. Moreover, the overlapping of the waterproof membrane on the upper and bottom panels ensures waterproofing at the horizontal joints (Fig. 5d). A steel plate and a membrane ensure waterproofing at the truss connection. Details of the whole solution applied to a pilot building are shown in section 3.2.

Different geometric variables (i.e. distances, lengths, diameters, angles, radiuses, and reciprocal positions) of the e-PANEL and e-EXOS have been associated with specific parameters through the Revit software in order to ensure the replicability of the retrofit intervention to different boundary conditions; furthermore, various parameters have been concatenated by using specific mathematical formulas. Each of these specific parameters is classified into *shared parameters groups* and then reported in tables related to a particular project domain, i.e. sizing, construction, assembly, visibility, materials. Hence the BIM *families* are applied within the BIM model of the building (Fichera and Guardo, 2022). An application example of a retrofit intervention by the e-EXOS and e-PANEL is analysed in Section 3.2, with reference to the selected residential pilot building.

Fig. 4 (a) Main critical connection nodes; (b) configuration of nodes for different sliding movements of the components.

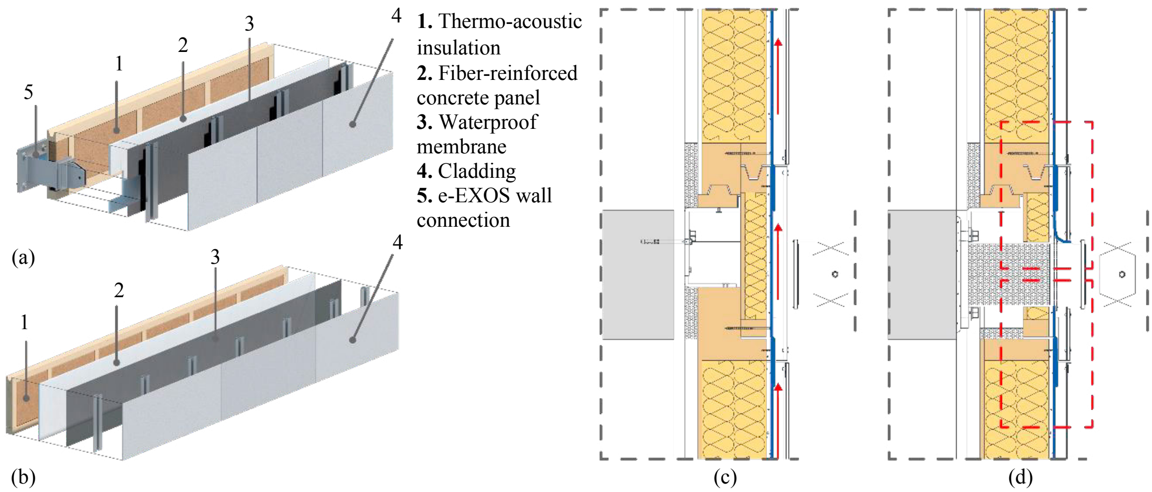


Fig. 5 (a-b) Horizontal joint cover with and without the e-EXOS wall connection; (c) detail of the e-PANEL ventilated air cavity (vertical section); (d) detail of the overlapping of the waterproof membrane (vertical section).

3.2. Application of e-SAFE building component on the BIM model of a pilot building

The pilot building (Fig. 6) is a five-storey apartment block built in the 1970s and located in a suburban neighborhood of the city of Bucharest, in Romania. It is representative of many coeval residential blocks in Bucharest in terms of structural deficits, poor energy efficiency and low architectural quality.

The pilot has a rectangular floor plan with a total area of around 1700 m^2 and a small and narrow central court. It has five storeys and a total height of 14 m. Each floor has four 80-m^2 apartments. The building has a RC framed structure, with frames mainly oriented along the longitudinal direction, resulting in low seismic performance in the orthogonal one. The infill walls are 35-cm thick and made of solid bricks; therefore, they have a non-negligible structural role. The architecture image is quite anonymous; the only identifying feature is the striped color variation along the two main fronts.

The infill walls are not insulated. The intermediate floors and flat roof are characterized by RC slabs (23-cm thick), without thermal insulation too. The windows have PVC frames, double-pane gazing and no external sun shading systems. The thermal transmittance values (U) of external walls, windows and roof floor are quite high, namely 1,8 W/m^2K, 2.7 W/m^2K and 1.2 W/m^2K, respectively.

Fig. 6 Eastern front of the pilot building.

The design of the proposed retrofit system started with the laser scanner survey of the building fronts (Fig. 7) and was followed by the scan-to-BIM process of the building data. Then, specific configurations of the e-EXOS trusses and e-PANELs have been conceived in order to: i) ensure the retrofit system remarkable performance in terms of anti-seismic protection, energy and technological efficiency and architectural integration; ii) maximize the standardization of the prefabricated elements to optimize the production process and ensure the replicability of the retrofit interventions under different boundary conditions; iii) make the installation process fast and efficient.

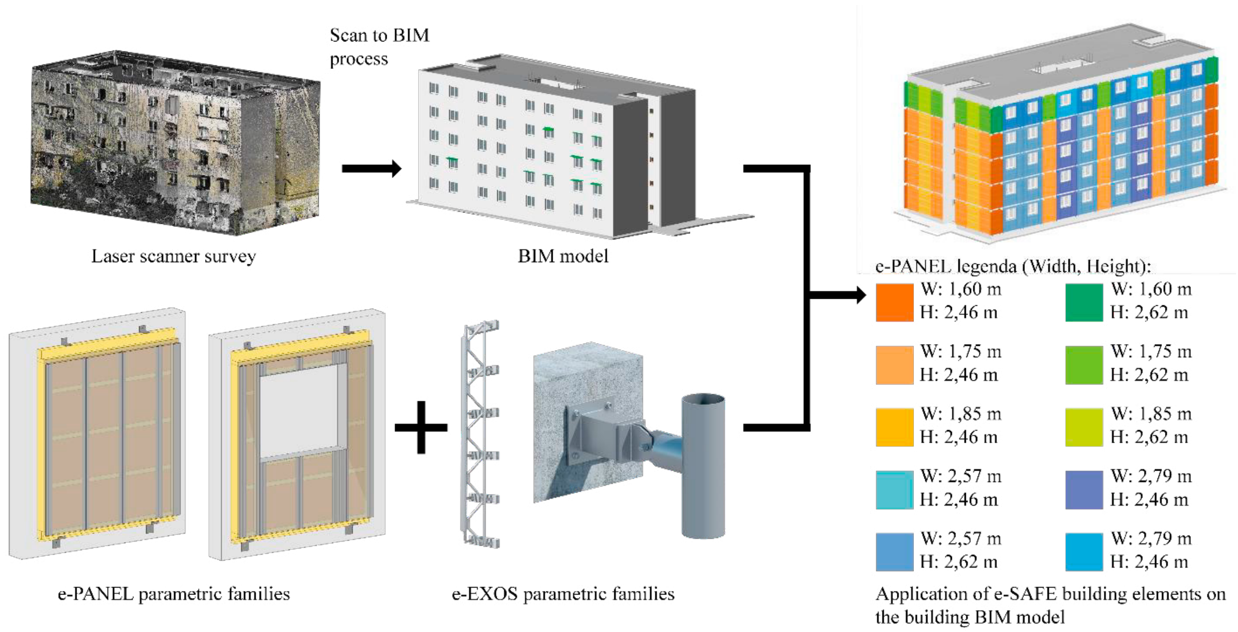


Fig. 7 Scheme of the first steps of the proposed methodological process applied to the pilot building.

The e-EXOS trusses consist of a set of rods and nodes, which are manufactured and assembled off-site so that each truss is made of three pre-assembled portions that are bolted to each other on-site afterwards. Each truss is anchored to the existing building perimetral beams and a new foundation, which is separated from the existing one. The beam-truss connections are designed to prevent the horizontal relative displacements between the existing building and the truss (Fig. 8), while the vertical ones are not constrained thanks to a vertical slotted hole in the anchor plate. On the other hand, the foundation-truss one is a pinned connection. In this way, in the event of earthquake each truss rigidly rotates in the plane perpendicular to the building façade by transmitting a set of forces to the existing structure that reduces the concentration of drift in few storeys.

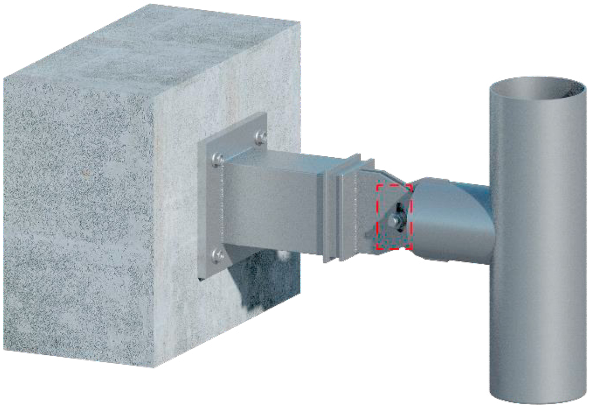


Fig. 8 Beam-truss connection.

As regard the e-PANEL, it is designed according to the main stratification described in Section 3.1.

The panels are 210-mm thick and include (Fig. 3b): i) 10-mm thick marine plywood board; ii) 150-mm thick wood-fiber thermal-acoustic insulation layer (λ = 0,038 W m^{-1} K^{-1}); iii) 12,5-mm thick cement-based board; iv) waterproof vapour-open membrane; v) 30-mm thick ventilated air cavity; vi) 6-mm thick porcelain cladding layer. The above stratification ensures the outer walls a U-value of 0,29 W m^{-2} K^{-1}.

The standardization of the panels was achieved by maximizing the number of elements with the same height and width in order to optimize the production and installation processes. Specifically, ten type of panels have been design, that mostly differ in the width size (Fig. 7).

Fig. 9 shows the rendering of building after the application of the proposed seismic and energy retrofitting solution.

Fig. 9 Rendering of the pilot building at post-renovation state.

4. Conclusions

This paper analyses the application methodology of a retrofit intervention for RC framed buildings that combines the use of a structural exoskeleton made of 3D steel trusses (called e-EXOS) with prefabricated, wood-based insulating panels (called e-PANEL) to be applied to the external envelope of the building.

The proposed methodology first involves surveying the current state of the building by laser scanning of the façades and then transferring the building data to BIM. Next, the e-SAFE building components are designed, and BIM parameterized. Then, the e-SAFE parametric components are applied to the BIM building model. Overall, the e-EXOS and e-PANEL technologies are the result of a design method that integrates multidisciplinary knowledge to ensure the retrofit system remarkable performance in terms of seismic resistance, energy and technological efficiency, as well as architectural integration. Furthermore, working in a BIM environment and parameterizing all the e-SAFE building components allow optimizing the design retrofit process.

The first steps of the proposed retrofit methodology were validated through the application on a pilot building. This allowed to verify the possibility of parameterizing the e-SAFE technologies to ensure replicability of the retrofit intervention under different boundary conditions, in relation to geometric, climatic and structural requirements.

The next steps in the methodological process will involve the production of the e-SAFE components, their installation and maintenance.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Building Energy Modelling for Historical Buildings: Current Distribution of Literature Case Studies in View of Climate Change

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Abstract

Building Energy Modelling (BEM) applied to historical buildings is rising as a non-invasive and useful means to improve their energy and environmental performance by supporting informed choice of appropriate solutions for sensitive renovation. Being climate data one of the main inputs of simulations and considering the life span of historical buildings, it is increasingly important to support BEM reasoning with future climate conditions for the design of effective and climate-change-proofed adaptation strategies. A systematic literature search was carried out through the Scopus database and identified 67 journal articles published between 1997 and 2022 on the use of BEM for the energy efficiency of historical buildings. To investigate the extent to which climate change will likely affect the outdoor forcing conditions in the reviewed case studies, their locations were paired with the climate classes according to the Köppen-Geiger classification maps provided by Beck et al. (2018) for the recent past and far future. The results were then discussed in light of the climate classification of the architectural sites in UNESCO's World Heritage List (WHL) for the same reference time periods. According to the literature review, it emerged a substantial representation in current research of case studies in temperate (i.e., Cfa and Csa) and cold (i.e., Dfb) climate classes together with a scarcity of case studies involving arid climate classes (i.e., BSh, Bsk, and BWh), although the latter ones are expected to house almost 30% of the WHL architectural sites in the future.

Keywords: Climate change; Building Energy Modelling; Historical buildings; Köppen-Geiger classification; UNESCO sites.

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1. Introduction

Nomenclature

AEC	Architectural, Engineering, and Construction
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Modelling
HVAC	Heating Ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
PRISMA	Preferred Reporting Items for Systematic reviews and Meta Analyses
RCP	Representative Concentration Pathways
SSP	Shared Socio-economic Pathways
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHL	World Heritage List of UNESCO sites

The European goal of reducing energy consumption and greenhouse gas emissions requires an increased effort to plan effective and sustainable strategies for the Architectural, Engineering, and Construction (AEC) sector, which is responsible for 30-40% of their total share (Gevorgian et al. 2021). Historical buildings, conventionally defined as constructions built before 1945 using artisanal and pre-industrial techniques (L. Mazzarella 2015), are typically associated with low energy performances. Nevertheless, they can play a key role in this call for sustainability, as they hold a high energy-saving potential thanks to their distinct features, which were proficiently designed to harmonise the building behaviour with the reference climate (Calcerano, Cecchini, and Martinelli 2017).

Energy efficiency is also strictly related to conservation, as keeping historical buildings in use is a way to promote their durability (G. Carbonara 2015). A relevant impulse to research on this topic has been driven by European projects focussing on intervention design (e.g., 3ENCULT (Troi and Bastian 2015) and BEEP (Gigliarelli et al. 2022)) and impact modelling (e.g., Climate for Culture (Leissner et al. 2015) and HYPERION (P. Choidis et al. 2021)). In particular, the project BEEP "BIM for Energy Efficiency in the Public sector" (2019-2022), financed in the framework of the European Neighbourhood Instrument Cross-Border Cooperation "Mediterranean Sea Basin Programme" (ENI CBC Med), addressed the issue of energy efficiency of the built heritage public sector in the Mediterranean area, implementing operative protocols based on innovative digital tools of analysis, design, and decision-making (Calcerano et al. 2023).

Building Energy Modelling (BEM) is rising as a non-invasive and useful means to assess energy efficiency and thermal comfort in historical buildings (A. Martínez-Molina et al. 2016). Although modelling the behaviour of complex historical buildings can be particularly challenging (Akkurt et al. 2020), BEM simulations can be used to study appropriate renovation solutions for improving their energy and environmental performance (Buda et al. 2021). Weather data is one of the principal input of simulations, since the outdoor forcing factor significantly affect the energy consumption required to reach thermal comfort and conservation requirements (van Schijndel and Schellen 2018).

The 6th assessment report published in 2023 by the Intergovernmental Panel on Climate Change (IPCC 2023) warned about the expected changes in climate conditions in the future under various Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) of greenhouse gases. Considering the life span of historical buildings and the increasing risks for cultural heritage (Nguyen and Baker 2023; Verticchio et al. 2023), it is necessary to integrate BEM simulations with climate data providing information on long-term processes for the design of timely and effective climate adaptation measures (C. Ballard et al. 2022; Hao et al. 2022).

The aim of this research is to investigate the extent to which climate change will likely affect the historical buildings that have been studied so far through BEM for energy efficiency purposes based on a systematic survey of the literature case studies. In this way, useful insight is provided to discuss the current state of the art in the field of the energy efficiency of historical buildings and to identify possible research topics that could be explored further.

2. Materials and methods

A systematic literature search was carried out using the Scopus database to retrieve scientific records reporting case studies on the application of whole-building dynamic simulation to historical buildings. The three steps (i.e., Identification, Screening, Inclusion) of the method of Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) were followed to obtain a comprehensive subset of documents on the reviewed topic (Fig.1). The database was initially queried on all its fields using the string ("dynamic simulation" AND "historical building*") to identify recurrent terminology to be used for further interrogating it. This initial search matched 278 documents from 1997 to 2022. Then, more tailored queries were used to search in the database fields Title-Abstract-Keywords, by properly combining, through the Boolean operators "AND" and "OR", the expressions "dynamic simulation", "performance simulation", "thermal simulation", "hygrothermal simulation", "historic* building*", "built heritage", and "heritage building*". This second search matched 295 documents, to which 47 journal articles were added based on the references cited in the initial subset, obtaining a final group of 620 records. After removing duplicates and records not available online, 453 documents were screened by title and abstract and the resulting 177 eligible ones were assessed by full-text reading to exclude case studies that could not be considered relevant for the reviewed topic (e.g., studies only addressing simplified or 2D simulations across single walls, computational fluid dynamics, and the characterisation of construction materials). Finally, 105 documents published between 2011 and 2022 were included in the study, from which 67 journal articles specifically focussing on energy efficiency were selected for the following elaboration.

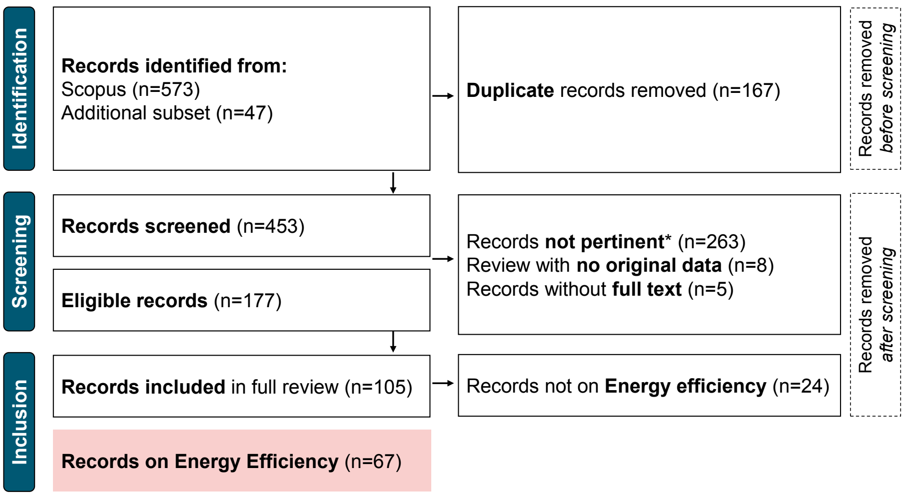

Fig. 1. PRISMA flow diagram for systematic reviews showing the number of documents selected after each step of the process.

A total of 86 case studies was identified out of the 67 reviewed documents as some of them reported more than one case study. The locations of the sites relative to the case studies were paired with past and future Köppen-Geiger climate classes to evaluate the extent to which climate change could likely affect their outdoor forcing conditions. The Köppen-Geiger classification maps elaborated by Beck et al. (2018) were chosen as they are derived from ensembles of several climate sources and offer accurate high-resolution maps at a 1-km grid. These maps are available only for two reference time periods, i.e., the Recent Past (1980–2016) and the Far Future (2071–2100) according to the worst IPCC emission Scenario RCP8.5 (representing a no-policy mitigation baseline scenario). By counting the number of sites fitting into each Köppen-Geiger class in the Recent Past and comparing it with the ones in the Far Future scenario, it was possible to evaluate the expected changes in the climate classification of the reviewed case studies.

To better contextualise the discussion of the results from the climate mapping of the reviewed case studies, the location of the UNESCO sites enlisted in the World Heritage List (WHL) was also investigated. A subset of 255 strictly architectural sites was selected from the whole group of WHL sites distributed around the globe based on criteria II (i.e., those exhibiting “an important interchange of human values […] on developments in architecture, […] town-planning or landscape design”) and IV (i.e., those being “an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates significant stage(s) in human history”), excluding WHL sites having a prevalent archaeological and natural value (i.e., sites without the term “building” in their description). Finally, the WHL architectural sites were matched with their past and future Köppen-Geiger climate classes as described for the case of the reviewed case studies.

3. Results and discussion

The analysis of the 86 case studies reported in the reviewed articles highlighted that most of them are located in Europe, with the exception of two research works performed in Saudi Arabia and one in Canada (Fig.2). Italy can be considered the leading country in the field of dynamic simulation of historical buildings, where 60% of the studies have been carried out. This outcome, already observed in literature reviews dedicated to energy efficiency and thermal comfort in historical buildings, may be explained by both the richness of built heritage availability in Italy and the attained level of scientific development on the topic.

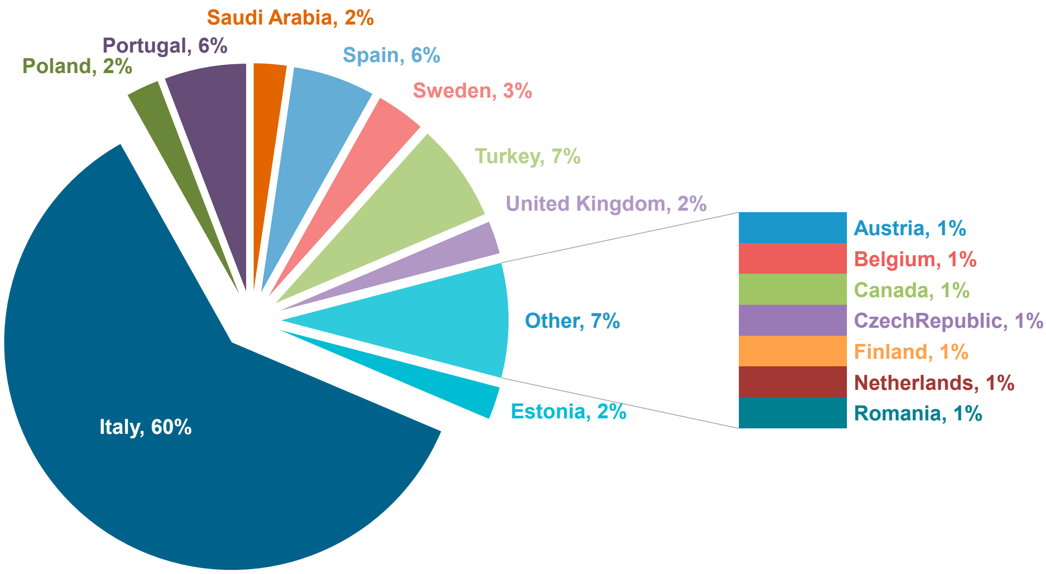

Fig. 2. Case studies per country (percentage out of the 86 reviewed ones) on the dynamic simulation of historical buildings for energy efficiency.

To study the possible impact of these changes in the indoor climate conditions within historical buildings and to investigate suitable adaptation strategies, climate projections from regional models have been employed in some of the reviewed studies in addition to present weather datasets. Among the reviewed case studies, 6 records (7% of the total) reported to use climate projections from regional models (in addition to present weather datasets) as an input for simulation to evaluate future energy consumption.

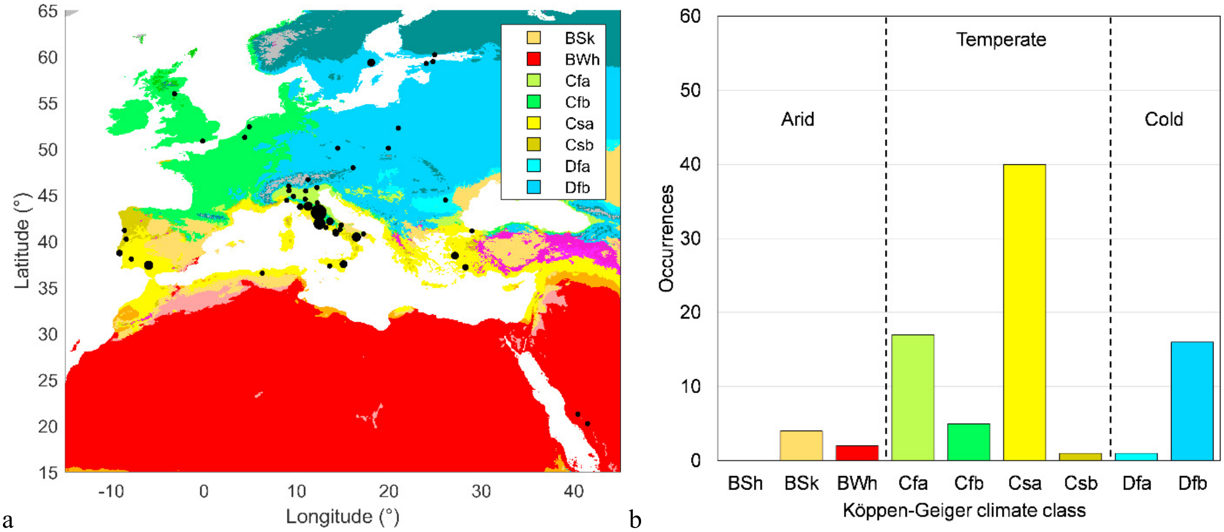

Fig. 3. (a) Köppen-Geiger (KG) maps in the Recent Past (based on Beck et al. 2018) with the location of reviewed literature case studies (indicated as black points of different sizes based on the number of occurrences in the same position) and (b) number of reviewed literature case studies in each KG climate class.

Fig.3 shows that in the Recent Past most of the 86 case studies reviewed from the literature are located in temperate climate classes (i.e., Csa = 40 sites, Cfa = 17 sites, Cfb = 5 sites) and cold climate classes (i.e., Dfb = 16 sites), representing together around 90% of the total. According to the climate classification in the Far Future (Fig. 4), the distribution of the climate classes paired with the reviewed case studies is expected to radically change: while the future occurrences in Csa are expected to increase (up to 55 sites), they are expected to considerably decrease in Cfa and Dfb (up to 9 and 3 sites, respectively); moreover, a substantial rise concerns the future number of case studies in BSh arid steppe climate class (from 0 sites in Recent Past to 6 sites in Far Future).

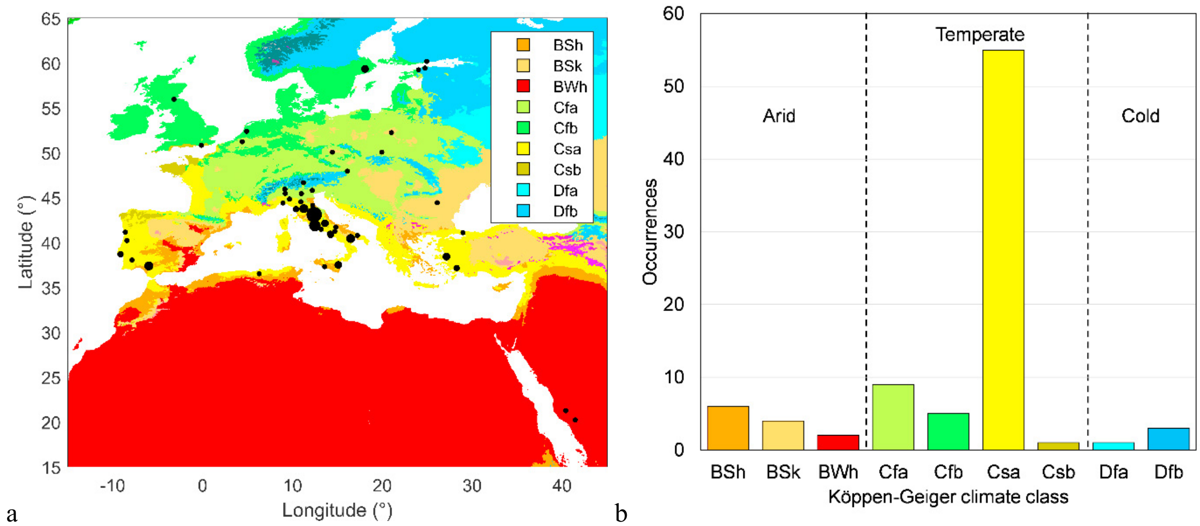

Fig. 4. (a) Köppen-Geiger (KG) maps in the Far Future according to IPCC scenario RCP 8.5 (based on Beck et al. 2018) with the location of reviewed literature case studies (indicated as black points of different sizes based on the number of occurrences in the same position) and (b) number of reviewed literature case studies in each KG climate class.

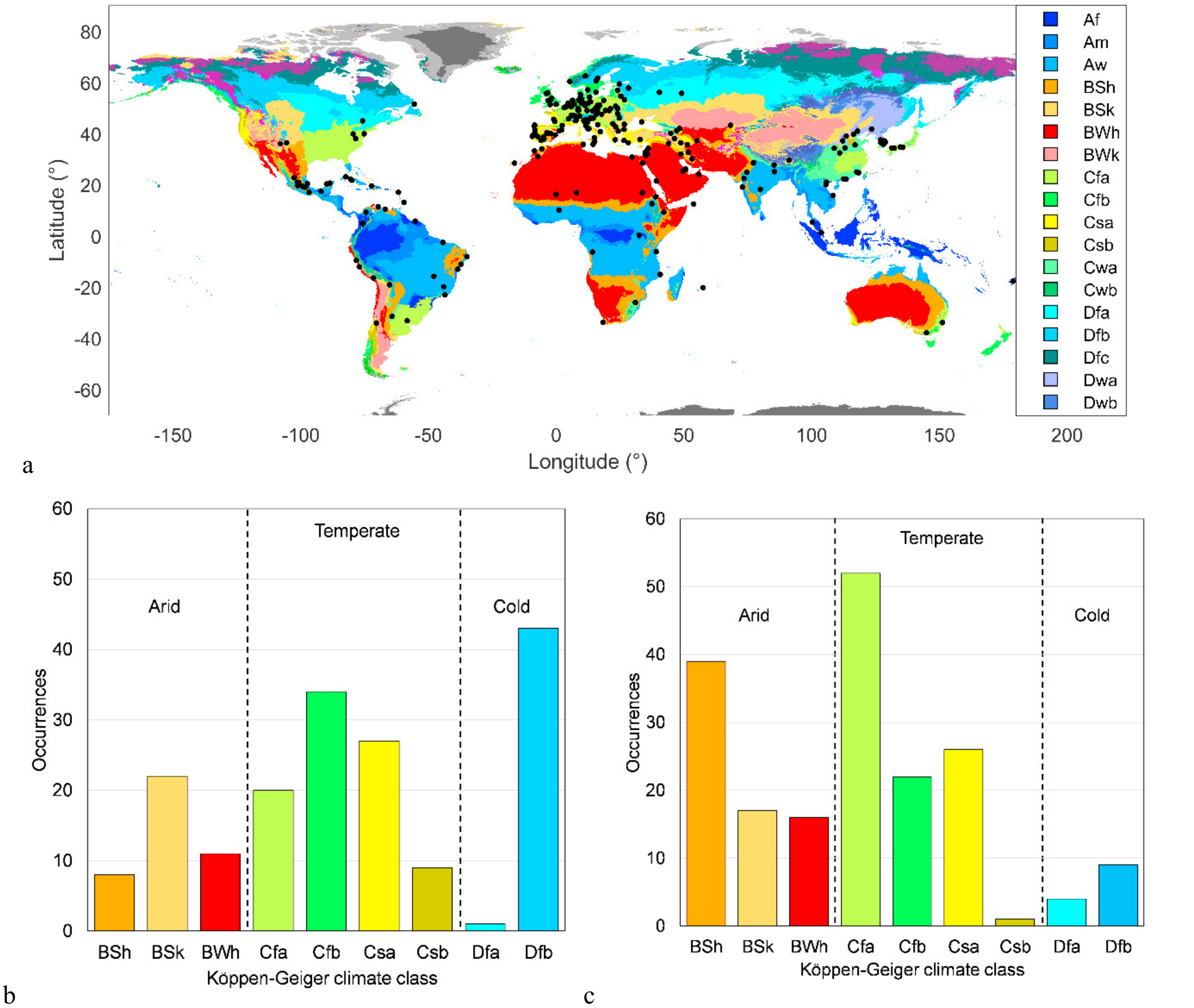

Fig. 5. (a) Köppen-Geiger (KG) maps in the Far Future based on Beck et al. (2018) with the location of the WHL architectural sites (indicated as black points of different sizes based on the number of occurrences in the same position) and (b, c) number of WHL architectural sites in each KG climate class in Recent Past (b) and Far Future (c).

Fig.5a shows the location of the 255 WHL architectural sites plotted on the global Köppen-Geiger classification maps for the Far Future, while the map for the Recent Past is not here reported for the sake of brevity. The distribution of the WHL sites around the globe covers 18 of the 30 existing Köppen-Geiger climate classes. In the Recent Past (Fig. 5b), the occurrences of WHL sites in temperate climate classes (i.e., Csa = 27 sites, Cfa = 20 sites, Cfb = 34 sites) and cold climate classes (i.e., Dfb = 43 sites) represent together around 50% of the total. In the Far Future (Fig. 5c), the number of WHL sites located in Cfa is likely to increase (up to 52 sites), while it is expected to decrease for Cfb and Dfb (up to 22 and 9 sites, respectively). A remarkable future rise is projected in the number of WHL sites in BSh arid steppe climate classes (from 8 sites in Recent Past to 39 sites in Far Future).

Table 1 provides the percentage of reviewed case studies and WHL architectural sites per each past and future Köppen-Geiger climate class calculated out of their respective total number. The climate classification in the Recent Past emphasized that the reviewed case studies mostly represent temperate climate classes Csa (47%), Cfa (20%), and cold climate with warm summer Dfb (19%), which overall cover around 90% of the sites. In the Far Future, the percentage of reviewed sites in Cfa and DFb is likely to respectively reduce to one-half and one to one-sixth of their values in the Recent Past, accompanied by a shift to Bsh for 7% of case studies.

Table 1. Description of the Köppen-Geiger climate classes (based on (Beck et al. 2018)) and percentage of reviewed case studies and WHL architectural sites in each class for present and future climate scenarios. * Percentage calculated out of the total number of reviewed case studies (n=86). ** Percentage calculated out of the total number of WHL architectural sites (n=255). It is worth noticing that the 9 climate classes considered (based on those represented by the reviewed case studies) cover 69% of WHL architectural sites in the Recent Past and 73% in the Far Future.

Abbreviation	Köppen-Geiger climate class description	Case studies*		WHL architectural sites**	
		Recent Past	Far Future	Recent Past	Far Future
BSh	Arid, steppe, hot	0%	7%	3%	15%
BSk	Arid, steppe, cold	5%	5%	9%	7%
BWh	Arid, desert, hot	2%	2%	4%	6%
Cfa	Temperate, no dry season, hot summer	20%	10%	8%	20%
Cfb	Temperate, no dry season, warm summer	6%	6%	13%	9%
Csa	Temperate, dry and hot summer	47%	64%	11%	10%
Csb	Temperate, dry and warm summer	1%	1%	4%	0%
Dfa	Cold, no dry season, hot summer	1%	1%	0%	2%
Dfb	Cold, no dry season, warm summer	19%	3%	17%	4%

Looking together at the percentages of both the reviewed case studies and WHL architectural sites, it can be noticed that the current understanding derived from the literature case studies in the temperate climate classes may be crucial to cope with the impact of climate change, as they are expected to represent more than one-third of WHL architectural sites in the Far Future. On the contrary, the high percentage of reviewed case studies currently in the cold climate class Dfb may be less beneficial, as the future percentage of WHL architectural sites in this class is expected to be very low. Finally, a current scarcity of scientific studies was highlighted in literature case studies located in arid climate classes, although they will likely represent a significant share of the WHL architectural sites in the Far Future.

5. Conclusions

The ongoing research on the application of whole-building dynamic simulation of historical buildings can greatly contribute to adaptation to climate change in terms of energy efficiency. The current understanding derived from literature case studies located in temperate climate classes can be decisive in designing effective and climate-change-proofed adaptation strategies, as the future share of architectural sites enlisted in UNESCO's World Heritage List (WHL) and located in these classes is expected to be high (almost 40% of the total). On the contrary, the relevant number of case studies currently in cold climate classes may be less beneficial as they will likely be less representative of future WHL architectural sites. A current gap in the reviewed research field was identified for arid climate classes, where few literature case studies were located despite the future percentage of WHL architectural sites in these classes is expected to be relevant (about 28% of the total).

Acknowledgements

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Climate Change monitoring with Art-Risk 5: New approach for environmental hazard assessment in Seville and Almería Historic Centres (Spain)

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Abstract

Currently, climate change is significantly impacting historic cities, altering energy demands, and influencing tourism patterns. In this context, the analysis of extensive datasets derived from satellite imagery offers a means to monitor the effects of climate change on both urban and territorial scales.

Art-Risk 5.0 is an open digital tool designed to easily track temperature variations, precipitation patterns, urban heat islands, and vegetation health using satellite resources. The applications in two historic cities in southern Spain, Almeria and Sevilla was analyzed to assess the impact of climate change.

The outcomes of Art-Risk 5.0 have provided valuable data for diagnosing the impact of climate change in these historic cities. The major climatic hazards identified in southern Spain are high temperatures, torrential rainfall, and droughts. Additionally, over the past 20 years, an increase in maximum temperatures and drought intensity has been observed in Sevilla and Almeria. On the urban scale, urban heat islands are concentrated in neighborhoods with limited green and blue infrastructure.

The ability to analyze time series of climate data from satellite images makes Art-Risk 5.0 an extremely useful tool for monitoring the impact of climate change and promoting sustainable adaptation policies.

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Keywords: Climate Hazards; Cloud Computing; Cultural Heritage; Geoespacial Analisys; Satellite Resources.

1. Introduction.

Climate change is affecting citizens and Cultural Heritage in historic cities. Increases in temperature, changes in precipitation patterns, and the occurrence of extreme weather phenomena such as heavy storms, floods, and wildfires have serious worldwide consequences (Bonazza, 2020; Cacciotti et al., 2021; Fatorić & Seekamp, 2017; Kapsomenakis et al., 2022; Sesana et al., 2018).

The impact of climate change on historic cities largely depends on the characteristics of each city and its ability to confront these threats (Bonazza et al., 2020; Crowley et al., 2022; Hofmann, 2021). For this reason, one of the main challenges for researchers is to gather information and develop efficient methods and digital tools to monitor climate hazards at the local level. Having this information is essential for developing comprehensive risk assessment. These models assess the presence of threats in the environment, the vulnerability of cities and populations, and their resilience, which is influenced by prevention and mitigation measures implemented by governments (Mendes et al., 2021). The primary advantage of these models is they enable the design of adaptation and mitigation measures tailored to the real needs and the evaluation of the effectiveness of implemented actions.

In this context, satellite resources have become a crucial and continuously expanding data source. Advances in remote sensing have significantly increased the variety of available satellite resources including multispectral images, Synthetic Aperture Radar images, estimated meteorological products, and climate reanalysis. These satellite products provide free, up-to-date, and consistent information for analyzing extensive areas over extended periods at local scale (Di & Yu, 2023).

The complexity involved in managing extensive satellite datasets has necessitated the development of new tools and methodologies, enabling cloud-based analysis. A prime example of this is Google Earth Engine (GEE) (https://earthengine.google.com/), a platform that stores satellite images collected by National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and other institutions over the past 50 years (Amani et al., 2020; Gorelick et al., 2017; Kumar & Mutanga, 2018). GEE stores vast amounts of satellite imagery in cloud-based storage, ensuring efficient retrieval. Users query these datasets through a web-based platform, specifying desired parameters. The platform processes and analyzes the data in the cloud, leveraging parallel computing for rapid results. Once analysis is complete, users can visualize results online or download them for further use. This system streamlines remote sensing tasks, making large-scale analyses feasible. However, a significant drawback of GEE is its absence of a desktop interface, a feature available in other satellite analysis software such as SNAP or ArcGIS. This limitation can be overcome through the development of web-based applications designed to visualize the analyses. The creation of these applications not only aids in accessing satellite data but also streamlines the process of extracting valuable information, thus enhancing overall usability. Currently, the analysis of large volumes of data in these types of applications allows for assessing vegetation health and density (https://abocin.users.earthengine.app/view/foresthealth), sampling soil carbon presence (https://charliebettigole.users.earthengine.app/view/stratifi-beta-v21), or promoting the conservation of endangered species (https://species.mol.org/species/map/Perdix_dauurica), among many other possible applications.

Applied to risk management in historic cities and cultural landscapes the significant potential of GEE, cloud analysis, and geo-big data analysis has been emphasized (Agapiou, 2017; Cuca & Hadjimitsis, 2017; Moreno et al., 2022a). The first methods to monitor hazards related to climate change in heritage environments and assess the reliability of satellite resources are very recent (Elfadaly et al., 2022; Moreno et al., 2022b). In this context, designing digital tools in GEE allows replication of the proposed methodologies in others study cases and enhances the impact of research. An example of this is Art-Risk 5 (https://artrisk50.users.earthengine.app/view/art-risk5), a digital tool that calculates statistical maps and sequential graphs with precipitation, temperature, and vegetation values using the methodology for analyzing series of satellite images proposed by Moreno et al. (2023b; 2022b).

This study aims to describe the architecture and functioning of the Art-Risk 5.0 system, as well as to assess its applicability as a tool for monitoring the climate impact at a local scale in historic cities. The analyses carried out in Art Risk 5.0 have aimed to address three key aspects: 1) Identify most hazardous areas in southern Spain based on temperature and precipitation; 2) Graph meteorological values of temperature and precipitation from the last 20 years in Seville and Almeria; 3) Monitoring the presence of Urban Heat Island (UHI) in Seville and Almeria.

2. System Architecture of Art-Risk 5.0 and methodology

Art Risk 5.0 (https://artrisk50.users.earthengine.app/view/art-risk5), current register number: IPRUPO2023-010) is a digital application that leverages the statistical calculation capabilities of GEE to compute descriptive statistics, including means, medians, standard deviations, maximums, minimums, and percentiles, based on pixel values within a time series of satellite images. Through the utilization of reducers, functions, and map algebra, it facilitates the analysis of meteorological image datasets to derive climatic maps and evaluate the environmental hazard level.

Art Risk 5.0 facilitates map creation across four key categories: 1) Precipitation: satellites like Persiann-Climate Data Record CDR (with daily data intake since 1982 and coverage extending from 60° S–60°N Latitude and 0°–360° longitude at 0.25° spatial resolution) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (with daily data intake from 1981 and a spatial resolution of 0.05 degrees) are utilized. Calculations provided include summation, maximum, minimum, and the Standardized Precipitation Index (SPI). 2) Land surface temperature (LST): Moderate Resolution Imaging Spectroradiometer (MODIS. intake of data daily since 2000. Spatial resolution of 250-500-1000 meters) is used to produce maps of daytime, nighttime, and differential temperatures, as well as a frost count. 3) Urban heat islands are identified using Landsat 8 (revisit time of 16 days, launched in 2013. Spatial resolution of 30-100 meters), highlighting LST index percentiles. 4) Vegetation health is gauged with MODIS on board of Terra and Aqua satellites, and Sentinel-2 (revisit time of 5 days. Spatial resolution of 10-20-60 meters), with a focus on Normalized Difference Vegetation Index (NDVI), percentiles post cloud corrections.

Art-Risk 5.0 has a user-friendly interface (Fig. 1) divided into two main sections: a control panel on the left, and an interactive map on the right. Within the control panel, divisions are made for period selection, climatic variable choice, and area of interest specification. The analysis period is determined through three inputs: year, starting month, and ending month, with constraints ensuring no selection before 2002. Once set, between one to three climatic variables can be chosen, and, if required, a preferred satellite is selected. The area of interest is defined either by country selection from a dropdown or by drawing on the interactive map. All countries located between latitudes 60°S and 60°N can be selected, which includes most European, Asian, African, American, and Australian countries. Now, it is available in Spanish and English version.

Upon selection completion and the "Calculate" button's activation, maps are generated at the bottom right. A section emerges to the map's left for map downloads of different variables as geotiff files. When clicked within the designated area, graphs depicting the climatic variable's annual progression from 2002 are displayed. An arrow icon on each graph allows for viewing in a new tab, with multiple download formats available (*csv, *svg, and *png).

In the application to Seville and Almeria downtown, Art Risk 5.0 enabled the mapping of accumulated precipitation values, extreme rainfall events, drought, maximum temperatures, and temperature fluctuations in southern Spain, as well as the generation of trend graphs depicting maximum temperatures and drought values recorded between 2020 and 2022 in the historic cities of Sevilla and Almeria. The produced cartography was downloaded and migrated to a GIS for normalization based on a traffic light-type hazard scale.

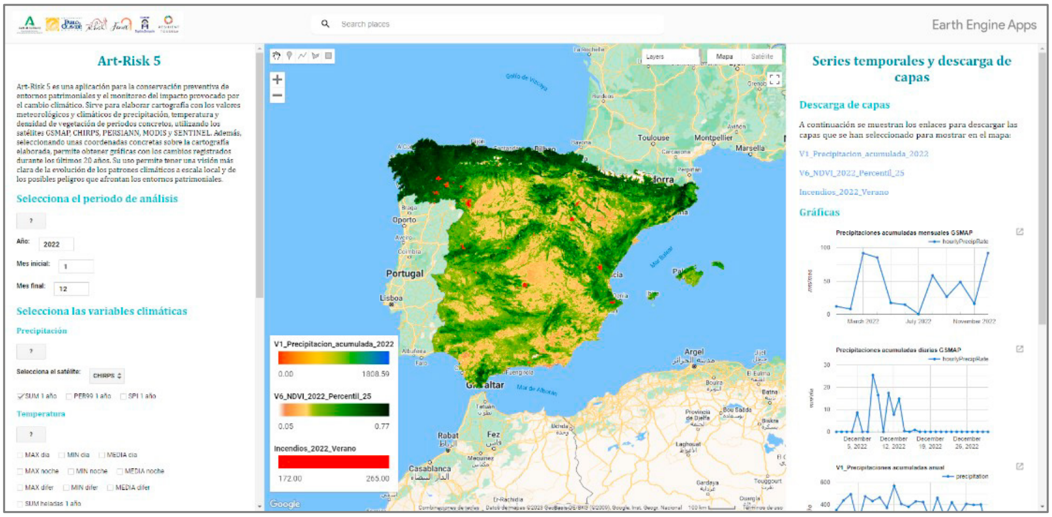

Fig. 1. Art Risk 5 interface (https://artrisk50.users.earthengine.app/view/art-risk5)

3. Climatic hazards and urban heat island in Southern Spain: Sevilla and Almeria

The maps obtained from Art-Risk 5.0 provide a visual representation of the climatic conditions in southern Spain and level of hazard of various meteorological factors. Figure 2 shows maps generated to assess maximum (a) and temperature fluctuations (b) based on MODIS LST images from 2022. All territory exhibits high hazard levels due to elevated LST, and particularly the Guadalquivir River valley in the centre of the region (Fig 2.a). Graphs (plots in Fig 2.a) show the same statistical calculations for the years between 2000 and 2022 for Seville and Almeria and confirm an increase in maximum temperatures in both cities, with Sevilla experiencing a more pronounced rise. Along the coastal areas, including Almeria, the moderating effect of the sea acts as a thermal regulator, reducing maximum temperatures and increasing minimums, thereby diminishing thermal oscillations (Fig 2.b).

Figure 3 presents the results of calculations from CHIRPS for accumulated precipitation (mm), intensity of extreme rainfall (mm), and occurrence of droughts (SPI) throughout 2022. In 2022, the Southwest region experienced more intense extreme precipitation (Fig 3.b), while the eastern region was the most affected by recurrent droughts (Fig 3.c). The geographical location and topography differences between Sevilla and Almeria result in distinct climatic peculiarities. Sevilla's proximity to the Guadalquivir River and its flat topography contribute to a continental Mediterranean climate, while Almeria exhibits an arid and desert climate. In this context, graphs (plots in Fig 3.c) illustrate SPI values for the past 20 years (2002-2021) in Sevilla and Almeria, indicating an increase in severity of droughts in recent years.

Figure 4 shows the local-scale impact of high temperatures recorded in Seville and Almeria in 2022, and the location of UHI according to Landsat images. UHIs are warmer microclimates resulting from factors such as building materials that absorb and retain heat, heat emissions from human activities like traffic and industry, poor air circulation, and a lack of vegetation in specific city areas. In Seville (Figure 4.a), UHIs are primarily found in the eastern neighbourhoods, which are distant from the river and green infrastructure, where heat-absorbing and heat-retaining construction materials are predominant. The city of Almeria has a larger urban area affected by UHIs, especially in neighbourhoods distant from the coast. The figures obtained for both case studies (Fig. 4.a and Fig. 4.b) highlight the essential role played by green and blue infrastructures in reducing high temperatures and creating cooler and healthier urban environments. This is mainly because rivers, coast, parks and gardens promote air circulation, provide shade, and have a cooling evaporative effect on the surrounding air (Veerkamp et al., 2021).

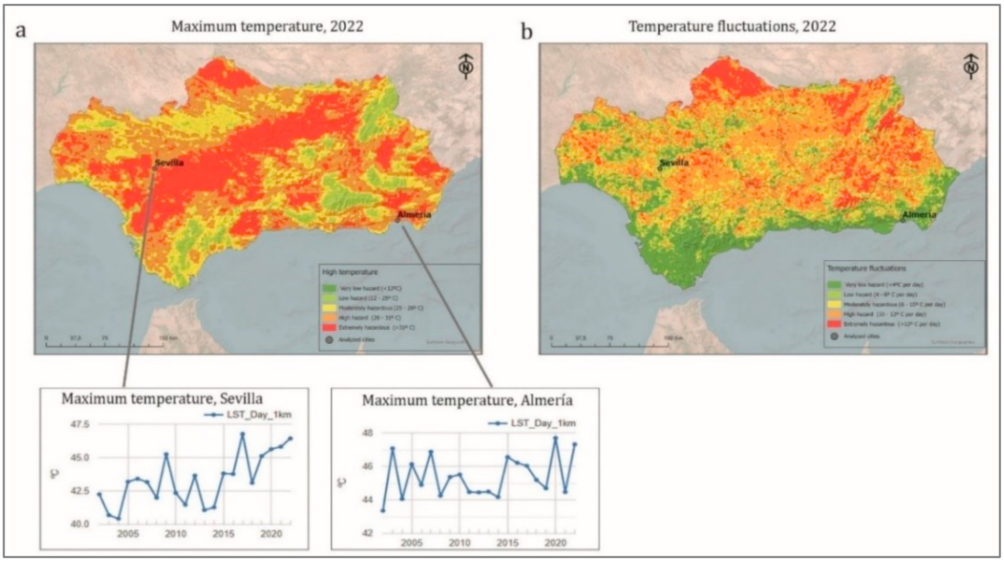

Fig. 2. Hazards by temperatures in southern Spain: (a) Map of maximum temperatures in 2022, and graph with maximum temperatures between 2000 and 2022 in Seville and Almeria; (b) Map of thermal fluctuations in 2022. Data obtained from Art-Risk 5.

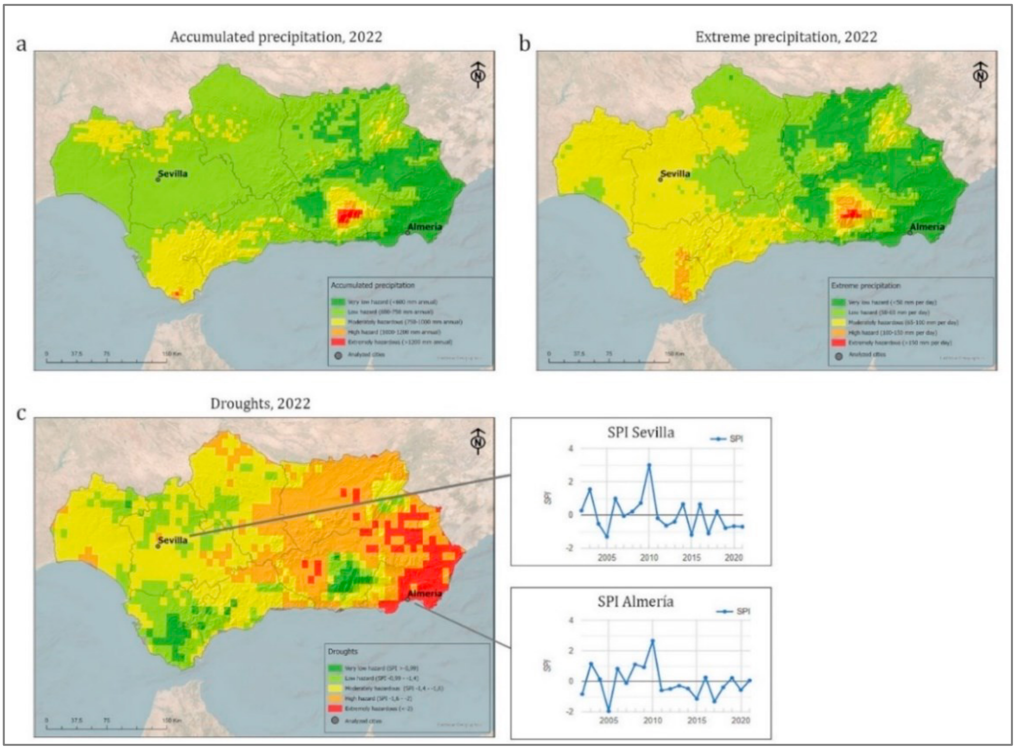

Fig. 3 Hazards by precipitation in southern Spain: (a) Map of accumulated precipitation in 2022; (b) Map of extreme precipitation in 2022; (c) Map of Droughts in 2022 and graph with annual SPI values between 2000 and 2022 in Seville and Almeria. Data obtained from Art-Risk 5.

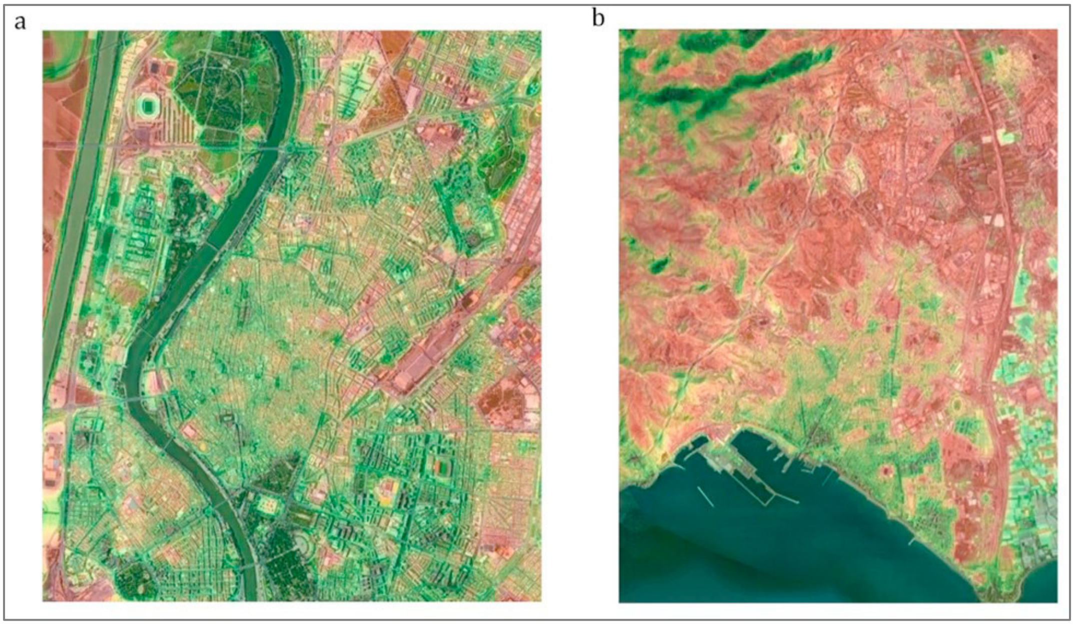

Fig.4: UHIs. (a) Seville; (b) Almeria. Green: cooler areas, red: warmer areas. Data obtained from Art-Risk 5.

4. Discussion

In this contribution an example of the effectiveness of ArtRisk 5.0 in visualizing precipitation and temperature hazards in Southern Spain, detecting the changes occurred in the last 20 years in Sevilla and Almeria, and in identifying the urban areas most affected by UHIs at a local scale, has been proved.

Cartography indicate that high temperatures, intense rainfall, and drought contribute to a high level of climatic hazard across much of southern Spain. This climate type is characterized by long, hot summers with temperatures often exceeding 30°C. In contrast, winters are mild, with temperatures rarely dropping below freezing. Precipitation is limited, typically concentrated during the autumn and winter months, often leading to the occurrence of heavy rainfall (Ministerio de Medio Ambiente, 2011).

The generated graphs revealed an increase in maximum temperature values in Seville and Almeria over recent years. These data suggest an alarming trend towards warmer and drier climatic conditions in the region, which could have significant consequences for the environment, cultural heritage, and society. The rise in droughts in Seville and Almeria align with other climate projections. Fig. 5 presents the Intergovernmental Panel on Climate Change (IPCC) forecast under the best-case scenario (SSP1-2.6), enabling a correlation of the recorded values in southern Spain with global precipitation climate trends. Even if the Paris Agreement (United Nations, 2015) is adhered to and greenhouse gas emissions are significantly reduced, changes in precipitation patterns are anticipated on a global scale (Masson-Delmotte et al., 2021; P.R. Shukla et al., 2020). According to IPCC forecast, an increase in droughts (yellow areas) is expected in all the Mediterranean basin, Central America, South Africa, and South America. Meanwhile, increased precipitation (blue areas) in Northern Europe, North America, Asia, and Africa heightens the risk of flooding in numerous historic cities.

In this context, the Art-Risk 5 tool facilitates the monitoring of climate change impacts at a local scale, enabling the generation of climatic hazard maps that can be seamlessly integrated into existing GIS models employed for heritage asset assessment and urban risk evaluation (Moreno et al., 2022c). Consequently, the utilization of Art-Risk 5 proves to be of substantial utility for historic city administrators.

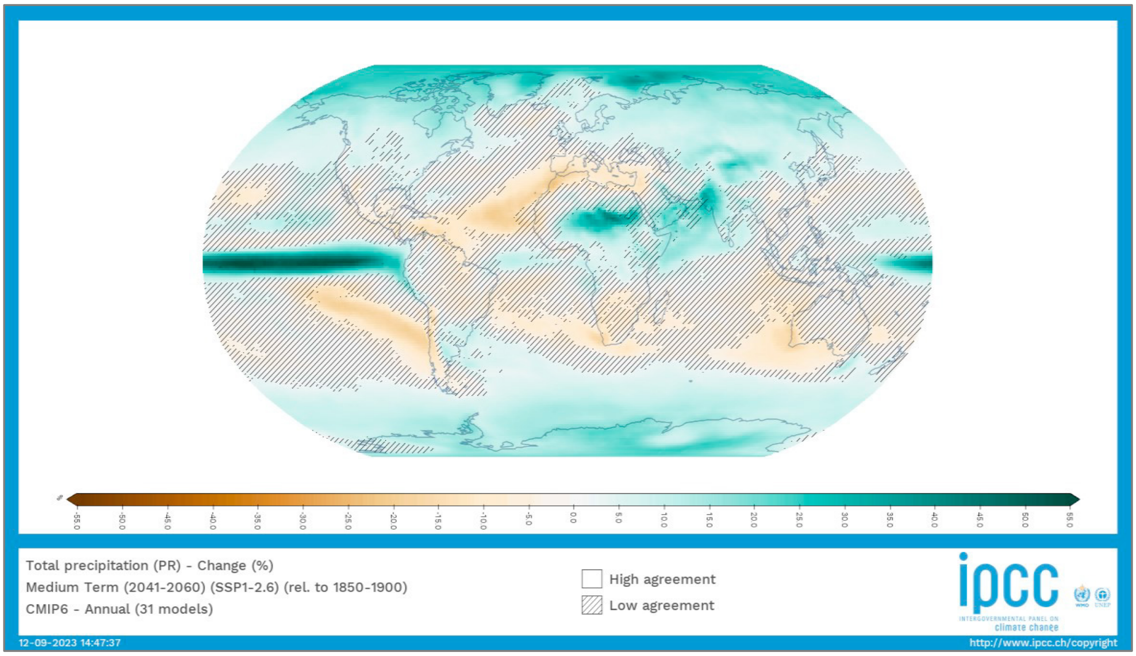

Fig.5. Forecast of mid-term precipitation patterns according to an emission scenario SSP1-2.6. Map obtained from the IPCC Working Group I Interactive Atlas (https://interactive-atlas.ipcc.ch/)

Further studies to integrate methodologies based on artificial intelligence into Art-Risk 5.0 could offer significant advantages. This combination could allow a retrospective assessment of critical environmental patterns using historical satellite imagery. Furthermore, the use of advanced algorithms would enhance analytical and pattern detection capabilities, expediting data processing and enabling real-time monitoring of environmental change impacts. This facilitates the identification of the most effective measures for climate protection and mitigation, thus contributing to well-informed decision-making in the context of sustainable management practices for historic cities.

5. Conclusions

Art-Risk 5.0 tool allowed to assess satellite data spanning up to 20 years, calculate climate statistics and maps of hazards in Seville and Almeria (Spain). This enabled to assess the level of hazard based on precipitation and temperature in southern Spain, with a focus on two historic cities: Almeria and Seville.

The results indicate that high temperatures, droughts, and heavy rainfall were the most hazardous factors. At the urban scale, the analysis of UHIs reveals that the presence of green and blue infrastructures in cities plays a protective role against high temperatures. Furthermore, analysis of satellite data from 2002-2021 revealed an increase in maximum temperatures and drought intensity in recent years in both Seville and Almeria. These results are aligned with the climate projections of the IPCC, which anticipate a continued rise in temperatures and the frequency of droughts between 2041 and 2060.

The situation observed in Southern Spain could have serious consequences for many historic cities if mitigation and adaptation measures to climate change are not taken. In this context, the use of digital tools like Art-Risk 5.0 by the urban managers allows and early anticipation and detection of climate and environmental changes, facilitating informed decision-making regarding available resources and the implementation of climate adaptation and mitigation measures. Additionally, Art-Risk 5.0 could help to assess the effectiveness of actions taken and contributes to raising awareness and promoting public understanding of climate issues.

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Condition assessment of timber in the old built heritage - a case study

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Abstract

Where the rehabilitation and repair of ancient buildings is prevalent, the primary focus is on preserving existing materials and construction techniques. To achieve this, it is crucial that technicians have the expertise and tools to assess the value of traditional materials. This article introduces a practical methodology for identifying and evaluating the physical-mechanical properties of wood in ancient ordinary buildings. The study is grounded in the latest technical-scientific guidelines at the European level and adheres to grading rules defined by European regulations, which have been adapted for structures in service. The methodology also addresses the assessment of widespread biological degradation. The study provides a robust foundation for the technical implementation of in-service inspection actions for wooden structures in built heritage in Portugal and Europe, but its findings can be extrapolated to other countries as well. As a practical illustration, we present and discuss the assessment of a beam representative of a 19th-century ordinary building's wooden floor structure. In this case study, we applied a practical and viable assessment strategy, supported by an on-site inspection procedure. We conclude that inspection work is fundamental to underpinning a well-structured project and that equipping technicians with experience in working with ancient buildings and a practical and straightforward methodology is key to successful condition monitoring. This work forms part of the research activity conducted at Civil Engineering Research and Innovation for Sustainability (CERIS) and has been funded by Fundação para a Ciência e a Tecnologia (FCT) as part of project UIDB/04625/2020.

Keywords: Timber, condition monitoring, built heritage, conservation; rehabilitation; biological degradation; assessment; visual strength grading

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1. Introduction

Rehabilitating the old buildings that fill the centers of most cities in Europe is a concern of growing importance that is recognized by decision-makers, both from a social, heritage and tourist point of view. Intervention in ancient residential buildings, most of which date from the late 18th century to the early 20th century, requires specific techniques and knowledge. In Portugal, most of these buildings are made up of masonry and timber as structural members. Timber is found in floors, stairs, and roofs, as well as inside the walls, creating an earthquake-resistant braced structure. However, the lack of a pragmatic approach to assessing wooden members in traditional buildings has led to a lack of interest in keeping this original construction technique by many technicians responsible and the consequent choice to demolish the existing structures as the best way to avoid any inconvenience.

To avoid this misconception, the right intervention approach should include a reliable assessment of timber structural condition that avoids the removal of many of the wooden elements in our heritage. In order to achieve redundancy in the assessment of timber members, correlation between non-/semi-destructive testing (NDT/SDT) techniques and wood properties are currently under significant scientific development, as can be seen in essential publications in literature as Kasal &. Tannert (2010), Dietsch & Köhler (2010) and Machado et al. (2015).

Regarding the type of NDT/SDT techniques that exist or are being developed, they can be characterized as mechanical, acoustic, and imaging. The mechanical methods, which are all less recent and well-established, are represented by drill resistance, penetration resistance, screw withdrawal and core drilling technique. The effectiveness of these methods is very well proven by science and practice, and they are very reliable, inexpensive, simple to apply in situ and to interpret the results (Piazza and Riggio, 2008; Tannert et al., 2014, Kloiber et al., 2014, Feio & Machado, 2015, Nowak et al., 2016; Frontini, 2017; Shaparov et al., 2019; Parracha et al., 2019). On the other hand, the most recent methods, which are already well implemented or under development, are mostly represented by acoustic or imaging tests. These include ultrasonic echo methods, ground penetrating radar, sonic or ultrasonic tomography, ultrasonic time-of-flight measurements, X-ray radioscopy, NIR spectroscopy or laser scanner, among others (Dackermann et al., 2014, Riggio et al., 2015; Wedvik, 2016; Cabaleiro et al., 2019; Vössing & Niederleithinger, 2018; Linke et al., 2019; Shabani et al., 2020, Rodrigues et.al., 2021).

Although mechanical, imaging, and acoustic methods are being tried and used in practice, Visual Strength Grading (VSG) still remains the established basis for assessing timber structures. It was the first non-destructive testing method and is still considered a fundamental tool for assessing timber structures (Cruz et al., 2015; Kasal & Tannert, 2010, Piazza & Riggio, 2008). Reasons for this are its apparent simplicity of application, no need for any special equipment, long experience gained from its use and its establishment in wood classification standards. Most of these methodologies were designed for new wood, prior to their one-site application. However, these strategies can also be adapted for use in existing buildings, with the necessary modification (Cruz et al., 2015).

For all the reasons explained above, it is considered that the combination of information from different sources is the more accurate way to assess the condition of timber members in service. This combination of information can be done using direct readings to calibrate the indirect readings taken in situ, which includes the validation of previously obtained regression models (Kandemir-Yucel, 2007; Henriques et al., 2011; Machado et al., 2015; Feio & Machado, 2015; Parracha et al., 2019; Morales-Conde, 2014, among others). Linke et al (2019) argue that to determine material properties accurately and reliably, VSG should always be combined with NDT or SDT methods.

This paper presents a methodological sequence for assessing timber members in service and developing, in somewhat detail, a case study of the assessment of a beam integral to a floor of a 19th century building. This assessment uses direct and indirect readings from visual inspection, penetration resistance testing, moisture content and core extraction for laboratory analysis. Finally, visual strength grading is carried out and all data collected are integrated together.

2. Assessment methodology

Flowchart in figure 1 summarizes the interactions between techniques, processes, and results within the scope of the recognition of timber structures in service. The 2nd part, corresponding to "Structural Analysis" is not under the scope of this article but is shown in the flowchart in figure 1 as it is the sequence to be followed by the previous actions.

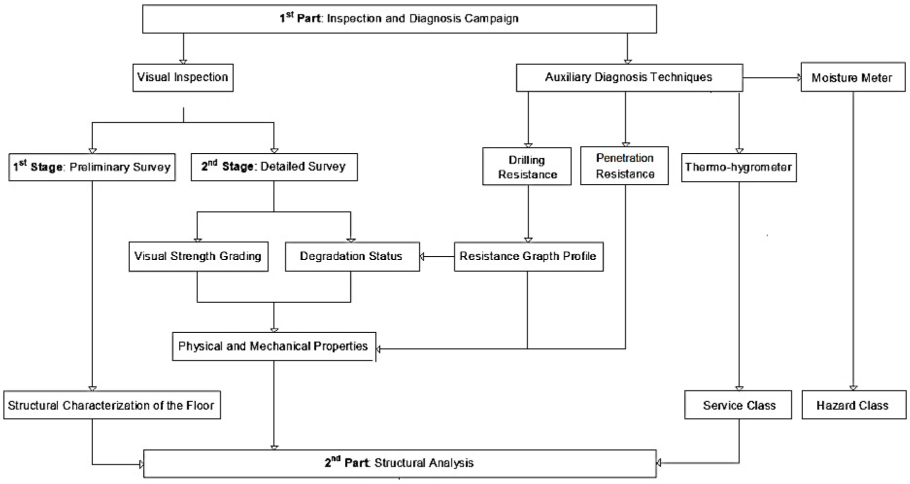


Fig. 1. Flowchart summary of the methodology to be adopted in the assessment of in-service wooden structures.

Before rehabilitating a building, the main concern is to recognize the structural and physical condition of its constructive elements. This can be a complex process, especially in timber structures, due to the diversity of deterioration mechanisms to which they can be subjected. Wood is susceptible to physical, chemical, and biological degradation agents. The agents that are most active in leading to wood degradation inside the building are biological agents. The process of assessing the hazard of biological degradation in construction considers two parameters: use class (EN 335-1:2013) and natural durability (EN 350-1:2016, Maxime et al., 2019). While the former deals with the types and intensity of biological degradation depending on the conditions to which the structure is exposed, the latter refers to the "intrinsic resistance of wood to attack by destructive organisms" (EN 350-1:2016). It is therefore important to know in advance what types of degradation we are likely to be looking for at each location in the structural timber element. A fundamental aspect in identifying the biological agent of degradation is the distinction between dry and damp wood, since rot fungi and subterranean termites only affect damp wood, with moisture content values above 20 percent. Inside buildings, you should expect all the wood to be dry. Cruz & Nunes (2012) point to an equilibrium value for water content in interior applications of old buildings (dry wood), which is in the range of 14 to 18 percent. Excessive humidity will only appear in the event of anomalies, which may be due to design, manufacture or lack of maintenance. In these situations, it is common to observe symptoms, such as stains, which suggest the continuous existence of water, both in the past and in the present.

Visual inspection covers all the global analysis actions, such as a general survey of the structure and the causes of the damage (active or extinct water intakes, overloading, design errors, among others), the location of the degradation, its level of severity and extent, and an assessment of the state of the connections. The intensity of the degradation, when it is caused by biological factors, can be assessed by directly analyzing the wood with a knife or another sharp object, detecting the presence of soft, crumbly material and looking for the area of intact material in the cross-section, i.e., the effective or residual cross-section. This includes an initial inspection, with the aim of characterizing the system structurally and assessing its general condition.

A detailed inspection will be carried out later, if it is considered that there are reasons to gain a deeper understanding of the timber structure (repairs due to visible poor behaviour, change of use of the building, among others). A distinction needs to be made between historic structures and other existing structures, even though many of the assessment methods are common to both. For historical structures, reinforcement should be considered as a last resort. If such intervention becomes necessary, it should be minimal and may necessitate the use of more precise and sophisticated techniques compared to those employed for other existing structures. This could lead to additional costs that would not typically be justified, as can be read in Cruz et al. (2015).

This study presents an example of a reliable approach using inspection and diagnosis based on accessible documents, for application to ordinary buildings.

3. Case Study: Inspection and assessment of a floor structure beam

A campaign was carried out to apply the principles of inspection in situ to an ancient building. The building, originally built at the last quarter of the 19th century, made of masonry and pine wood (Pinus spp.), is located in the historic center of Lisbon. The evaluation of beam V1 (Fig. 2), which is part of a floor, involved the following test methods:

- Survey of the wood member's moisture content.
- Identification of the geometric conditions and state of conservation of the structural members.
- Characterization of surface hardness of structural members with penetration resistance tests.
- Extraction of cores for laboratory study.
- Grading of some representative beams using the VSG methods.

3.1. Physical and mechanical characterization

3.1.1. By visual inspection

Beam V1 comprises part of the second floor of the building. Visual analysis identified two critical sections SC1 and SC2 (Fig. 2 (b)), which can be defined as having a combination of knots and being close to the mid-span, i.e., in areas with high stress levels (Cruz et al., 2015). The inspection was carried out as follow: the visual analysis showed that both the beam and the adjacent ones were of poor quality, poorly squared and very irregularly cut, with several occurrences of single or double wane, combination of knots, fissures, and woodworm or wood boring beetle damage. The dimensions of beam V1 were surveyed (Fig. 2 (a)), and it was found that the cross-section varied considerably along its length. Fig. 2 (c) shows the beam in profile, highlighting the double wane. As for the beam water content, seven measurements were taken, of which the highest and lowest were rejected. Measurements showed that the wood was perfectly dry. There were also no signs of high moisture in the wood in the past.

Possible signs of degradation by biological agents have been looked for. No degradation by subterranean termites or rot fungi was detected. However, there were signs of xylophagous beetle infestation quite intensely on the edges and face of the beam. It is known that this type of degradation is limited to sapwood in pinus spp species (EN 350:2016) and is generally superficial in the wooden element. This was confirmed by the tests carried out, so a continuous strip of around 1 to 2 cm on both the edges and the face could be considered useless. On the other hand, the strong blurring, usually double, reducing the dimensions of the edge and face to less than 2/3 of the dimensions of the piece, also means that only part of the section was useful. Thus, deducting the effect of biological degradation and shrinkage from the section, an effective (residual) cross-section of 8.5 x 13 cm was obtained for beam V1, as shown in Fig. 2 (a). It is worth noting the presence of cracks, generally radial and visible from the lower edge. These cracks did not run through the thickness and were between 1.0 and 1.5 m long.

Fig. 2. (a) Beam cross-section; (b) The floor and beam V1 with critical cross-sections; (c) Beam V1 in the zone of critical cross-section 2.

3.1.2. By penetration resistance tests

Penetration resistance testing was also carried out using a device for measurement of the resistance to penetration with energy of 6J, originally called pilodyn®, in areas with no apparent degradation. Seven tests were performed and the highest and lowest were rejected. The five readings considered suitable are shown in Table 1, with the values for each, their average and standard deviation. The estimated values for density and mechanical strength, obtained by correlation with the average of the measurements, are also presented. These correlations are the result of studies carried out by the first author published in Henriques et al. (2011) and Henriques (2024), from which the correlation equations (1) and (2) respectively, were drawn:

Compressive strength:

$$\sigma_i = \frac{(Depth_i - 30{,}409)}{-0{,}3572} \quad \text{(MPa)} \tag{1}$$

Density:

$$\rho_i = \frac{(Depth_i - 32{,}295)}{-0{,}0309} \quad \text{(kg/m}^3\text{)} \tag{2}$$

Where:
- σ_i – estimated compressive strength of reading i
- $Depth_i$ – reading i
- ρ_i – estimated density of reading i

3.1.3. By collection of wood cores and laboratory analysis

As the collection of wood cores is a semi-destructive test, only one or two specimens were taken from each beam to check the values obtained from the penetration resistance tests. In the beam V1 one wood core was extracted. The wane zone was chosen for the extraction to ensure the radial / orthogonal direction to the rings, in order to accurately measure the growth rate (Fig. 3 (a)). Wood cores of the members were extracted using a 14 mm diameter cutter, which resulted in cuttings with a diameter of 7 mm and a maximum length of 16 cm (Fig. 3 (b) and (c)).

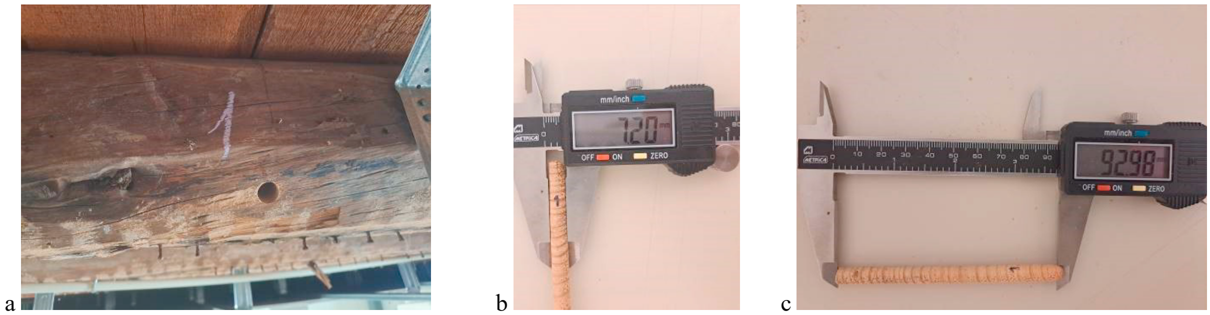


Fig. 3. (a) Location of the wood core hole; (b) and (c) Measuring the dimensions of the wood core

From the laboratory analysis of the wood cores, it was possible to:

- estimate the species of wood as Scots pine (Pinus sylvestris, L.);
- observe that the growth of the wood was fairly regular, with a normal distribution of rings between the pith and the bark, with an average growth rate of 4.22 mm/year.
- measure the dimensions and mass of the sample to calculate the wood density, after stabilization in a conditioned environment at RH = 65 ± 5 % and T = 20 ± 2 ºC which lead to a water content of 12%.

The beam V1 had a low water content, with the average value of the measurements being 9% (table 1). However, the laboratory test on the wood core was carried out with a water content of 12%. For this reason, the density estimated by the *in situ* penetration resistance tests was corrected in order to make a proper comparison with the real density values obtained in the laboratory. For this correction, we used the empirical expression published by

Carvalho (1996) for calculating the reference transverse tension strength from values obtained in wood with moisture contents other than 12% (Equation 3).

$$\sigma_{t12} = \sigma_{tH}[1 + k_3(H - 12)] \quad (3)$$

Where:
- k_3 is generally considered equal to 0.015
- σ_{t12} – reference transverse tensile strength for MC = 12%
- σ_{tH} –transverse tensile strength for H%
- H – MC different from 12%

Table 1 shows data obtained from in situ tests (moisture content and penetration resistance) and from laboratorial tests. The real density data was obtained from the wood core that was extracted and compared with the values estimated by the penetration resistance test. There is an excellent agreement between these values, with a discrepancy of less than 5%. Both sets of data indicate a low wood density. Based on this, the conclusion can be drawn that the penetration resistance test is a reliable method for estimating wood density, as it closely aligns with the actual density data obtained from the extracted wood core. Furthermore, both methods consistently indicate that the wood in question has a low density.

Table 1. Data from in situ and laboratorial tests

	Moisture content (H%)		**Penetration test (mm)**			**Penetration average corrected for H% (mm)**	**Estimated average compressive strength (MPa)**	**Density (kg/m³)**		
	each test	average	each test	average	Std (mm)			**Estimated** *(penetration)*	**Real** *(core)*	Differential (%)
Beam V1	8.7		19.5							
	9.5		18.5							
	8.8	9.0	20.5	20.7	1.9	19.8	**27.2**	**405**	**387**	4.8
	9.1		21.5							
	9.0		23.5							

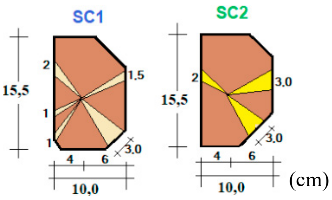
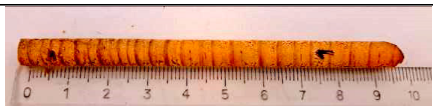
3.2. Visual Strength grading

Beam V1 has two factors described in the standard BS 4978:2007 as leading be excluded from the grades: insect damage and wane that reduces the full edge and face dimensions to less than 2/3 of the dimensions of the piece. However, since it is considered that the beam will be reduced to its residual cross-section for rehabilitation purposes, these two hindering factors no longer exist or become irrelevant. In the case of elements in service, it is not important to know whether the element shows signs of biological degradation. What is important is to quantify the extent of this degradation to estimate the loss of the member's resistance capacity (Machado et al. 2009). In order to strength grading the structural member, two critical sections SC1 and SC2 were analysed. These critical sections were defined according to Cruz et al (2015): both are located near the mid-span, simultaneously combining the highest stress state with the occurrence of combinations of knots and double wane. The beam was graded according to significant parameters for wood in service (Machado et al, 2009): knots, slope of grain and rate of growth, in accordance with BS 4978:2007, since it is Scots pine. The authors decided to also consider fissures due to their extent. Wane and biological degradation will be removed by considering only the effective cross-section of the member as relevant. This standard establishes parameters and measurement criteria that can lead to two grades: General Structural (GS) or Special Structural (SS). Table 2 shows the values and grade obtained.

3.3. Conclusion of the case study

The conclusion is that the beam can be classified as class GS, which for Scots Pine corresponds to strength class C14, according to NP 1912:2013. This class allows for an average density of 350 kg/m³, according to EN 338:2016. The tests carried out showed that the beam has a density of around 400 kg/m³, representing safety in relation to the class. Regarding compressive strength, this class allows structural members to have a characteristic value of 16 MPa or higher, according to EN 338:2016. The average value estimated for the beam is 27.2 MPa, which also represents safety in relation to the class. Its wane and biological degradation lead to the consideration of an effective (residual) section of 8.5 x 13 cm. With the data collected, it is possible to carry out a structural analysis. If the decision is made to retain this beam in the structure, it will likely require reinforcement.

Table 2. Visual Strength grading of the beam V1 according to BS 4978:2007.

Key VSG	Measurement of characteristics versus VSG standard criteria		GS	SS
Knots		cross-section SC1 has a larger knot area: $TKAR_{SC1} = 21,5 / 137,5 = 0,16 < \mathbf{1/2}$ $MKAR_{SC1} = 5,75 / 32 = 0,18 < \mathbf{1/3}$		X
Slope of Grain		Slope of grain ≈ ***0***		X
Rate of Growth		Ring width$_{average}$ = *75/2* = *3,57 mm* < ***6 mm***		X
Fissures	Not through the thickness and not longer than **1.5 m**		X	

4. Conclusion

This study underscores the criticality of conducting thorough diagnoses of structural timber conditions in historic buildings. A variety of diagnostic methods are available, some of which are well-established, while others are still in the developmental phase. The Visual Strength Grading (VSG) methodology is a proven and reliable approach, especially when used in conjunction with Non-Destructive Testing/Stress-Diagnostic Testing (NDT/SDT) methods. Its application to in-service timber members should be grounded in fundamental features such as knots, grain slope, and growth rate, with other defects and characteristics analyzed on an individual basis. The case study demonstrated that data gathered through visual inspection, penetration resistance testing, and VSG can effectively support the structural analysis of existing buildings. This is since data has been obtained from a variety of methodologies, which have been meticulously correlated and integrated.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Development of a hybrid timber and aluminum based unitized façade system resilient to the future weather conditions in Europe via monitoring campaigns and computational models

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Abstract

The StaticusCare project aims to develop a hybrid timber and aluminum unitized façade system (HUF) equipped with a predictive maintenance system (PMS) for Nordic climates, which will be based on the digital twin concept and fed by an Internet-of-Things system. The use of timber in the structure elements of the façade system aims to reduce the typical system's CO_2 footprint by 70–75 %, and the non-renewable energy consumption by 53–56 %. Nonetheless, ensuring that this novel system is durable in the Nordic current and future climate conditions is necessary. For this purpose, the HUF system will be installed in a two-floor building, monitored by a multi-sensor campaign, and replicated computationally to assess the energy use and indoor environmental quality, as well as the hygrothermal performance of the building elements for contemporary climate and under various climate change scenarios. The maintenance of the buildings with the façade system installed will be based on a PMS that is backed by an open-source python heat, air, and moisture transport (HAM) software. This one-dimensional software will be validated using a commercial one. To analyze specific problems, such as air infiltration and moisture entrapment, a two-dimensional HAM model will also be developed. In addition, building energy simulations will be performed to test several parameters affecting the indoor climate quality and energy use. Finally, the current outdoor weather files for the HAM simulations will be built based on multi-year datasets following the ISO 15927-4 methodology and the Perez model, whilst the future weather files will be based on multi-year datasets following the same methodology for two future scenarios. This multi-step methodology will allow to thoroughly test and design the HUF façade system whilst minimizing the risk, e.g., mold growth, for current and future conditions.

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1. Introduction

It has been widely recognized that pervasive changes have to be performed, at all levels of our society, to mitigate climate change and its expected negative effects, by reducing the anthropogenic greenhouse emissions drastically. This scope has led the industry and the scientific community to work on developing more environmentally friendly solutions.

In the construction sector, one of the solutions is to use, for example, building materials that are less energy intensive, such as timber (Ahmed & Sturges, 2015), and, therefore, have lower embodied energy and CO_2 emissions. Another positive aspect of timber is the fact that contrary to most of the materials used in the building construction sector, timber is a renewable material within a human lifespan. This is of the utmost importance nowadays due to the great construction levels as well as the fact that materials are a limited resource (European Commission, 2020).

Bearing all the above considerations in mind, an innovative hybrid unitized façade (HUF) system has been created in the context of the StaticusCare project (StaticusCare, 2022), financed by EEA and Norway grants. This more sustainable façade uses glulam timber to replace part of the typical aluminum frame system, while offering equivalent structural performance for this type of application. Timber has a typical embodied energy of 4.6 MJ/kg and embodied CO_2 of 0.4 tonnes CO_2/tonne (Ahmed & Sturges, 2015) and aluminum has a typical embodied energy of 201.0 MJ/kg (ca. 44 times higher than glulam timber) and embodied CO_2 of 15.1 tonnes CO_2/tonne (ca. 43 times higher than glulam timber) (Ahmed & Sturges, 2015). Hence, it is easy to understand why this is a better façade system by means of climate mitigation, aside the good mechanical, thermal capability of wood, among its other positive characteristics (Pastori et al., 2022).

In addition, since it is a unitized system, it can be quickly installed compared with traditional façade systems. This feature is extremally interesting because it has the advantage of protecting quickly the building envelope and the indoor environment from outdoor damaging sources (e.g., precipitation). Finally, the HUF system will include Internet-of-Things (IoT) sensors to be able to feed the digital twin models, which will be integrated into the building maintenance system (BMS) to safeguard the building, as well as its indoor environmental quality (IEQ).

However, due to the innovative nature of this system, it is necessary to prove that it behaves appropriately in a given climate, and that it will be able to withstand current and future conditions during its service life. The multi-step methodology, as described in the following section, has been created for this purpose. In addition, as shown by (Pastori et al., 2022), a great number of studies can be found in literature about the benefits of using a unitized system in terms of their structural behavior, but only a small number deal with their hygrothermal behavior and environmental impact. This study also intends to increase the knowledge of this type of system. Finally, this paper summarizes the multi-step methodology that will be followed to achieve the previously stated goals. More detailed information for each step can be found in these references (Coelho & Kraniotis, 2023a, 2023b; Loli et al., 2024; Ostapska et al., 2023).

2. Methodology

2.1. Step 1: Case-study with HUF system

The Hybrid Unitized Façade (HUF) system will be installed in a two-store building in order to assess its hygrothermal performance and to study the indoor climate quality. The building is located in Vilnius, Lithuania, which is classified as a humid continental climate with a Köppen classification of Dfb (Kottek et al., 2006). Vilnius has a humid and cold winter, where the temperatures are frequently below zero, and a humid and warm summer, while it has a moderate precipitation throughout the year.

The existing building façade (Figure 1a), which has a northeast orientation, will be replaced by the HUF system (Figure 1b). The HUF is composed by three different zones, namely: Section A) Opaque zone – bent tin sheet, mineral wool insulation, enameled glass (U-value = 0.13 W/(m^2K) (Coelho & Kraniotis, 2023b)); Section B) Frames – made from glue laminated timber beams and aluminum (U-value = 0.38 W/(m^2K) (Coelho & Kraniotis, 2023b)); and Section C) Transparent zone – triple glazed glass unit (U-value = 0.50 W/(m^2K) (Coelho & Kraniotis, 2023b)).

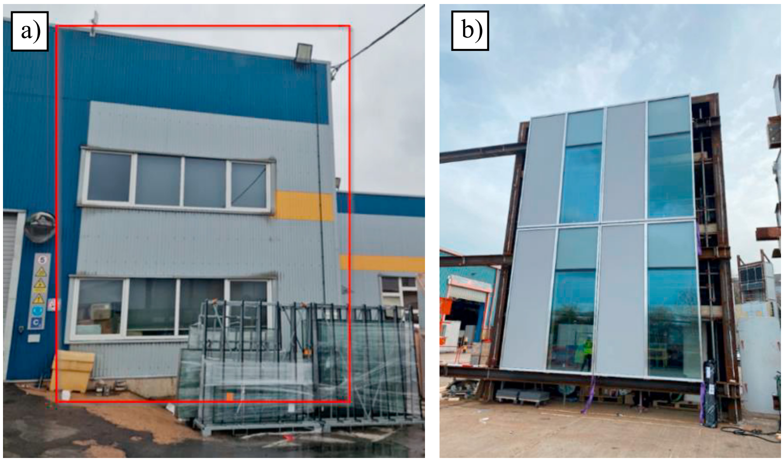

Figure 1 – Building where the HUF system will be installed and monitored (a) and example of four units of HUF system (b)

2.2. Step 2: Monitor the case-study

The monitoring campaign that will be installed in the case-study will act at three different levels, namely: 1) indoor climate, 2) surface and interior HUF and 3) outdoor climate.

The *indoor climate* will be monitored firstly to assess the quality of indoor climate (with and without the HUF system) in terms of thermal comfort, visual comfort, indoor air quality and energy consumption. Objectively, the following indoor parameters will be measured at different locations and heights, namely: 1) air temperature, 2) relative humidity of air, 3) mean radiant temperature, 4) air velocity, 5) illuminance, 6) CO_2 and 7) total VOC.

These values can also be used to build spatial interpolation-based maps, which allow the assessment of the indoor climate quality to perform the necessary changes, if need be (e.g. (Yu et al., 2021)). Subsequently, registered data – air temperature and relative humidity – will be used as inputs for the one-dimensional model. This data will also be used for model calibration for the whole-building models, i.e., WUFI®Plus and IDA ICE.

The conditions in the *interior of the HUF system* and *in their surface* will be used to both assess the hygrothermal performance of the HUF system, and to calibrate the one-dimensional models. The hygrothermal performance of the HUF will be assessed in terms of: 1) mold growth, 2) surface and interstitial condensation risk, 3) air permeance and 4) transient U-value. Subsequently, the following parameters will be measured at different locations of the façade, namely: 1) temperature, 2) relative humidity, 3) moisture content and 4) air infiltration.

Finally, the *outdoor climate* in the vicinity of the case-study will be monitored using a complete outdoor station that will measure, at least with hourly frequency, the following meteorological parameters: 1) air temperature, 2) relative humidity of air, 3) air pressure, 4) global radiation, 5) diffuse radiation, 6) long-wave counter radiation, 7) precipitation, 8) wind direction and 9) wind speed. These values will be used to explain the indoor behavior, and to build the necessary weather files for simulations, e.g., .wac file for WUFI and .try file for IDA ICE. Finally, the CO_2 and total VOC will also be monitored outdoors to establish relationships with the respective indoor climate measurements.

2.3. Step 3: Building modelling

The building modelling will be performed by two different types of strategies, namely: SketchUp and Revit. In WUFI®Plus, the geometry of the building can be developed externally by one of these two software. SketchUp allows for a rapid generation of complex geometry. Revit, on the other hand, can be coupled with other stages of designing and constructing the building, i.e., via BIM, as well as being coupled to a LCA software (subsection 2.4), despite being more complex to use. In addition, the geometry in IDA ICE can also be generated and imported from REVIT.

Aside from the geometry of the case-study, other parameters are also of key importance for the hygrothermal behavior of the building, namely the internal gains. These gains are usually due to the occupants' use of the building, and it is accounted by considering the gains due to human, equipment, and lighting system. In Norway, this is normally accounted by means of the day-profiles that exist in the Norwegian specification (SN-NSPEK 3031, 2021), which are building typology dependent. Note that in accordance with the software used, this day-profile loads might have to be transformed (Coelho & Kraniotis, 2023b). For the case-study, specific day-profiles for both monitored rooms will be built.

2.4. Step 4: Building performance simulation

The building performance simulation will be developed at two levels, namely: 1) hygrothermal performance, and 2) environmental impact assessment. The first level is subdivided into three sections, i.e., one-dimensional (using WUFI®Pro and HAMOPY), two-dimensional (using WUFI®2D) and whole-building simulation (using WUFI®Plus and IDA ICE). The second level corresponds to a cradle-to-grave life cycle assessment (LCA) using OneClickLCA.

The latter assessment is one of the bases of the StaticusCare project since it aims to produce a less polluting system by means of using a hybrid system, in which part of the traditional aluminum frame is replaced by timber. This step will be based on the quantity of materials used to build a unit of the HUF system and the respective environmental product declarations (EPDs). In addition, a comparative LCA will be performed between the conventional system (i.e., aluminum frame) and the hybrid system (i.e., timber and aluminum frame), which will be structural and thermally equivalent systems, to quantify the reduction of the CO_2-eq. emissions by means of replacing aluminum with timber.

The aim of using the HAMOPY, a python-based HAM software, is to integrate it into the building maintenance system (BMS), which is possible due to its high flexibility. Firstly, this software has been compared against the commercial software, WUFI®Pro (Ostapska et al., 2023), which has been extensively validated in various different conditions (Coelho & Henriques, 2023), for the assembly sections (Coelho & Kraniotis, 2023a). However, due to the façade configuration, the one-dimensional simulations, which due to their fast simulation speed can be successively incorporated into BMS, will have to be adapted from the two-dimensional results by means of the sections that will be run or by means of including heat/moisture sources. In addition, the most probable risk spot locations in the assemblies were identified through a two-set procedure: 1) a workshop with SINTEF researchers who have extensive experience with moisture in constructions, and 2) a questionnaire that was directed to facility managers in Scandinavian countries (Loli et al., 2024).

The whole-building simulation models – WUFI®Plus and IDA/ICE – will be used to obtain specific indoor conditions for the locations (see subsection 2.5) in which the indoor climate will not be measured. This software will also be used to assess the indoor climate and the energy consumption for the different locations that will be run considering climate change (see subsection 2.5). Finally, these models will be used in the final step of the project to build a building physics digital twin of the case-study to be used to ensure an optimal indoor climate for its occupants, but also ensure the longevity of the building through its service life.

2.5. Step 5: Weather/climate files

For current conditions, the measured data of temperature (°C), relative humidity (%), air pressure (hPa), global radiation (W/m^2), precipitation (mm/a), wind direction (°) and wind speed (m/s) for Oslo, Trondheim and Tromsø were downloaded from the *Norwegian Centre for Climate Services* (NCCS, 2022). Initially, thirty years of data – 1990-2019 –were downloaded for each previously mentioned meteorological parameter and each location. However, since the hourly data was only measured from 1992 for Oslo, 1996 for Trondheim and 1998 for Tromsø, the periods were limited respectively to 27, 23 and 21 years' of data (Coelho & Kraniotis, 2023b), which are still valid for the performed assessments.

An user independent code was developed to find and fill the existing weather data gaps (Coelho & Kraniotis, 2023b). These wide ranges of data were transformed into test reference years (TRY) by means of using the methodology of standard (EN ISO 15927-4, 2005). The global radiation was divided into its diffuse and direct parts using the DIRINT model (R. Perez et al., 1990; R. R. Perez et al., 1992). Finally, the .wac files were created. All these procedures are performed using the authors' developed code (Coelho & Henriques, 2021; Coelho & Kraniotis, 2023b).

Subsequently, part of the same procedure will be applied to build the future weather files. For that, the meteorological parameters will be downloaded from the CORDEX online database (CORDEX-2, 2019). This process will be followed for two Representative Concentration Pathway (RCP) climate change scenarios – i.e., RCP 4.5 (an intermediate GHGs emission scenario) and RCP 8.5 (and a high GHGs emission scenario) (Climate Change - SPM, 2014) – for the near-future (NF, 2035–2064) and far-future (FF, 2065–2094). The goal is to simulate the assembly under different types of European climates, namely, oceanic climate, continental climate, Mediterranean climate and arctic climate, and to see the differences and optimize the assembly in accordance.

3. Results

The development of the digital twin models of the case-study is the culmination of the whole-project (Figure 2). These models will be a part of the BMS that will be updated in real-time from the integration of the monitored data from the case-study (Figure 2). Consequently, facility managers can keep track of the building's hygrothermal and building physical status and thus, reduce future rehabilitation costs. It also enables identifying critical conditions for the building itself (i.e., risk spots), as well as for the indoor environmental quality (IEQ) by means of recognizing problems in the building physics scope. These can be, e.g., an indoor temperature lower than setpoint temperature due to a faulty HVAC system or interstitial condensation within the assembly, to name a few.

The development of this innovative multi-field methodology is time-consuming since it is based on information from a variety of different scientific fields. Having this in mind, by developing a code specifically for that purpose and using tools in the methodology that can be efficiently connected, its application to other buildings in the future will be a much more straightforward and quick process.

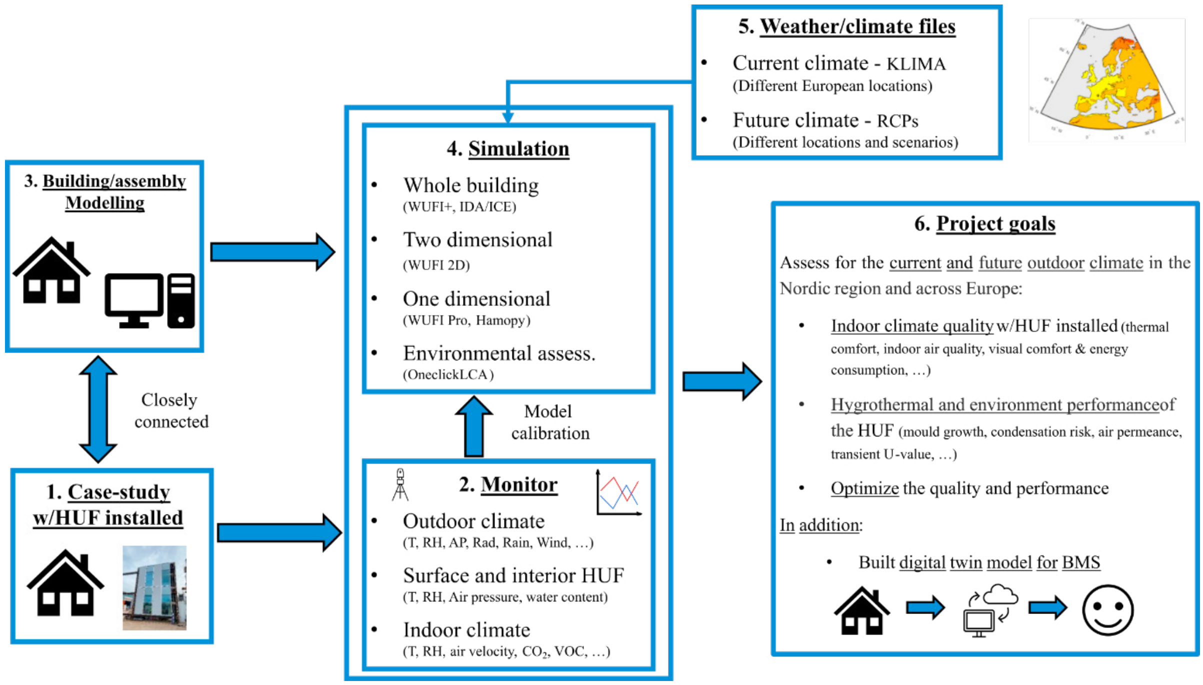

Figure 2 – Overall methodology of the StaticusCare project

4. Conclusions

This paper presents the methodology for the StaticusCare project concerning the development of a more sustainable and less-polluting aluminum and timber unitized façade system that can withstand current and future weather conditions. In addition, this façade system will have integrated IoT sensors so that its preservation can be incorporated into the building management system. This feature will be achieved by means of creating digital twin models of the real building, which will be fed by the data measured by the IoT sensors. Finally, these models will be used to assess the building's current state and, in case it is necessary, propose improvement measures.

This methodology will be based on a long-term and multi-sensor monitoring campaign of a real building with the HUF system installed and on the computational modelling of the building by multi-purpose software. Overall, the methodology comprehends six main steps, namely: 1) Build the case-study; 2) Monitoring campaign; 3) Case-study modelling; 4) Case-study performance simulation; 5) Weather/climate files; and 6) Build digital twin. This multi-step methodology will be applied in the future, either partially or globally, to real façade construction projects.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Diagnosis of Historic Reinforced Concrete Buildings: A Literature Review of Non-Destructive Testing (NDT) Techniques

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Abstract

Non-destructive testing (NDT) techniques are employed by many authors as reliable and effective methodologies to investigate the current conservation state of historic buildings and to follow up its evolution in response to the surrounding environmental changes. This paper briefly reviews the scientific articles dealing with NDT techniques applied to historic reinforced concrete (RC) buildings. To this purpose, 32 articles were selected through the steps of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) flow diagram and critically analysed. It emerges that Acoustic Emission and Ultrasonic techniques, Thermography, Rebound Hammer, and Electromagnetic techniques (e.g., Eddy Current and Ground Penetrating radar) are commonly employed due to their ability to detect damage in RC structures. As a result, the combined use of acoustic and mechanical methods (also known as “SonReb” Rebound Hammer and Ultrasonic Pulse Velocity) is found to be the approach more frequently used in the revised documents. This work allows to guide in the selection of NDT techniques to study the rate of decay, if any, and shows the way towards the development of new early warning approaches for historic RC structures.

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Keywords: Non-destructive testing; reinforced concrete; historic construction; literature review; PRISMA.

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1. Introduction

Starting from the twentieth century, churches, museums, and warlike buildings have been built with reinforced concrete (RC) due to its good performance in strength and durability. However, RC structures can be damaged by climate-induced deterioration factors due to extreme environmental events as well as to the daily exposure to external climate conditions (Ayinde et al. (2019), Boccacci et al. (2023)). Evidence of degradation due to use and time typically reveals the necessity to enhance an existing building's life expectancy in surviving weathering action, chemical attack, embedded chemicals, alkali-aggregate reactivity, seismic forces, fires due to overloaded electrical circuits, etc. (Kumar et al. (2021). In this framework, non-destructive testing (NDT) techniques are commonly performed to investigate the cause of damage and to implement repair actions aimed at improving the life expectancy of reinforced concrete buildings, and restoration actions also aimed at preserving and revealing the aesthetic and historic value in the case of historic RC structures (Sharma et al. (2016)).

NDT techniques are commonly used on field to assess the characteristics of concrete material in existing and historical buildings, as they allow to reduce the use of semi-destructive and destructive experimental tests that inevitably require invasive sampling of materials (Santini et al. (2020)). However, NDT techniques can also integrate destructive testing techniques as in the case of the estimation of in situ concrete strength, in every case the critical step remains to correlate the NDT test results and actual concrete properties. Indeed, standards and guidelines suggest correlating these results to the ones collected through destructive tests on cores and, as a consequence, these correlations can be used to derive additional strength values from NDT results (Masi et al. (2016)).

Therefore, this contribution provides a systematic literature review based on scientific articles dealing with NDT techniques applied to historic reinforced concrete buildings. Outcomes may assist in implementing structural health monitoring and condition monitoring campaigns tailored to optimize maintenance and repair works and to extend the life expectancy of structures limiting the occurrences of failures or disruptions.

2. Methodology

The first step of the literature review included an exploratory survey to pinpoint the most common non-destructive testing (NDT) techniques employed for the condition monitoring of reinforced concrete buildings. This was done to extrapolate appropriate keywords for conducting the systematic literature review that was performed using a three-step process following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram (Page et al. (2021)). The PRISMA has allowed to organize the collection and identification of relevant scientific records to be included in the analysis and review processes. The methodology conducted for the research topic is summarized in Figure 1. The PRISMA is a three-step process: 1) Identification, 2) Screening and 3) Inclusion. The identification was conducted in *Scopus* (searching within "Article title, Abstract and Keyword") and *Web of Science* (searching within "Topic", standing for Title, Abstract, Author keywords and Keyword plus) through the combinations of a set of keywords. This search included all documents in the databases until the end of April 2023. The combination of keywords was organized in 5 strings (Table 1) where keywords have been connected via the Boolean operators "AND" and "OR". The search initially yielded to a total of 1207 records; successively, the number of documents was reduced by excluding those that: (i) were NOT published on peer reviewed journals or as conference articles or as book contributions, (ii) were NOT available online, (iii) were NOT written in English. After that, 233 duplicates were removed, bringing the total to 585 documents.

Table 1. Search strings of keyword combinations used in the PRISMA Identification step.

Research	Keyword combinations
1	Acoustic emission AND reinforced concrete AND building
2	(Ultrasonic OR impact echo) AND reinforced concrete AND building
3	Thermography AND reinforced concrete AND building
4	Rebound hammer AND reinforced concrete AND building
5	(Electromagnetic OR eddy current OR ground penetrating radar) AND reinforced concrete AND building

436 out of 585 articles were excluded after the reading of the abstract as they dealt with the following topics:

- Type of concretes containing fibers as reinforcement.
- Concrete infrastructures other than buildings.
- Very modern concrete structures (<20 years).
- Use of NDT on restoration works/repaired or treated surfaces.
- Fire/earthquakes damaged structures performance evaluation.
- Effect of thermal insulation.
- Estimation of rebar diameter, location, and cover thickness.
- Study of the electromagnetic properties of building walls.

The remaining articles were further screened by removing those presenting the use of NDT not directly performed on the structures. Consequently, 115 articles were discarded, while 32 articles were finally included and analyzed in the review.

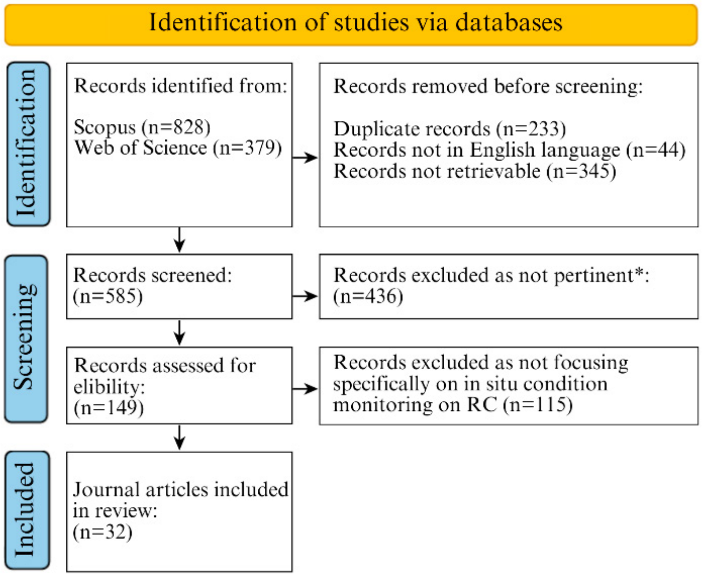

Fig. 1. Prisma flow diagram for systematic reviews showing the number of documents selected after each step.

3. Results and Discussion

3.1. NDT techniques for reinforced concrete in situ monitoring

In Figure 2 IDs are assigned to the revised articles and then reported and classified according to the NDT techniques employed in the investigations. The IDs highlighted in bold indicate works combining *in situ* and laboratory tests on real samples. Laboratory tests mainly consisted of mechanical tests (i.e., compression strength assessment through compression tests) and chemical tests (i.e., carbonation depth assessment through phenophtalein indicator). Most of the revised articles presented a combined approach between acoustic and mechanical methods, especially consisting in the *SonReb* method; a combination of Sonic and Rebound Hammer for determining concrete strength (Ji et al. (2023), Boussahoua et al. (2023), Kumar et al. (2021), Santini et al. (2020), Masi et al. (2016), Pucinotti (2015), Guida et al. (2012), Shariati et al. (2011), Pucinotti et al. (2005)).

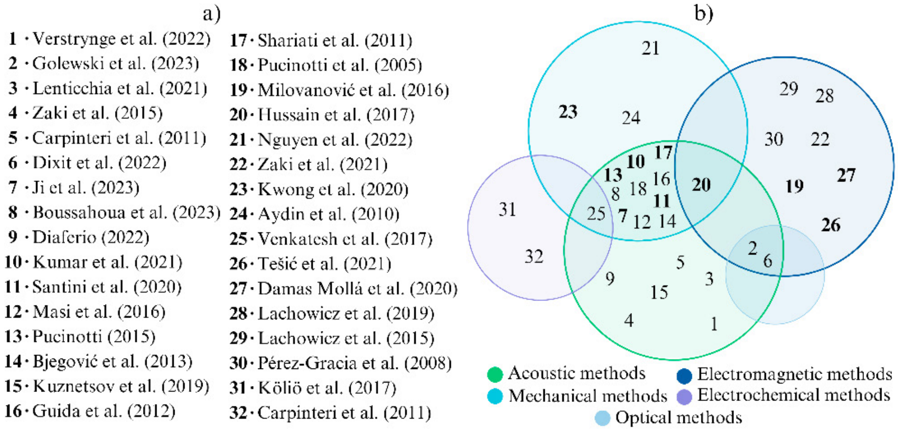

Fig. 2. (a) IDs assigned to each bibliographic reference; (b) IDs of the revised articles clustered in different categories according to the NDT method presented. IDs in bold indicate documents presenting a combined approach (in situ monitoring and in laboratory tests).

Table 2 reports an overview of NDT techniques for *in situ* detection and monitoring of reinforced concrete decay in buildings. It is worth noting that among the acoustic techniques used in the damage evolution assessment: Ultrasonic Pulse Velocity (UPV) and Acoustic Emission (AE) were the most exploited ones being cost-effective and sensitive techniques able to detect and locate the active defects (i.e., AE), and having a large penetration depth useful to estimate size, shape, and nature of the concrete damage (i.e., UPV). Ultrasonic Tomography follows the two mentioned techniques, as tomographic maps are considered to be a valid tool in the case of degradation assessment of the built heritage (mostly used to detect flaws and internal defects in concrete, as well as for rating the rebar corrosion). The Rebound Hammer, used to estimate the concrete strength and surface hardness, is frequently employed in several articles as it is simple, fast and the instrument is convenient to carry; furthermore, norms and standards have been widely formulated to guide its engineering applications. Among the electromagnetic (EM) techniques: Ground Penetrating Radar was the most used one and it has been usually employed to accurately locate and delineate rebar, flaws, cracks, and voids, even if attenuation derived from the coexisting influence with other phenomena (i.e., variations of moisture and chlorides) are unavoidable and make the results difficult to interpret. Infrared Thermography, Radiography and the others EM techniques listed in Table 2 resulted to be less frequently used (mostly to monitor flaws, cracks, voids, surface temperature and moisture content). Electrochemical techniques and Optical techniques were again less used (probably due to the high cost of the equipment especially in the latter case), but still considered reliable methods for estimating flaws and rate of corrosion by many authors.

In most documents, the results obtained are presented by the authors in a mixed way both quantitatively (i.e., through the use of graphs and tables) and qualitatively (i.e., through degradation maps and descriptions); however, the outcomes are never presented only in a qualitative way.

Table 2. Overview of NDT techniques for in situ monitoring of RC buildings according to the revised literature. The first column reports the NDT category; the second column indicates the main measurands; in the third column *PM is used for periodic measurements and CM stands for continuous monitoring; the fourth column reports the IDs of revised articles employing that technique. The last column indicates the monitored parameters of each of the applied technique.

NDT Category	Measurand	(PM)/(CM)	IDs	Monitored parameters
Acoustic				
Ultrasonic Pulse Velocity	Pulse velocity	PM/CM	2, 6, 7, 9, 13, 14, 17, 18, 20, 25	Strength, modulus of elasticity, flaws, surface hardness, rate of corrosion
Acoustic Emission	AE parameters	CM	1, 2, 3, 4, 5, 6	Rebar corrosion, concrete cracking
Ultrasonic Tomography	Wave velocity	PM	2, 11, 15	Flaws and defects internal detection in concrete, delamination/debonding
Impact Echo	Wave velocity	PM	20	Flaws and defects internal detection in concrete

NDT Category	Measurand	(PM)/(CM)	IDs	Monitored parameters
Mechanical				
Rebound hammer	Rebound value	PM	7, 13, 14, 17, 18, 20, 21, 23, 24, 25	Strength, surface hardness
Electromagnetic				
Ground Penetrating Radar	Electromagnetic wave velocity	PM	20, 26, 27, 28, 29, 30	Flaws, cracks, moisture content, voids, rebar location, depth of concrete
Infrared Thermography	Radiation power	PM	19, 20, 22	Cracks, concrete quality, surface temperature
Radiography	X-ray attenuation	PM	6, 20	Surface and subsurface defects, voids, concrete quality
Eddy Current	Eddy Current	PM	6	Surface flaws, concrete cracking
Computerized Tomography	X-ray attenuation	PM	2	Flaws and defects internal detection in concrete
Electrochemical				
Half-cell potential test	Potential	PM/CM	20, 25	Carbonation depth, chloride ingress, rate of corrosion
Linear Polarization Resistance	Corrosion current	PM/CM	31, 32	Rate of corrosion
Optical				
Digital Image Correlation	Strain	CM	2	Surface flaws and cracks
Optical fiber sensors	Strain or refractive index	CM	6	Corrosion, displacement, cracks

3.2. Case-studies

The 32 articles were analyzed in terms of the type of research approach they used. It emerged that 10 out of 32 documents were review articles, although always completely or partially focused on the topic of in situ monitoring of RC buildings. The remaining majority (22 out of 32) were original research articles presenting real case studies.

In Figure 3, information about the geographical distribution, the year of construction, and the building's typology of each of the 22 real case studies is reported. In most cases, the monitored buildings were located in Europe (mainly in Italy, Spain, Poland and Finland), followed by Asia (especially in India, Vietnam and Malesia). USA and Algeria respectively presented one case for each, and four research articles did not specify the location of the monitored case studies (Figure 3a). The number of case-studies built for each time span from 1900 to 2000 is also reported in Figure 3b. Most of the monitored buildings were built between 1950 and 1975 while in 7 cases out of 22 the year of construction was not specified. In some documents, the year of construction is only approximated (i.e., the 1970s). The number of case studies is also reported for each building's typology (Figure 3c): in 6 cases, out of 22 the authors did not specify the type of monitored building, but in the remaining cases they were historic buildings in 6 cases, residential in 5 cases, civil buildings in 4 cases and industrial in just 1 case. By comparing the different case studies, the use of the same NDTs for the same type of building did not emerge, on the contrary, the same technique was frequently used to assess damage evolution in buildings with different uses. The general characteristics specified for each case study (i.e., location, year of construction and building typology) were also compared and it came out that when the location information of the case study is missing, information on the age of the building and its typology are also missing in the same articles, preventing a proper contextualization of the site.

Moreover, the most monitored zones of the reinforced concrete buildings investigated by the revised literature, were found to be the columns (Boussahoua et al. (2023), Diaferio (2022), Kumar et al. (2021), Santini et al. (2020), Masi et al. (2016), Pucinotti (2015), Kuznetsov et al. (2019), Guida et al. (2012), Shariati et al. (2011), Nguyen et al. (2022), Kwong et al. (2020), Aydin et al. (2010), Venkatesh et al. (2017)), followed by outdoor walls (Carpinteri et al. (2011), Boussahoua et al. (2023), Pucinotti (2015), Kuznetsov et al. (2019), Pucinotti et al. (2005), Lachowicz et al. (2015), Köliö et al. (2017), Carpinteri et al. (2011)), beams (Boussahoua et al. (2023), Masi et al. (2016), Pucinotti

(2015), Shariati et al. (2011), Kwong et al. (2020), Venkatesh et al. (2017)), slabs (Kumar et al. (2021), Shariati et al. (2011), Kwong et al. (2020), Venkatesh et al. (2017), Damas Mollá et al. (2020), Pérez-Gracia et al. (2008)) and pillars (Lenticchia et al. (2021), Kumar et al. (2021), Lachowicz et al. (2019)). Indoor walls, staircase, and balconies were monitored in very few cases (Carpinteri et al. (2011), Kwong et al. (2020), Köliö et al. (2017)).

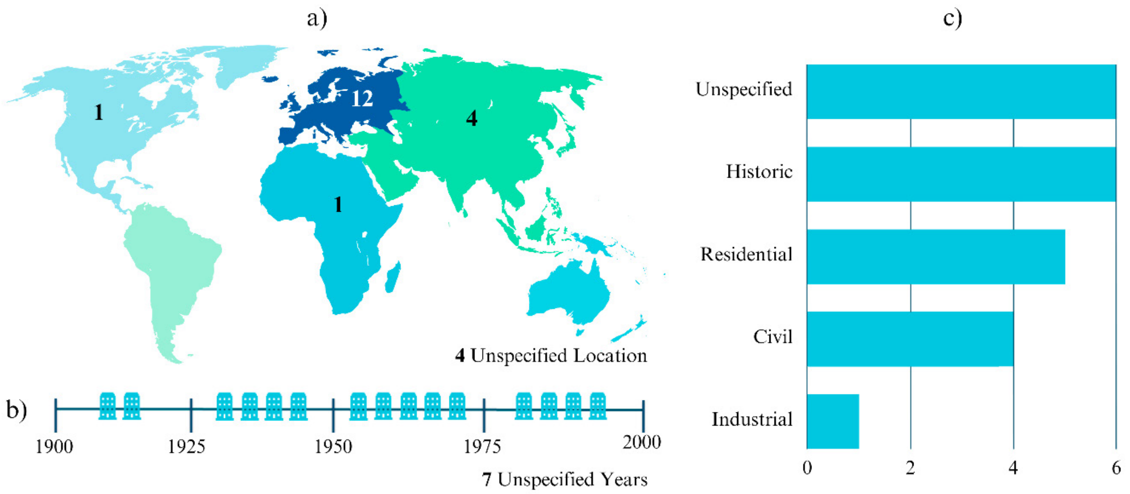

Fig. 3. Information about (a) geographical distribution; (b) year of construction; (c) building typology of the investigated case studies.

Moreover, the articles included in the present review were examined in order to comprehend the reasons behind this type of research topic. In general, the following driving motivations were obtained: assessment of the state of conservation of RC buildings (both in terms of durability and structural integrity as well as surface defects); establishment of correlation between destructive and non-destructive test results (especially in case of mechanical methods such as compressive strengths tests); formulation of appropriate sustainable measures for structural repair and rehabilitation; proposal of improvements to the current standards (both national and international) for NDT use on RC buildings (especially about sampling and evaluation) and, finally, investigation on the mechanical properties of basic materials such as steel and concrete.

Regarding the diagnosis of reinforced concrete-built heritage, among the review and original research articles, only 7 out of 32 documents dealt with historic reinforced concrete buildings. These documents (Lenticchia et al. (2021), Pucinotti (2015), Guida et al. (2012), Hussain et al. (2017), Damas Mollá et al. (2020), Lachowicz et al. (2019), Carpinteri et al. (2011)) put the emphasis on the necessity of a comprehensive understanding of the higher complexity of heritage structures, and on the need to better investigate their behavior and vulnerabilities. In this framework, the preservation of the original materials was found to be an important factor to be considered when choosing the NDT procedure to be performed in damage assessment of RC heritage structures (Hussain et al. (2017)). From here, some authors (Damas Mollá et al. (2020)) also proposed a multi-disciplinary working approach to understand the construction from its first designs to its final execution, including the characterization of current alterations. In this sense, an integration of historical, architectural, geometrical and geological studies is proposed with a common objective. The characterization of the materials used to build historic structures is said to be important to gain insight on the materials and technologies available at the time of their construction (Pucinotti (2015), Damas Mollà et al. (2020)). However, it emerged from the revised literature that only mechanical characterization of concrete is usually performed (especially to assess its strength) while concrete chemical and microstructural characteristics are usually not addressed. Only 2 articles out of 32 (Köliö et al. (2017), Carpinteri et al. (2011)), presented climate data analysis combined to the NDT test results to estimate the impact of environmental agents on the RC state of conservation.

4. Conclusions

In conclusion, the importance of RC buildings condition monitoring by NDT techniques has been widely recognized as effective in evaluating the conservation state of such structures, without causing concrete damage due to cores drilling and also allowing in situ results. Based on the outcomes of this review we can trace the main findings and what is still missing and less addressed. The main conclusions can be drawn as follows:

- As the quality of the concrete material is usually expressed as a function of its compressive strength, the combined use of acoustic and mechanical methods (also known as "SonReb" Rebound Hammer + Ultrasonic Pulse Velocity) was found to be the approach more frequently used in the revised documents, to improve the accuracy of concrete compressive strength prediction. Among the electromagnetic methods, the Ground Penetrating Radar (GPR) is one of the most widely used and validated techniques.
- Columns and outdoor walls were found to be the most monitored zones among all the revised documents. It emerged a very high variability of the mechanical properties of concrete within a whole building due to intrinsic no homogeneity, casting, curing, and different environmental degradation and accidental events which the structure can be subjected during its lifetime (factors that should be accurately considered when choosing the points to be monitored).
- Outcomes of the revised articles are usually delivered by the authors both quantitatively (i.e., graphs and tables) and qualitatively (i.e., degradation maps and descriptions), but never only in a qualitative way.

Future works in this area should be addressed to:

- Further investigate RC historic buildings in the framework of built heritage, always specifying key information for the contextualization of the case studies (i.e., location and date of construction).
- Enhance the design and performance of the various NDT detection instruments that will bring more sophisticated and sensitive devices guaranteeing reduced margins of error.
- Conduct in situ indoor monitoring campaigns to assess the existing risk affecting the inner part of RC building envelopes as none of the reviewed articles dealt with indoor monitoring.
- Further explore the impact of environmental agents on RC conservation state/structural integrity thanks to a multidisciplinary approach that includes the combination of NDT test results, climate data analysis and material characterization for historic reinforced concrete buildings.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Energy demand for indoor climate control in museums: challenges and perspectives in time of a changing climate

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Abstract

The control of indoor climate conditions was considered the best approach to reduce the occurrence of climate-induced risks, but heating and air conditioning systems, if inefficient, are now resulting insufficient to meet a sustainable energy demand of these spaces. This study investigates the potential changes in heating and cooling energy demands in museums under the extreme Shared Socio-economic Pathways climate scenario (SSP5-8.5), considering temperature thresholds suggested by standards for limiting thermal-induced degradation. The expected increase of the outdoor temperatures will be responsible for a decrease in the total energy demand in museums located in Trondheim and for a slight increase in museums in Rome. In the latter, the significant decrease in the heating demand will be not sufficient at compensating the sharp increase in cooling demand. Although the thermal insulation of the building envelope makes it possible to decrease the energy demand due to the reduction of the conduction heat transfer, this solution could be responsible for overheating issues, especially in summertime and middle-low latitudes, due to a higher solar gain with respect to higher latitudes. This opens new insight into the design of multi-option passive solutions in museums to avoid the use of energy-demanding systems.

Keywords: climate change; energy demand; musuems; thermal insulation;

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1. Introduction

In the last decades, investigations on the impact of future climate scenarios on the preservation of outdoor and indoor heritage are demonstrating the increasing threats posed by climate change in the European area (Bertolin, 2019; Bonazza & Sardella, 2023; Califano et al., 2023; Kotova et al., 2023; Verticchio et al., 2023). If outdoor heritage is directly exposed to more frequent adverse events (e.g., heavy precipitation, heat waves, high-polluted days), also indoor heritage can indirectly suffer from these outdoor climate conditions. Since the beginning of 20th century, the control of indoor climate conditions was considered the best approach to reduce the occurrence of climate-induced risks, but heating and air conditioning systems, if inefficient, are now resulting insufficient to meet a sustainable energy demand of these spaces.

Although the linkage between climate change and cultural heritage degradation has been recognized also by the latest European Commission's priorities 2019-2024, few efforts have been devoting to reducing carbon footprints and environmental impact of buildings preserving collections. Both the implementation of passive solutions (e.g., thermal insulation of building envelope) and the use of renewable energy sources would allow to minimize the use of energy-intensive systems for a tight control of the indoor climate also in museum environments that would contribute in turn to meet the requirements of the Green Deal to make the European Union climate neutral in 2050.

This study investigates the potential changes in heating and cooling energy demands in museums under the extreme Shared Socio-economic Pathways climate scenario (SSP5-8.5), considering temperature thresholds suggested by standards for limiting thermal-induced degradation.

Nomenclature

A	total surface area of the building (m^{-2})
CDD	Cooling Degree Days (°C)
ED	Energy Demand ($kWh{\cdot}m^{-3}{\cdot}year^{-1}$)
h	hours (h)
HDD	Heating Degree Days (°C)
out	outdoor
T	air temperature (°C)
thresh	threshold
U_{value}	thermal transmittance ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
V	total volume of the building (m^{-3})

2. Methods

2.1. Future outdoor climate scenarios

Two sites were selected since this study has been conducted in the framework of the “ERASMUS+ Inter-institutional agreement 2023-2028” between the Sapienza University of Rome (Italy) and the Norwegian University of Science and Technology of Trondheim (Norway), with the aim of providing information in support of the management of future climate impacts on museums located in these two cities.

Daily data of air temperature (T) at Rome (Lat. 41.9° N and Long. 12.5° E) and Trondheim (Lat. 62.7°N and Long. 11.3° E) were extracted from the Copernicus Climate Data Store (CDS). Recently, the Intergovernmental Panel on Climate Change (IPCC) has issued the Sixth Assessment Report (AR6) (Pörtner H.O. et al., 2022). The Sixth phase of the Coupled Model Intercomparison Project (CMIP6) dataset used in this analysis was generated by Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) (Lovato et al., 2022), providing data for recent past climate (RP, 1981-2010) and the extreme scenario SSP5-8.5 for the near future (NF, 2021-2050) and far future (FF, 2071-2100). SSP5-8.5 represents the highest greenhouse gases emissions with a radiative forcing reaching 8.5 $W{\cdot}m^{-2}$ by 2100.

T data were used to calculate the number of tropical nights, summer days and frost days in past and future climate, as follows: tropical nights occur when daily $T_{min} > 20°C$; summer days occur when daily $T_{min} > 25°C$; frost days occur when daily $T_{min} < 0°C$.

In addition, T data were used to compute the total energy demands due to both heating and cooling process. Results were then compared to put in evidence challenges and perspectives in managing indoor climate conditions in museums of the two cities.

2.2. Energy demand in museums

The energy demand of a building required to control indoor climate conditions is directly related to the difference between an outdoor climate variable and the corresponding expected indoor value. The greater the difference between outdoor climate conditions and the desired indoor threshold, the higher is the energy needed for heating/cooling (Hao et al., 2022). The “degree-days” indicator (eq. 1), indicated as DD, represents the number of °C that the outdoor temperature (T_{out}) must increase or decrease to reach a specific threshold value (T_{thresh}):

$$DD = \sum_{i=1}^{N} T_{out,i} - T_{thresh} \quad (1)$$

As (EN 16893, 2018) provides both minimum and maximum value of T in accordance with the vulnerability of specific materials, we separately computed heating degree-days (HDD) and cooling degree-days (CDD), based on the equations reported by the UK Met Office (CIBSE, 2006). In this case, T_{thresh} for HDD was set equal to 16°C to ensure thermal comfort of visitors/staff in wintertime, whereas T_{thresh} for CDD was set equal to 20°C as precautionary T to limit thermal-induced risks in vulnerable materials suffering from chemical degradation (e.g., paper). The cooling setpoint was chosen by the necessity to prioritize the preservation of collections rather than the thermal comfort of visitors/staff in summertime ($T_{thresh} = 26°C$, which is valid for occupants engaged in near sedentary physical activities).

The calculation of the energy demand (ED) is based on a straightforward assumption that considers only the conduction heat transfer through the opaque components in the total heat balance of the building. Under this assumption, convection and radiation heat transfers as well as other thermal gains and losses can be considered negligible. It means that transparent components are small sized and/or covered by shutters, and ex/infiltration are limited. For this reason, the total energy demand (ED_{tot}) in $kWh \cdot m^{-3} \cdot year^{-1}$ can be computed as the sum of the heating energy demand (ED_{heat}) and cooling energy demand (ED_{cool}) given by eq. 2 (Frasca et al., 2023; Las-Heras-Casas et al., 2021):

$$ED_{tot} = ED_{heat} + ED_{cool} = \frac{h}{1000} \cdot \frac{A}{V} \cdot U_{value} \cdot \left(HDD + CDD \right) \quad (2)$$

where A is the total surface area of the building in m^{-2}; V is the total volume of the building space in m^{-3}; A/V is the surface-area-to-volume ratio in m^{-1}, i.e., the larger the A/V, there is more surface area per unit volume through which material can exchange heat; h is the number of hour in a day (24 h); U_{value} is the thermal transmittance in $W \cdot m^{-2} \cdot K^{-1}$ of opaque components. Starting from HDD and CDD, it is possible to estimate the total ED in a building under different thermal insulations. Here, we considered the un-retrofitted case of buildings with a A/V = 1 built before 1945 all around Europe (Pohoryles et al., 2020) with a $U_{value} = 2.5\ W \cdot m^{-2} \cdot K^{-1}$. In addition, the same building with two different thermal insulation retrofitting options ($U_{value,\ retrofit\ 1} = 1.6\ W \cdot m^{-2} \cdot K^{-1}$ and $U_{value,\ retrofit\ 2} = 0.85\ W \cdot m^{-2} \cdot K^{-1}$) was also considered in the evaluation.

3. Results

Fig. 1 shows that the HDD in Trondheim will tend to decrease from RP to FF periods both in minimum and maximum values. HDD_{max} will pass from 20°C (RP) to 15°C (FF) at the end of January, whereas HDD_{min} will pass from 4°C (RP) to 1°C (FF) at the end of July. In addition, the number of the frost days will decrease from 177 to 81, meaning a significant reduction in the duration of the winter season. The number of both summer days and tropical nights is always zero in all periods and scenarios.

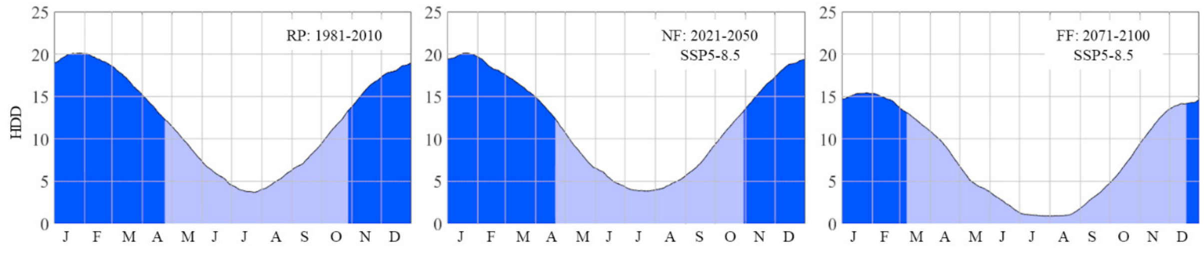

Fig. 1. Evolution of Heating Degree Days (HDD) in Trondheim from recent past (RP) to near and far future (NF and FF) in scenario SSP5-8.5 and the period corresponding to frost days (dark blue areas).

On the opposite, Fig. 2 shows that the CDD in Rome will tend to increase from RP to FF periods both in intensity (from 7°C to 14°C) and duration (from 5 to 7 months). Specifically, the number of the summer days will increase from 103 to 152 together with the number of the tropical nights (51 to 119). The occurrence of frost days has not been revealed.

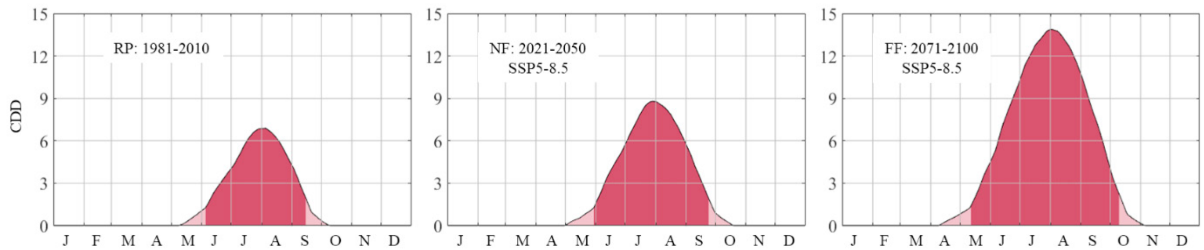

Fig. 2. Evolution of Cooling Degree Days (CDD) in Rome from recent past (RP) to near and far future (NF and FF) in scenario SSP5-8.5 and the period corresponding to summer days (dark red areas).

In Fig. 3, it is evident that the total ED in RP period is predominated by heating in both cities (red histograms). On average, the cooling ED in Rome is 30% out of the total ED (blue histograms; T_{thresh} = 20°C for CDD). It is worth noticing that if we propose a more sustainable setpoint to T_{thresh} = 22°C for CDD calculation as proposed by Spinoni et al. (2018) in other applications, the cooling ED would be a little more than 20% out of the total ED.

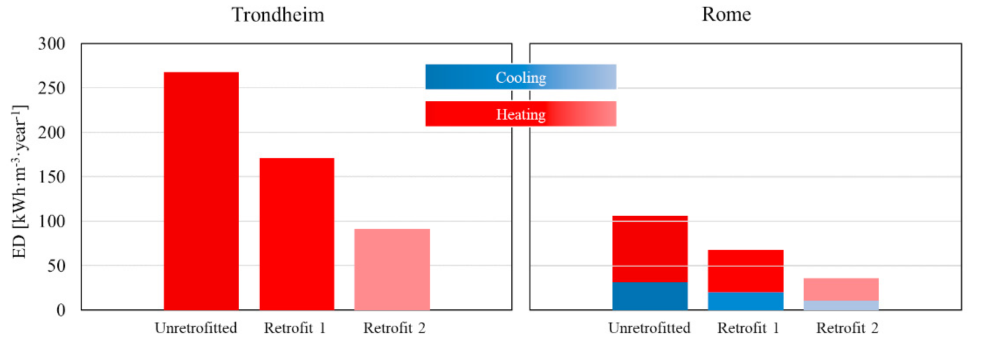

Fig. 3. Energy demand for heating (red bars) and cooling (blue bars) in Trondheim (left panel) and Rome (right panel) during the RP period in an un-retrofitted case and two retrofitted cases with thermal insulation of the same building.

Fig. 4 shows that in FF period the total ED of buildings in Trondheim keeps higher than that in Rome, even though the gap tends to be smaller. In Trondheim, the total ED will tend to significantly decrease (around 66%) but with the occurrence of a very small extent of cooling ED (less than 1 $kWh \cdot m^{-3} \cdot year^{-1}$, not visible in Fig. 4). In Rome, the expected increase of the outdoor temperatures will be responsible for tripling the cooling ED (blue bars) that will be in turn compensated by a significant decrease in the heating ED (red bars). However, the final effect on the total ED is a slight increase of only 8% with respect to RP.

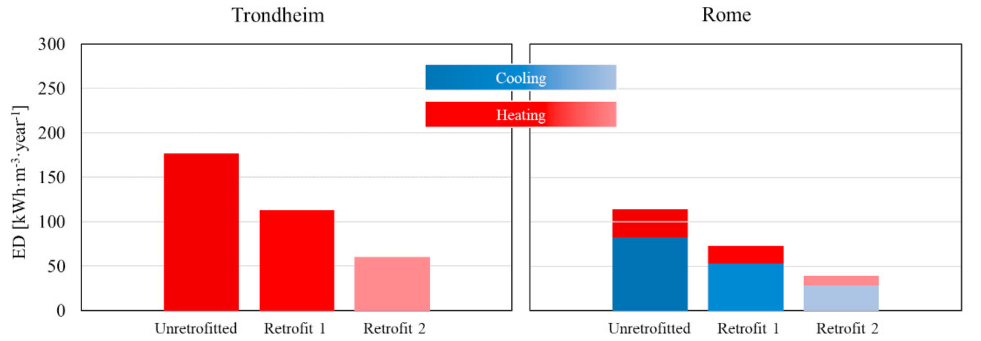

Fig. 4. Energy demand for heating (red bars) and cooling (blue bars) in Trondheim (left panel) and Rome (right panel) during the FF period under SSP5-8.5 scenario in an un-retrofitted case and two retrofitted cases with thermal insulation of the same building.

It is worth noting that the ED is here calculated taking into account only the conduction heat transfer through the opaque building components. It means that the effect of solar gains and ventilation is completely neglected. It follows that although low thermal transmittance values allow to reduce the energy demand (retrofit 1 and retrofit 2), overheating issues can be encountered in high solar gains and poor ventilation conditions, thus leading to an increase of cooling ED. In addition, such conditions can further be exacerbated by urban heat island and urban canyoning effects which are typical in urban contexts (Lopez-Cabeza et al., 2022) like the densely populated Rome (Battista et al., 2023; Salata et al., 2022).

4. Discussion and Conclusions

This study has investigated the potential changes in heating and cooling energy demands in museums under the extreme Shared Socio-economic Pathways climate scenarios SSP5-8.5 (corresponding to the highest greenhouse gases emissions with a radiative forcing reaching 8.5 W·m-2 by 2100). For the first time, degree-days were computed, taking as reference temperatures, the values suggested by standards to limit thermo-induced risks to vulnerable collections. It was found that in far future the total energy demand of museums in Trondheim will tend to significantly decrease in heating demand with a very low occurrence of summer cooling. On the opposite, museums in Rome will be much less energy-demanding in winter heating, but this reduction will be compensated by a higher cooling energy demand in summer. In this scenario, the gap between energy demands in Rome and Trondheim will tend to reduce, opening interesting perspectives in terms of the energy management of such sites. As an example, the occurrence of summer days and tropical nights will tend to increase in Rome (middle latitude), thus anticipating that retrofitting strategies should be tailored towards the identification of multi-option passive solutions in museums to avoid the use of energy-demanding systems, thus contributing to the reduction of the global carbon dioxide emissions.

One of the limitations of our approach is that the energy demand is computed taking into account only the conduction heat transfer of buildings, that might underestimate the future energy demands mainly in case of museums with large-sized windows without shutters. Indeed, although the thermal insulation of the building envelope makes it possible to decrease the total energy demand due to the reduction of the conduction heat transfer, this solution could be responsible for overheating issues, especially in summertime and at middle-low latitudes, due to a higher solar gain with respect to higher latitudes. In such cases, more sophisticated calculation methods, including convection and radiation heat transfers, should be applied. In addition, future energy demand quantification strictly depends on the uncertainty in the projected climate.

To sum up, the scenario of case studies with geographical high latitude range shown in this contribution could lay the foundation to stimulate a debate on how to define the next energy performance of buildings directives for countries of the European Economic Area according to future climate conditions.

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Evaluating the freeze-thaw vulnerability of soapstone monuments and geoheritage sites in the Parco del Paradiso (Chiavenna, Italy).

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Abstract

This study investigates the vulnerability of soapstone monuments and ancient quarries in the Parco del Paradiso, Chiavenna, to freeze-thaw cycles. It employs climate-based damage functions to assess the risk of weathering-induced damage. A crucial aspect of the assessment involves the study of the homogeneity and trends in the selected climate data sources in the area of the case study. These data sources are ground-based weather stations, and in-situ installed temperature-humidity data loggers. The findings of this contribution underscore the significance of appropriately chosen reference climatic series and validation tests in ensuring the accuracy of the climate signal to analyze freeze-thaw statistics for specific cultural heritage sites. These insights are essential not only for supporting reliable assessment of the vulnerability of these invaluable heritage sites, which have played a vital role in local architecture and trade since Roman times, and for the successive development of long-term preventive conservation and maintenance strategies.

Peer-review under responsibility of the ESICC 2023 Organizers

Keywords: freeze-thaw cycles; geoheritage; damage functions; microclimate; soapstone

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Nomenclature

AWS	Automatic Weather Station
F-T	Freeze-thaw cycles
FT_{Avg}	Freeze-thaw cycles/year computed using daily average dry-bulb temperature around 0°C
FT_{eff}	Freeze-thaw cycles/year computed using daily maximum and minimum dry-bulb temperature around -3 and 1°C
FT_{Mnx}	Freeze-thaw cycles/year computed using daily maximum and minimum dry-bulb temperature around 0°C
MOP	Monitoring period (2022/02/01-2023/01/31)
MWS	Mechanical Weather Station
Prec	Precipitation in mm/day
QA	Quality Assessment tests
RCP	Recent past (2016/01/01-2023/01/31)
RRP	Distant past (1961/01/01-1990/12/31)
T_{avg}	Average daily dry-bulb temperature in °C
T_{max}	Maximum daily dry-bulb temperature in °C
T_{min}	Minimum daily dry-bulb temperature in °C
WFD	Wet frost days

1. Introduction

Heritage sites are constantly challenged by the gradual process of weathering Smith et al. (2008). Depending on their location, open-air geoheritage sites (i.e., sites which encompass intrinsically important features of geology and culture at all scales, offering information or insights into the evolution of the Earth or history) can be particularly vulnerable to damage caused by freeze-thaw cycles Deprez et al. (2020). To implement effective maintenance practices and ensure optimal conservation, it is crucial to have a thorough understanding of these geological structures' vulnerabilities. In the Parco del Paradiso, located in Valchiavenna, Northern Italy, there are soapstone monuments and ancient quarries with deep historical significance exploited since Roman times Castelletti (2018). The geological composition of the park's outcropping rock belongs to the ultramafic body of the Chiavenna Unit Arrigoni et al. (2020), characterized by a broad local lithological diversity, including peridotite, chlorite schist, calc-silicate boudins, and talc schists, historically exploited for soapstone extraction Baita et al. (2014). This study delves into the evaluation of freeze-thaw damage vulnerability on soapstone, employing climate-based damage functions as a means to quantify and manage this peril. Soapstone, as other geomaterials, is characterized by porous structures and are susceptible to multiple freeze-thaw (F-T) cycles, particularly during cold seasons in temperate regions Ruedrich et al. (2011). These cycles involve the transformation of liquid water into ice within the pores, leading to mechanical fatigue damage. This damage mechanism entails the formation of cracks in the material and structural components due to the cyclic stress induced by the expansion of the soapstone when ice forms within the pores or pre-existing cracks Bertolin and Cavazzani (2022). The likelihood of fatigue damage, akin to the effects of repetitive tensile loading on the material's surface, increases with a higher number of F-T Liu et al. (2015). The F-T process could have a noteworthy impact by intermittently serving as a high-intensity event that can either generate openings within pores and fractures or facilitate the detachment of materials. Two notable European projects, the Noah's Ark project (2004-2007) Sabbioni et al. (2006) and the Climate for Culture (CfC, 2009-2015) Leissner et al. (2015) have highlighted the importance of study F-T cycle fluctuations in past, present and future to assess their impacts on the long-term conservation of stone materials/monuments. This study is primarily focused on the comparison of diverse climate data sources for assessing the F-T vulnerability of the soapstone geoheritage of the Valchiavenna. The data sources include ground-based weather stations managed by the Regional Agency for the Protection of the Environment (ARPA Lombardia) Maranzano (2022) and in-situ temperature-humidity dataloggers installed by the Milan University for a dedicated monitoring campaign carried out over the period from 2022/02/01 to 2023/01/31. The research explores the challenges of evaluating microclimate-induced degradation processes in geoheritage sites, confronting limited local data availability, and explores solutions to address the lack of clear data correction and validation guidelines, particularly in regions with complex topography.

2. Materials and methods

2.1. Parco Archeologico-Botanico del Paradiso

The Archaeological-Botanic “Parco del Paradiso”, located in Valchiavenna, Italy, within the "Marmitte dei Giganti" natural reserve, features Alpine terrain which is influenced by altitude, proximity to water bodies, and valley orientations. The park is notable for its ancient soapstone trench quarry dating back to the Roman period, as well as a botanical itinerary featuring rare species and exotic vegetation, anomalous in an Alpine terrain. Fig. 1 illustrates the examined geographical region situated atop a hill in the northeastern vicinity of the city of Chiavenna. The valley in this region exhibits a pronounced north-to-south orientation, while the slopes exhibit gradients ranging from 340 m to 400 m above mean sea level (m.a.m.s.l.).

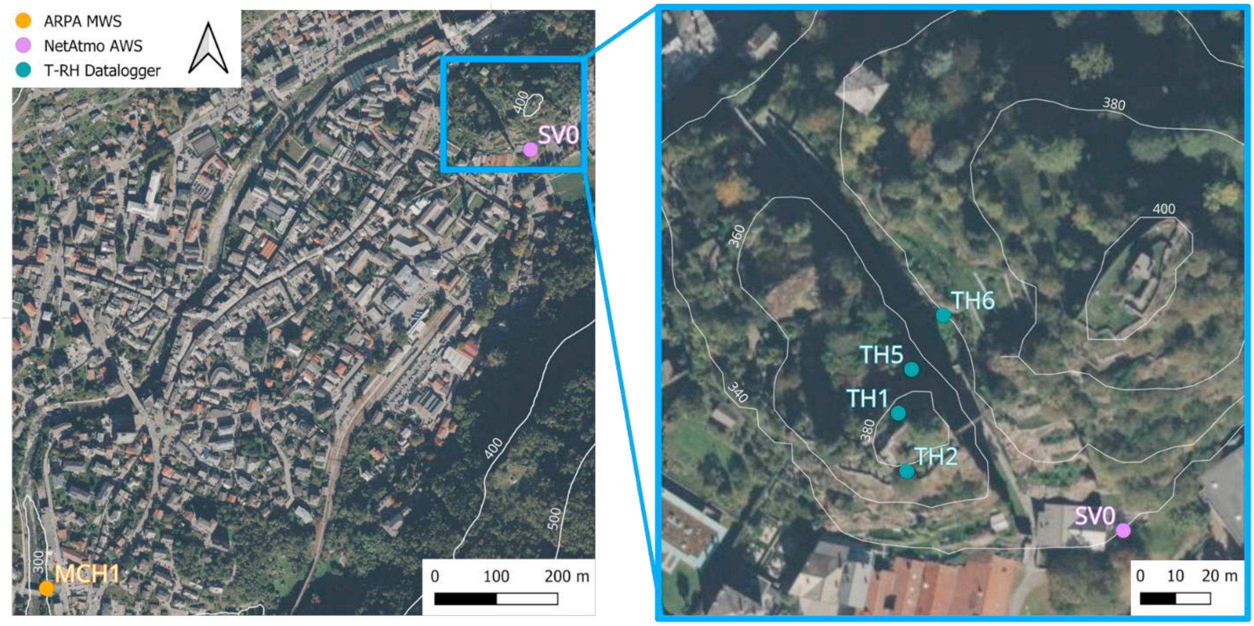

Fig. 1. The study area with a zoom window on Paradise Hill:, markers include an orange indicator for the Arpa Lombardia Mechanical Weather Station (MWS), a violet indicator for the University of Milan Automatic Weather Station (AWS), and teal markers for temperature (T) and relative humidity (RH) data loggers. The white lines are isopleths with indicated altitude in m a.m.s.l., the elevation data is sourced from a publicly available 5x5 meter DTM provided by Geoportale Lombardia. Basemap: Bing Maps Aerial (c) 2011 Microsoft Corporation and its data suppliers.

2.2. Climate datasets

Fig 1 reports, in the zoomed window, the thermo-hygrometric data loggers (i.e. TH1, TH2, TH5, TH6) installed by the Milan University to monitor the microclimate of the geoheritage gorge over a one-year period (February 2022-January 2023, later on defined as Monitoring period MOP). These dataloggers were strategically positioned approximately 10 cm from the outcropping rocks at a height of about 0.5 m above the ground. A NetAtmo automatic weather station (SV0) model NWS01-P named Valchiavenna Station of property of the Milan University that is also acquiring data in proximity to the monitored site since 2016 (Fig 1). Notwithstanding, a significant data gap existed for the more extended climatological period of the Distant Past (RRP) from 1961 to 1990 that could be used as reference in the environmental analysis. To overcome this data gap, historical ARPA mechanical weather station

(MCH1) data from a station located 1 km south-west, near the Lira River, within the same city, are used. This data supplementation consents to examine trends over the past, even though no data were available at the exact location during that period. The investigation examined three specific time intervals: the MOP, the Recent Past (RCP) encompassing the years 2016 to 2022, and the Distant Past (RRP). These intervals were selected, based on data accessibility and to facilitate a comprehensive temporal analysis of climate trends within the context of climate change. Data available from these sources are summarized in Table 1 with the ID of the station and dataloggers , the start-end dates and the period code, the elevation in meters above mean sea level (m.a.m.s.l.), the type of measured parameter and the continuity and completeness indices, assessing respectively gaps and observed data proportion, as calculated in Frasca et al. Frasca et al. (2017).

Table 1. Data from weather stations and dataloggers include IDs, dates, temporal period codes, elevation in meters above mean sea level, measured parameters, and continuity and completeness indices.

ID	Start-end	Period	Elevation (m.a.m.s.l.)	Data	Continuity	Completeness
MCH1	1961/01/01/-1990/12/31	RRP	301	T_{min}	1.00	0.80
				T_{max}	1.00	0.80
				Prec	1.00	0.83
SV0	2016/01/01-2023/01/31	MOP, RCP	363	T_{min}	0.98	0.93
				T_{max}	0.98	0.93
				Prec	0.97	0.84
TH1	2022/02/01-2023/01/31	MOP	376	T_{min}	0.99	0.91
				T_{max}	0.99	0.91
TH2	2022/02/01-2023/01/31	MOP	372	T_{min}	1.00	1.00
				T_{max}	1.00	1.00
TH5	2022/02/01-2023/01/31	MOP	358	T_{min}	1.00	1.00
				T_{max}	1.00	1.00
TH6	2022/02/01-2023/01/31	MOP	358	T_{min}	1.00	1.00
				T_{max}	1.00	1.00

To address missing data and erroneous readings in both SV0 and MCH1 climate series, a quality assessment and homogenization procedure was performed. In this process, nearby stations, specifically ARPA Automatic Weather Stations (AWS) and Mechanical Weather Stations (MWS) Maranzano (2022), were used as references to ensure the reliability and consistency of data for the target stations SV0 and MCH1. AWS data can be accessed on the following page: https://www.arpalombardia.it/temi-ambientali/meteo-e-clima/form-richiesta-dati/ (Last access on 30/06/2023) . Historical network data of MWS can be downloaded from the following portal: https://idro.arpalombardia.it/it/map/sidro (Last access on 30/06/2023). For SV0 data validation, 14 ARPA automatic stations from the ARPA Sondrio database were employed. All stations were selected within a 30 km radius from the target. Similarly, 11 mechanical stations were used for MCH1 data quality assessment and homogenization. Quality Assessment (QA) tests, including range, step, consistency, and persistence checks, were conducted before and after each homogenization step according to the thresholds reported in Estévez et al. (2011). The homogenization process comprised distinct phases: potential reference homogenization, reference selection, and target homogenization using the selected reference for each data series. Initially, data were gathered from ARPA Lombardia Automatic Weather Stations (AWS) and Mechanical Weather Stations (MWS) located within a distance of 30 km from Chiavenna. For MWS, daily maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation (Prec) were collected, while AWS data consisted of sub-hourly temperature and precipitation, subsequently aggregated into daily mean temperature (T_{avg}), T_{max}, T_{min}, and Prec. The data underwent an initial Quality Assessment test (QA-1), wherein individual parameter observations failing the test were eliminated and treated as missing values. The Climatol R package was employed for the homogenization of the potential reference series for each parameter, encompassing

T_{max}, T_{min}, and Prec Guijarro (2018). Subsequently, a second Quality Assessment test (QA-2) was applied to the homogenized series. Hierarchical clustering analysis, considering the correlation between time series derivatives for each parameter of MCH1 and SV0, was employed to identify suitable reference series for the target stations. The final homogenization of the target stations climate series, MCH1 and SV0, was performed again using the Climatol R package Guijarro (2018), followed by a concluding Quality Assessment test (QA-3). This comprehensive procedure was undertaken to ensure data reliability and consistency, enabling accurate computation of F-T cylces and facilitating meaningful comparisons in the analysis of climatic trends.

2.3. Freeze-thaw indexes

In literature, a straightforward index involves counting freeze-thaw cycles when the temperature crosses 0°C within a specified time frame Brimblecombe et al. (2011). In this study four different risk indexes have been used as follows. The annual freeze-thaw cycle (FT_{avg}) count was determined using daily average temperature data, with a cycle starting when the temperature fell below 0°C one day and rose above 0°C the day after. Furthermore, an index (FT_{Mnx}) was computed based on daily maximum and minimum temperatures, with cycles identified when the minimum temperature was below 0°C and the maximum temperature was above 0°C on the same day. The concept of effective freeze-thaw cycles (FT_{eff}) was also applied, utilizing a criterion of a minimum temperature below -3°C and a maximum temperature above 1°C on the same day Brimblecombe et al. (2011). Wet frost days (WFD) are calculated by counting the number of days when rainfall exceeds 1 mm/day and maximum temperatures is above 0°C, followed immediately by a day where the minimum temperature falls below 0°C within a specific year as adapted for this study from Grossi and Brimblecombe (2007). A different threshold is applied with respect to the aforementioned paper since the objective is to understand the worst-case scenarios.

3. Results and discussion

In Figure 2, the plot illustrates certain parameters of the climate data series after undergoing a validation and homogenization process. In particular, Figure 2a shows data from the MCH1 and SV0 weather stations, highlighting generally high validity values, exceeding 80% for the original data (grey bar in Figure 2a). The remaining percentage has been successfully imputed during the homogenization process (cyan bar in Figure 2a). Notably, there is an exception observed for the minimum temperature data at the MCH1 station, which required correction for the most recent data due to the identification of a breakpoint on 1979/02/01 (violet bar in Figure 2a). Figure 2b, on the other hand, displays the root mean square error (RMSE) between raw and validated data.

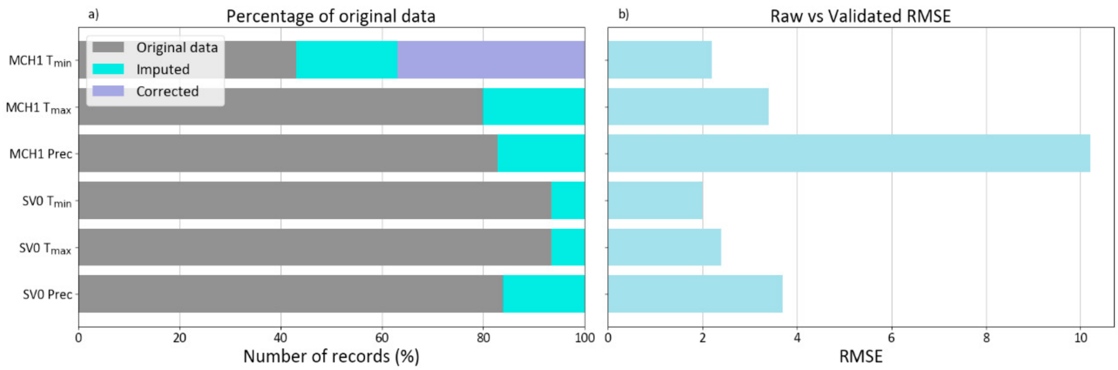

Fig. 2. The dataset obtained after the homogenization process. a) Percentage of original (grey), imputed (light blue), and corrected (violet) data for each variable at the target station MCH1 and SV0. b) Root-mean-squared error between raw data series and corrected data.

In MOP (TH1, TH2, TH5, TH6 and SV0), the count of freeze-thaw (F-T) cycles is notably low, with FT_{Avg}, FTeff, and WFD all registering at 0 events (Fig. 3a). Intriguingly, FT_{Mnx} indicates the potential for freeze-thaw events to occur in the vicinity of the geosite under study, but this phenomenon is observed only in specific locations. Specifically, these events are more likely to occur in the north-facing area of TH1 (green cell in Fig. 3a) at the hill's summit, as well as in TH6 (blue cell) and TH5 (violet cell) within the trench quarry. Figure 3b displays the typical thermal years for MCH1 (black thick line, averaged over a 30 year climatic reference period) and SV0 (blue thick line, averaged over 7 years), with overlaid values of monthly average, maximum, and minimum temperatures for each monitoring month retrieved by dataloggers. It is noteworthy that, in the vicinity of exposed rocks, summer temperatures exceed the historical yearly averages from recent and remote reference periods. A comparable, though attenuated, effect is observed in winter months for minimum temperatures. This disparity in temperature profiles accounts for variations in monitoring cycles among different thermos-hygrometers, attributed to their differing exposure and proximity to exposed rock formations.

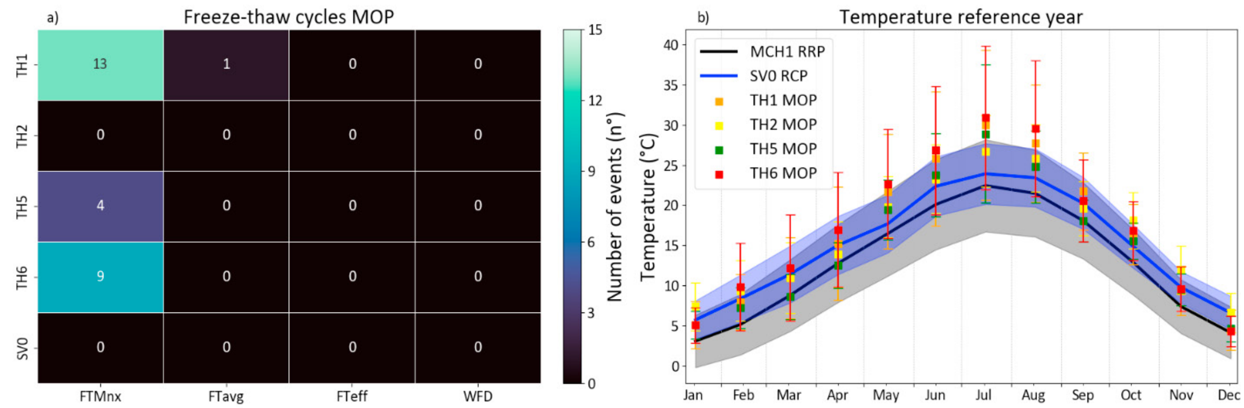

Fig. 3. a) Heatmap illustrating the number of Freeze-Thaw (F-T) cycles using various counting methods for dataloggers (TH1, TH2, TH5, TH6) and the AWS SV0 during the MOP monitoring period. b) Typical thermal years for MCH1 (black thick line, averaged over a 30-year climatic reference period) and SV0 (blue thick line, averaged over 7 years), with superimposed monthly average, maximum, and minimum temperatures as recorded by the dataloggers for each monitoring month.

The choice of methodology for counting cycles, whether utilizing average temperature (FT_{Avg}) or maximum and minimum temperatures (FT_{Mnx}), exerts a significant influence on the computed annual cycle counts when analyzing ground-based climate data (Fig. 4). When employing FT_{Mnx}, for the RRP dataset, the analysis revealed a total of 1116 cycles over 30-year-long period (mean=37.2 cycles per year, maximum=61 cycles, Figure 4a). Conversely the utilization of FT_{Avg} yielded a total of 93 cycles over a 30-year-long span (mean=3.23 cycles per year, maximum=8 cycles per year, Figure 4b). Employing the FT_{Mnx} methodology for the same station identified a total of 23 cycles within the RRP dataset, with an annual average of 3.28 cycles (see Figure 4c) and a maximum of 13 cycles observed in the year 2016. When average daily temperature data was input into the FT_{Avg} framework, the analysis yielded a total of 3 cycles over a seven-year-long period in the RCP dataset, with a maximum of 1 cycle occurring in any given year, resulting in an annual average of 0.43 cycles (see Fig. 4d). The process of homogenization and validation of climate data has therefore been proven to be invaluable in addressing the underestimation of freeze-thaw cycles, which can reach levels as high as 15.7% for MCH1 and 17.5% for SV0, primarily due to missing data.

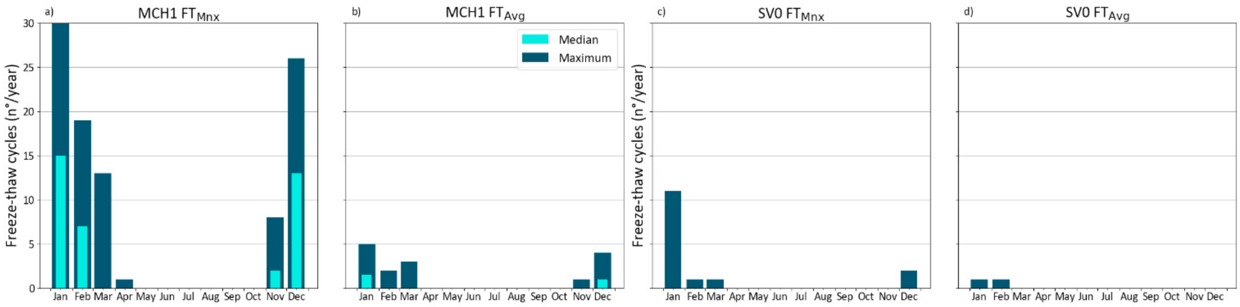

Fig. 4. Monthly bar plots indicating the count of Freeze-Thaw (F-T) events. Dark blue bars represent the monthly maximum values, while light blue bars represent the medians for: a) MCH1 Station - FT_{Mnx}, b) MVCH1 - FT_{Avg}, c) SV0 - FT_{Mnx}, d) SV0 - FT_{Avg}. MCH1 counts are relative to the 30-year period RRP, while SV0 counts are relative to the 7-year RCP.

To assess the trend in the past and recent periods, linear interpolation was performed using FT_{Mnx} (Figure 5a-c) and WFD data (Figure 5d). By examining the slope of the interpolating line, one can infer whether the number of F-T has increased, decreased, or does not exhibit a trend. This analysis was extended to all AWS and MWS stations utilized during the homogenization phase, and the slope was plotted as a function of the station's elevation for comprehensive analysis (Figure 5c-d). The analysis of freeze-thaw cycles over time reveals a decreasing trend for both target stations (Figure 5c). Notably, SV0 has limited available data years. Examining the slope of the interpolating line, it becomes evident that the trend is less clear for the AWS stations but consistently decreasing for the MWS (Figure 5c-d). This suggests a decreasing number of freeze-thaw cycles over the years, with a more pronounced decrease at higher elevations. Additionally, there is a more observable decrease in WFD (Figure 5d).

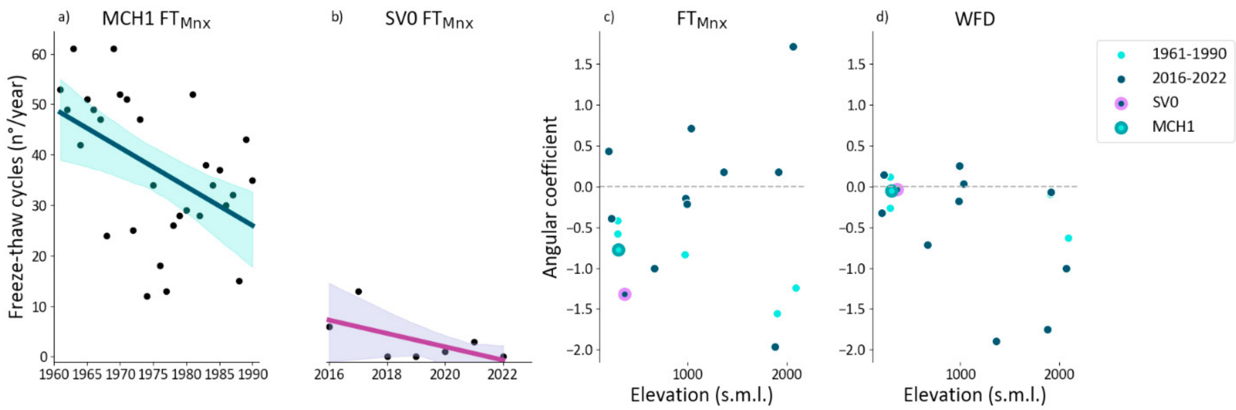

Fig. 5. a) Number of freeze-thaw cycles per year for station MCH1 calculated with FT_{Mnx}, with a trendline obtained through linear interpolation. b) "Number of freeze-thaw cycles per year for station SV0 calculated with FT_{Mnx}, with a trendline obtained through linear interpolation. c) Slope of the trendlines for each station used in the homogenization process as a function of elevation for cycles counted using FT_{Mnx}. d) Slope of the trendlines for each station used in the homogenization process as a function of elevation for cycles counted using WFD.

4. Conclusions

Studying F-T effects on stone heritage is crucial for material preservation and visitor safety. In this work, there is a difference in the count of annual F-T occurrences depending on the freezing and thawing thresholds and the initial dataset, considering whether it includes T_{avg}, T_{max}, or T_{min}. The rocks in the Parco del Paradiso, specifically those from the old soapstone quarry, experience limited freeze-thaw cycles, predominantly in the north and northwest-facing areas. The imputing and homogenization processes of temperature data have proven valuable for estimating F-T occurrences and studying the impact of climate change on both the geoheritage and its surroundings. In fact, there is an observed trend in the number of freeze-thaw cycles in Valchiavenna, influenced by the elevation. Over the years, the number of cycles has decreased, particularly at elevations above 1500 m. In future studies, the thermo-hygrometric datasets processed in this study will be utilized to assess additional damage functions in a multi-risk scenario.

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Fine sandy concrete reinforced with polypropylene fibre for rural and desert housing

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Abstract

This research aimed to design a low-cost fibre concrete as an alternative to earth-concrete reinforced with biomaterial fibres, where the latter is characterized by mechanical defects such as low strength, water degradation and air erosion, as well as the continuous deformation related to the self-compression and unlimited subsidence of the bearing surface soil.
The designed concrete is composed of fine sand, cement at small quantities and polypropylene fibre available on the daily market. This material is easy to form due to the availability of fine sand in nature and the possibility of its production without much skill. At the same time, it is made at a low cost and short implementation time, unlike earth concrete where it needs time to dry and acquire the appropriate strength. Laboratory work has shown good results as the light density, the large ductility, and an acceptable strength capacity of this material.

Keywords: Earth concrete; Sandy concrete; Macro polypropylene fiber; Concrete strength; Workability; Ductility.

1. Introduction

From the beginning of human civilization man has found in natural caves his refuge to protect himself from climate change and animal threats (Jahren 2018). The second leg of the civilization trip was the exploration of natural materials to build its habitat; Thus, man has used the natural materials available in his environment to meet his safety, and family and social obligations (Sparavigna 2011). Hence, from the mud he designed the earth-concrete to build his habitat and his house of worship where earth-concrete is used mainly to form load-bearing walls. However, the poor performance of this material forced the builder to adopt relatively large thicknesses to achieve the structural objectives. At an advanced time, and before the appearance of firebrick, man introduced the fibre of plants to treat the defects of this natural composite material (Sparavigna 2014). Admittedly, this material was characterized by an

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acceptable ductility, but it was not immune to the phenomenon of water and air erosion, self-degradation and the continuous deformation of the soil (Maini 2005, Bredenoord 2023).

Currently, to deal with these shortcomings, researchers are directing their work along two axes. The first group worked on soil characteristics to improve the properties of earth-concrete (Obonyo 2010, Guettala 2006, Arooz 2018, Ronsoux 2013); while the second attempted to get better material by investigating the properties of fibre plants such as vegetable straw (Demir 2006) banana fibres (Mostafa 2016), rice husk and ash (Damanhuri 2020).

In underdeveloped countries, especially in rural and deserted areas where mud does not exist, cost and ease of implementation become the two main construction criteria. To meet these two conditions, this work aims to provide an alternative to fibre earth concrete that is easy to manufacture and fulfils the respective properties for construction safety.

Meanwhile apart from the use of steel fibres, a third trend has appeared where the engineer chooses to use fibres produced industrially, such as glass fibre (Annamaneni 2023**)**, polyester fibre (Mohsin 2020), carbon fibre (Ghanem 2019), macro synthetic fibres (Bolat 2014), and polypropylene fibres (Ravishankar 2021).

In addition, all research works on polypropylene fibre show how the fibres act within the concrete and the rate of improving its mechanical properties. Blazy and Blazy (2021) showed the possibility of using polypropylene fibres enhanced on concrete for architectural elements of public spaces. Matar and Zéhil (2019) studied the ability to use polypropylene fibre to improve the physical and mechanical properties of recycled aggregate concrete. Nasser et al. (2018) proved that the addition of propylene fibres for 1.5% of the cement volume improves significantly the strength of concrete in compression. Ahmad et al. (2021) worked on many volume ratios of polypropylene fibre to detect its performance on fresh concrete and hard concrete properties under compressive strength, split tensile strength and flexure strength. Magnur et al. (2017) approved the same results. Memon et al. (2018) showed the inverse role of fibre length where they observed that with an increase in the size of fibre the compressive strength decreased significantly.

On the other hand, research is carried out on the use of dune sand as the main aggregate for concrete. Ahmad et al. (2022) presented a review of the effect of Dune sand on concrete properties. They indicated that dune sand can be used in concrete up to 40% without any negative effect on strength and durability; therefore, they indicated that the negative impact of this fine aggregate on strength and durability was due to poor grading and fineness, which restricts the complete (100%) substation of dune sand, but they noted its negative effect where a significant decrease in flowability was observed.

The use of dune sand as a natural material remains conditioned by its availability in nature on the one hand and its mineralogical composition and its physical and mechanical properties on the other. Tsoar (1997) has extensively studied the physical properties of this material, and its mobility and ecological implementation. Al-Shammery and Jasim (2018) have studied the mineralogy of sand dunes found in the region of the southeast of Iraq and tried to determine its origin or source; likewise, Nasir et. Al. (1999) have worked along the same line on the genesis of heavy minerals in coastal dune sands implemented in south-eastern Qatar.

Based on this panoramic review, this study seeks to propose a conception and suitable solution for the use of dune sand as the main aggregate, reinforced with macro polypropylene fibre, for housing construction in rural or desert areas in underdeveloped countries, where mud is not available.

2. Materials and methods

2.1. Concrete composition

In this investigation, the concrete was designed from natural white dune sand for a maximum size of 1.18 mm (figure 1), cement type CEM I/ 32.5 N/mm^2 and polypropylene fibre.

The laboratory test gives the following values for the physical and mechanical properties of sand: Specific gravity 2.61 g/cm^3, dry density 19 kN/m^3, specific surface area 114 cm^2/g, finesse modulus 1.4%, sand equivalent 83%, humidity 0.3%, and absorption 2.67%; while, the mineralogy composition was as follows: SiO_2 (72.2%), F_2O_3 (2.2%), Al_2O_3 (11%), CaO (5.7%), K_2O (2.6%), Na_2O (2.3%), MgO (1.7%), LOI (2%).

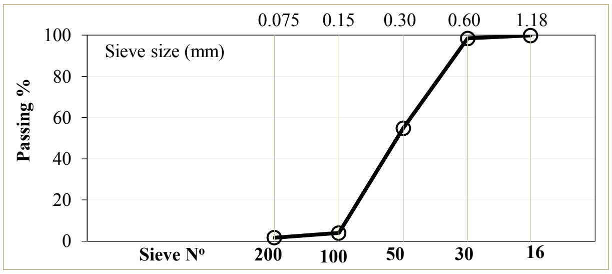

Figure 1: granular composition of dune sand

The macro polypropylene fibre (PPF) is a synthetic textile fibre that has a linear structure based on the monomer C_nH_{2n}. The (PPF) is not degradable with soil and not decomposed by water. Table 1. gives the general physical, mechanical, and chemical specifications of the Polypropylene fibre (Kiron 2021, Mansfield 1999). In accordance with ASTM 4268 standard, the Engineering Toolbox Site and Kochem website, the physical and chemical properties of polypropylene used to produce polypropylene rope are summarized in Table 1**.**

Table 1: Physical and chemical properties of Polypropylene fibre

Relative density	0.90-0.91	Thermal conductivity	6.0 (with air as 1.0)
Tensile strength (MPa)	>500	Abrasion resistance	Good
Elasticity (MPa)	3500	Chemical resistance	Excellent
Elongation at break (%)	10 to 45	Resistance to mildew, moth	Excellent
Moisture absorption (%)	0 to 0.05	Ability to protest friction	Excellent
Softening point (ºC)	140	Ability Against Acid affect	excellent
Melting point (ºC)	110-180	Ability Against Insect	Excellent

The fibres used are extracted from rope 0.6 cm in diameter, provided from the local market for domestic use (Figure 2). The rope was cut to a size of 4 and 8 cm; the measurement gave an average value of 0.3 mm of diameter for singular fibre. The laboratory tests gave the value of 0.905g/cm3 for density and 80 MPa for the tensile strength.

Figure 2: polypropylene fibre

2.3. Concrete mix batches

To calibrate the effect of the macro polypropylene fibre for a wide perception of this material on the behaviour of concrete, the fine sandy concrete was prepared for an amount of 250 kg of cement per cubic meter. In the second step, the fibres were added to the concrete during mixing in 2 sizes (4 and 8 cm) and 2 amounts of weight (2.5 and 5 kg/m3). The first control mix (M(0)) without fibre was designed to define the resistance value of an eligible batch for a fibre of 8 cm. The addition of Polypropylene fibre showed the impossibility of providing a batch of W/C =0.7 for a suitable slump. Thus, the M(0) batch was modified to M(0/0) by increasing the amount of water to reach a value of W/C=1.55 which allowed the production of a concrete capable of accepting the fibres in the mixer and ensuring easy mixing and a valuable consistency. The main information on the concrete batches and the average output after the compression test are detailed in Table (2), where the values of Slump and Compression Strength are reported as the average value of 5 samples for each batch

Table 2: Coding samples and input and output information

Batch	Fresh concrete density Kg/m^3	Number of fibres per cube	W/C	Fibre length (cm)	Fibre ratio	Slump	Average load (P) (kN)	Strength	ΔH	Strain ε%
M(0)	1840	0	0.70	-	-	8.0	108.00	4.800	0.4	0.27
M(0/0)	1702	0	1.55	-	-	18	20.50	0.911	0.2	0.13
M(4/2.5)	1717	3297.4	1.55	4	2.5	6.7	62.17	2.763	9	6.00
M(8/2.5)	1717	1648.7	1.55	8	2.5	6.1	68.70	3.053	10	6.67
M(4/5.0)	1737	6594.8	1.55	4	5.0	5.9	82.20	3.653	12	8.00
M(8/5.0)	1737	3297.4	1.55	8	5.0	5.1	79.30	3.524	13	8.67

2.4. Sampling

To investigate the role of fibre on the concrete behaviour 5 cubic samples of 15 cm were taken for each batch. The total number of trial tests was of 25 samples coded as in Table 3. According to ASTM-192 recommendation, 15 samples were cured for 24 hours, and conserved in water with a temperature of 22±2C°.

3. Experimental results and discussion

3.1. The consistency

Analysis of the effect of fibre length and weight on the slump of fibred concrete, in both cases either for 2.5 and 5 kg of fibres either for 4 and 8 cm length, shows that the fibres decrease the consistency and significantly reduce the slump of the fibered concrete (Figure 3).

Figure 3: slump test

The conception of concrete mix for W/C=1.55 gives the concrete high fluidity; however, the addition of fibre significantly reduces the workability (figures 4, 5). This phenomenon could be explained by the special structure of the fibres which act as an interstitial textile that behaves according to the intensity of the interlocking of the fibre itself and their amount of number in the concrete batch (Table 2).

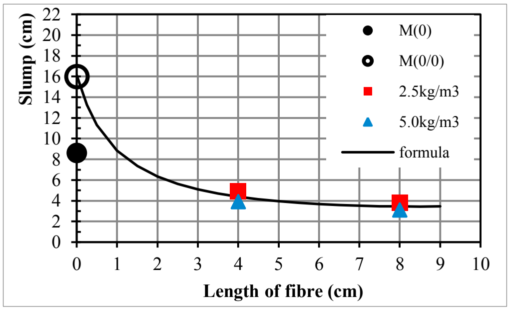

Figure 4: role of fibre length

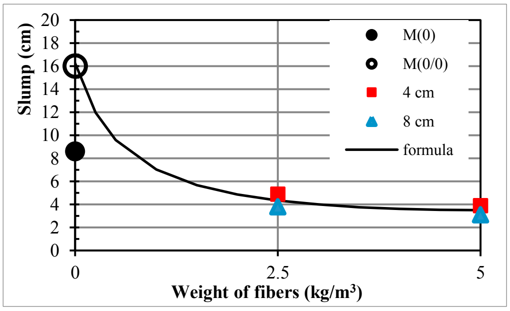

Figure 5: role of fibre weight

To control the quantity and the length of fibres, the general relationship, between a slump and either fibre length or weight, is proposed by mathematical simulations following the equations:

For length $$S = \frac{1}{[6.2\ x10^{-2} + (5.42\ x10^{-2})L - (3.21x10^{-3}\ )L^2]} \quad (1)$$

For weight $$S = \frac{1}{[6.16x10^{-2}\ + (8.98x\ 10^{-3})\ W - (8.99x10^{-5}\ )\ W^2]} \quad (2)$$

Where: S slump (cm), L fibre length (cm), W fibre weight (kg/m^3).
The previous mathematical simulation allows choose the adequate length and quantity, where it seems that the optimal values should be respectively less than 2.5 kg of weight and 4 cm of length.

3.2. The compression strength

Concrete was subjected to the mono-axial compression test, per set of 5 samples, after an age of 28 days. The control samples (M(0)) collapsed for an average load of 108 kN (4.8MPa) and the collapse shape took a regular pyramid form (Figure 6). Furthermore, the samples M(0/0) collapsed under an average load of 20.9 kN (1.2 MPa), with the drop of strength caused by the huge quantity of water that reached 375 l/m$_3$.
Whereas the concrete reinforced with polypropylene fibre maintained its cubic shape (figure 7) and recovered some strength according to the length and the fibre ratio (figure 8). Moreover, the specimens are collapsed after a large deformation due to the enormous ductility that the concrete gained by the addition of the fibre, where the deformation (ε) reached a value of 8% for M(8/5.0).

Figure 6: Collapse form of M(0)

Figure 7: Collapse form of M(4/25)

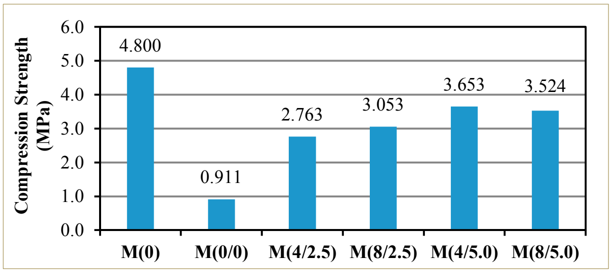

Figure 8: relation between compression strength and both length and weight

Figures 9, and 10 show that the increasing rate of compressive strength is more sensitive to the weight of the fibre than to its length. On the other hand, the rise of the length from 4 to 8 cm is insignificant contrary to the weight which can add a significant value to the resistance of the concrete. This result is confirmed by the number of fibre for M(4/5.0) and M(8/2.5) where the strength of the first is better than the second one. Thus, for better feasibility it is interesting to find the balance between weight and length to make the granular medium more homogeneous and give it better consistency.

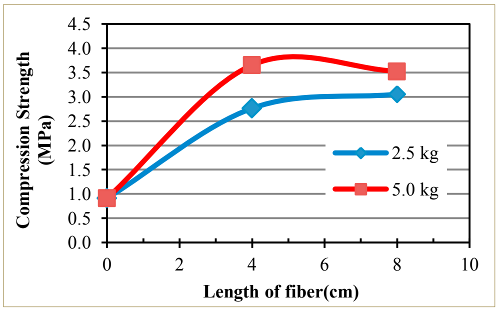

Figure 9: Role of length of fibre

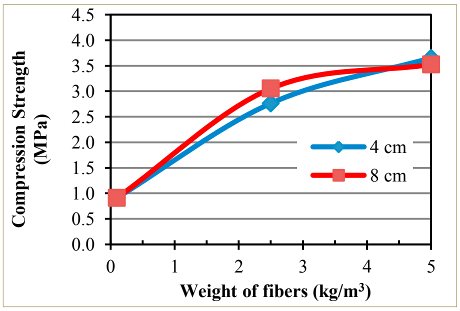

Figure 10: Role of weight of fibre

3.3. The ductility

The value of the deformation was noted before the sample lost the capacity to resisting to the applied loads (Table 2). These values prove that the most important contribution of the fibre to the concrete properties is the large ductility before rupture.

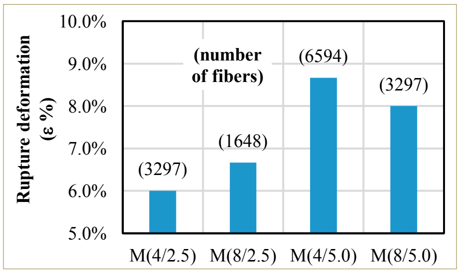

Figure 11. Relation of fibres' number and collapse deformation

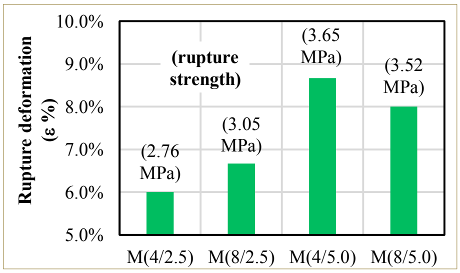

Figure 12. Relation of stress and collapse deformation

The value of the collapse deformation, as shown in figure (11), depends on the length, the weight of fibres, and consequently the number of fibres; where all these factors contribute to the strength of the fibre concrete (figure 12).

These results allowed to conclude that the concrete batch M(4/5.0) is the best mixing where it assures a wide ductility and significant strength.

4. Contribution of fibre on the compression strength

Several studies have been interested in knowing the way in which the fibre acts within the concrete. Cox (1952) introduced his original theory of stress transfer from the paper matrix to the fibre, which could be used in the same way for fibre concrete. Li and Stang (2001), Laranjeira (2010) proposed a probabilistic parameter (*f*) to take into account the random distribution of fibre in concrete batch. They proposed a probabilistic parameter (η_{ϕ}), its value is defined by integration of the density function of 2 parameters p(z), p(Φ), where (z) is the center of gravity of fibres and (Φ) its orientation in the space, where it takes the form ($\eta_{\phi 3D}$) and has the value $\eta_{\phi 3D}$ =1/2.
Taking into account this parameter, the total compression load F_t is transferred within the concrete body in proportion between plain concrete and fibres:

$$F_t = F_f + F_c \tag{3}$$

Where F_t, F_f, F_c are respectively the applied force on the total section, the portion force on the fibres, and the portion force on the plain concrete. Meanwhile, due to the high flexibility of the fibre, they form in the mixture a kind of space mesh tissue. This leads to looking at the contribution as an integral body in the matrix of the concrete. From this point of view, the contribution of the fibres is calculated by the difference in strength between the two cases plain concrete and fibre concrete, (Figure 13).
As shown the fibre of 4 cm length and 5 kg volume ratio has the best performance between the four composition of fibre concrete; that confirm the results given below regarding the ductility and the strength of the fibre dune sand. On the other hand, the number of fibres remains the dominant factor to assure a better homogeneity of concrete mix for fresh and hard concrete. Figure (14) shows that the effect of the number of fibres is not limited for 4cm length as well as for 5 kg weight able to increase strength; contrary to 8 cm length here its effect stagnates.
Hence, the addition of fibre to the concrete batch needs a good choice of the physical properties of the fibre as well as the volume ratio to have the better number that composes the space fibre tissue in the matrix of the dune sand concrete.

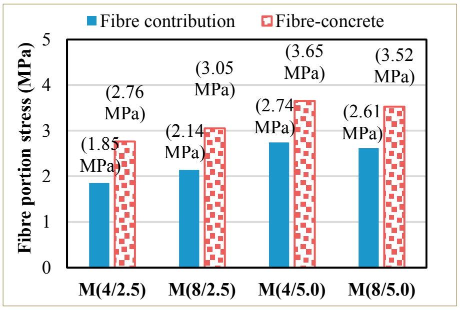

Figure 13. The fibre contribution to the strength of concrete

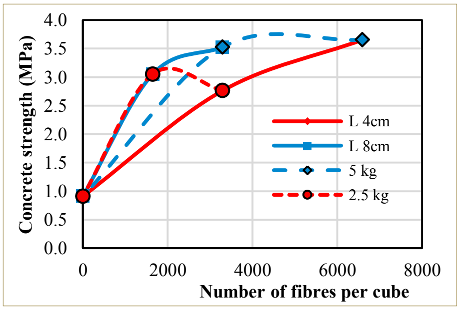

Figure 14. Effect of number of fibres

5. Conclusion

The study proves the feasibility of using polypropylene fibre to improve the mechanical properties of dune sand concrete under compression loads. Generally, polypropylene fibre has the ability and the performance to improve moderately the strength of the sand dune concrete and to significantly increase its ductility and its toughness.
However, the length and the weight, consequently the number of fibres, condition the performance of the hardened concrete, where for the same weight ratio of fibre, the experimental results show that for the fibre for 4 cm of length and 5 kg of weight perform the concrete better than fibre for 8 cm of length and 2.5 kg of weight.

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Harvesting Solar Energy for Sustainable and Resilient historical areas. A Norwegian Case study

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Abstract

Toward cities' energy transition, historical urban areas are at risk of being abandoned due to energy inefficiency and high costs of retrofitting. Deployment of renewable energy solutions, such as solar energy technology, can strengthen resilience of these areas by fostering energy independence and lowering operational costs, while preserving their cultural and historical value for both cities and their residents. However, the integration of solar systems into these culturally significant urban spaces, brings challenges and barriers that require thoughtful and multi-criteria evaluation and prioritization to safeguard their inherent value and ensure their resilience for the future. In this paper, a literature review was conducted to identify conservation criteria/challenges that define successful implementation strategies for solar integration in historical urban areas. The findings suggest that challenges such as non-invasiveness, compatibility, and reversibility need to be addressed. Additionally, legislative gaps emerge as main barrier that requires targeted interventions. The study evaluates whether these challenges and barriers are consistent with those found in Møllenberg neighborhood in Trondheim, Norway as a case study historical area or whether such area requires specific and tailored measurements. The results offer insight into potential solutions and strategies to integrate solar technology for increasing the resilience of historical urban areas.

Keywords: solar energy; BIPV; challenges; barriers; historical neighborhoods; Norway

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1. Introduction

Nowadays, approximately half of the world's population lives in cities, two-thirds of the world's energy consumption is generated by cities, and 70% of the world's carbon emissions are released by cities each year (Net Zero by 2050 – Analysis, 2022). In this scenario, achieving net-zero emissions goals requires climate and energy actions in cities. The technical feasibility and economic viability of 100% renewable energy systems are underway in most regions of the globe (Bogdanov et al., 2021) and among the renewable energy sources (RES), solar energy is considered to be one of the most effective and applicable at building, neighborhood, and city scale (Gong et al., 2019). However, the integration of solar technology within urban contexts, especially in historical areas, is still a fundamental challenge that requires a multitude of criteria to be addressed like feasibility and acceptability (Lobaccaro et al., 2019). To achieve climate neutrality in 2050 (Commission, 2020) and, the Green Deal objectives (Kazak, 2020), using RES including solar energy has a pivotal importance. In that regard, one of the latest trends in photovoltaics applications reports that "(*Approximately 100 Million Households Rely on Rooftop Solar PV by 2030 – Analysis*, n.d.)". To fully decarbonize the electricity system, solar PV will have to be installed on suitable urban surfaces (i.e., roofs, facades, and ground). In the energy sector - with levels of competitiveness that mostly depend on the fluctuation of electricity prices and taxes - households become essential in the decarbonizing development. Policies toward sustainable transition are increasingly complex, as are the barriers to PV adoption: the more mainstream PV becomes, the more new barriers like conservation and technical limitations stifling its development are encountered (Pvps, 2021). Through a literature review, this study aims to explore barriers and challenges tied to incorporating solar technology systems and getting deep within the Norwegian historical district of Møllenberg, in Trondheim (lat. 63°25' N). The structure of the paper continues as follows: Section 2 presents the methodology of the scoping review and the case study; Section 3 includes the results of the scoping review, and the discussion of the results from a challenges, barriers, and opportunities perspective in the Norwegian historical context; and Section 5 concludes the paper with some suggestions for future developments.

2. Methodology

Employing the "scoping methodology" outlined by (Arksey & O'Malley, 2005), this article examines information from selected papers categorized according to factors challenges, barriers, opportunities of deployment of solar systems in historical urban areas in papers and reports. The clustering and organization of this information yield challenges which are conservation criteria as milestones and barriers as obstacles. A short definition of the adopted conservation criteria at the light of the implementation of solar technologies in historic urban areas is as the follow(Akbarinejad et al., 2023):

2.1. Challenges/Conservation criteria

1. **Viability**: economic viability refers to the difference between the total costs in a Building Integrated Photovoltaic (BIPV) installation (i.e., initial cost, operation, and maintenance) and the income (i.e., electricity price sells to the grid defined by local feed-in tariffs). If the difference is smaller or equal to the costs of electricity consumption from the grid, then the project is viable or even profitable (Polo López et al. 2021).
2. **Feasibility**: economic feasibility is the analysis of costs/benefits that can be evaluated through economic indicators such as the Net Present Value, the Levelized Cost of Energy, the return on investment, or the payback period (Sommerfeldt and Madani 2017).
3. **Integration**: integration of BIPV to the existing urban surfaces should address architectural and aesthetic aspects (Polo López, Troia, and Nocera 2021). A "morphological integration" indicates that the layout and shape of the panels harmonise with the surrounding built environment (Durante, Lucchi, and Maturi 2021).
4. **Reversibility**: technical reversibility means that it is possible at any moment to take away the BIPV installation and go back to its original condition. Reversibility also means that it is possible to replace the BIPV panels without affecting the integrity and the historic value of the structure (Kandt et al. 2011). This means that – if applied to historic buildings - the PV installation should be attached as a mountable and demountable structure that would avoid affecting the features of the property while replacing them (Sudimac, Ugrinović, and Jurčević 2020).

5. **Compatibility**: the compatible criterion is covering several aspects such as technical (e.g., choice of materials, fixing system and hygrothermal components - avoiding the development of moisture), structural (i.e., to avoid excessive deflection due to e.g., snowfall, wind gusts, and ageing), aesthetic (e.g., choice of colour, texture of materials, spatial layout and morphological fit (P. López 2020)), chemical (difference in chemical components and properties between old and new materials that could react together or weathering at different degradation rates (Polo López et al. 2021)) and functional (more complex for BIPV that implies multi-functional properties beyond the merely generation of electricity, but also replacing tiles, the façade or the windows and therefore in need of fulfilling multi-functions).
6. **Reliability & safety**: Reliability refers to the assessment of the quality and durability of the transformation after the BIPV installation, which should be made in a way to avoid maintenance and decay (De Medici 2021). Whereas safety is evaluating the risks generated by the installation (e.g., fire and electrical safety, maintenance operations).
7. **Non-invasiveness**: this criterion has a twofold significance. On the one hand, non-invasiveness corresponds to the conservation value of keeping some authentic features on the building, on the other hand, it can be interpreted as the idea of not “tricking” the eye and exposing clearly what is authentic and what has been added (Kandt et al. 2011). The replaced parts of a building envelope should be distinguishable from the rest, while still being designed in harmony with its environment (Polo López et al. 2021; Polo López, Troia, and Nocera 2021).
8. **Acceptability**: Acceptability is complex to predict or measure as it is not tangible or material value. It strongly depends on the significance of a place and or building’s values e.g., historical, sentimental, symbolic, cultural, and social and whether those values are respected through the transformation. It can be seen as an individual perception or a community’s perception.

2.2. Barreires

1. **Economic barriers**: Economic barriers to PV-BIPV installations in historical areas primarily revolve around high initial costs, lengthy payback periods, and the elevated expenses associated with expert consultations to preserve architectural integrity, contributing to property owners' reluctance **(**Jackson Inderberg et al., 2020; Kandt et al., 2011a; Mete Basar Baypinar, Enes Yasa, Selahattin Ersoy, Cem Beygo, Kerem Beygo, n.d.; Polo López, Troia, et al., 2021; Rosa, 2020)
2. **Geographic barriers:** The geographical barriers to BIPV implementation predominantly arise from location-specific legislation protecting cultural heritage and variances in local outdoor temperature affecting PV efficiency, coupled with policy and insufficient sunlight or landscape restriction. (Ibrahim et al., 2021 ; Sánchez-Pantoja et al., 2021).
3. **Technical barriers:** Involves limitations due to the need to preserve the historical integrity and aesthetic of an area, affecting the types or modifications of solar installations permissible and lack of standardized data in this field. (Durante et al., 2021; Formolli et al., 2022; Imenes, 2016; Mete Basar Baypinar, Enes Yasa, Selahattin Ersoy, Cem Beygo, Kerem Beygo, n.d.; Pelle et al., 2020; Polo López, Troia, et al., 2021; Rosa, 2020)
4. **Legislation Barriers:** Legislative and procedural barriers, including complicated authorization processes and a lack of clear legal guidelines, hinder the implementation of Building-Integrated Photovoltaics (BIPV) in historic districts, with stringent regulations and fragmented legislation causing variations in solar initiatives between countries and within regions (Kandt et al., 2011a; Lucchi et al., 2022; Pelle et al., 2020; Polo López, Troia, et al., 2021; Sesana et al., 2019). The inconsistencies, unclear regulations, and the absence of universal solutions due to the unique nature of each site create uncertainties and deter advancements in integrating renewable energy solutions in protected and historically significant sites, despite the overarching support and encouragement from EU legislations and programs like Horizon 2020 for energy efficiency and renewable energy incorporation.(De Medici, 2021; *Horizon Europe*, 2022)
5. **Conservation criteria:** Revolve around the challenges and restrictions associated with conserving the architectural and cultural heritage of historical areas, limiting modifications and implementations of solar energy systems.(Ibrahim et al., 2021; Meraz, 2019; Polo López, Troia, et al., 2021; Roszczynska-Kurasinska et al., 2021; Sesana et al., 2019; Tsoumanis et al., 2021)

6. **Social barriers**: rooted in acceptability and non-invasiveness conservation criteria, impede the integration of BIPV in historic buildings due to a prevalent lack of awareness, knowledge, and communication among citizens, stakeholders, and interdisciplinary experts, and a dearth of illustrative pilot projects and clear guidelines (Elena et al., 2017; Kalliopi et al., 2022; Kandt et al., 2011a; Sánchez-Pantoja et al., 2021) Combined with a lack of collaboration and co-creation among scientists, policy-makers, and professionals, there is a void in understanding and implementing viable BIPV solutions for heritage conservation contexts due to the lack of exploration of social acceptance and aesthetic impacts of renewable technologies.(Mete Basar Baypinar, Enes Yasa, Selahattin Ersoy, Cem Beygo, Kerem Beygo, n.d.)

2.3. Case study area

The pilot city is Trondheim (lat. 63°25' N), ranks as Norway's third-largest city and a population of approximately 190,500 inhabitants. The selected study area is the historical neighborhood of Møllenberg. This neighborhood consists mainly of two-story wooden houses from the 1880s and 1890s Møllenberg was primarily a working-class neighborhood inhabited by families with children. In recent years, many of the wooden houses have been converted into student housing. (Fig 1).

Fig 1: A Bird’s view of Møllenberg, Trondheim, Norway

Beside the difficulties in renovating because of the buildings’ significance, the climatic constraints remain the main limitation in Møllenberg as well as in similar high latitude sites subjected to significant seasonal and day length variations, prolonged period of darkness in winter, and low sun angles during winter and mid-seasons which lead to increased overshadowing by buildings and landscape, along with cooler temperatures due to the wider distribution of solar irradiation (Formolli et al., 2023; Westerberg & Glaumann, 1990). Notwithstanding, these sites become remarkably well suited for PV installation during summer. (Formolli et al., 2023; Westerberg & Glaumann, 1990). This potential has to be exploited to balance the preservation of the significance of a historical district located in a high latitude city (Sandvik, 2006)

This research employs a multi-step methodology, initiating with an extensive literature review to evaluate challenges and barriers in solar technology implementation. A focused case study in Norway is then conducted to compare theoretical insights with real-world scenarios, allowing for the formulation of practical, validated guidelines to overcome the identified barriers suggested in fourth step. This approach aims to harmonize the integration of renewable energy technologies in historic areas by addressing the challenges both theoretically and practically.

Figure 2 Multi-step Methodology

3. Results and discussions

As a first step of the methodology, the Table 1 compiles the review of 34 articles focused on the challenges and barriers to the integration of solar technology in historical buildings. Challenges are represented by white dots, and barriers are symbolized by black dots in Table 1.

Table 1 References to challenges and barriers retrieved in literature.

	References	Challenges								Barriers					
		Viability	Feasibility	Integration	Reversibility	Compatibility	Reliability & Safety	Non-invasiveness	Acceptability	Economic	Geographical	Technical	Conservation	Legislation	Social
1	(Kandt et al., 2011a)				○					●		●	●	●	●
2	(Guttormsen & Fageraas, 2011)													●	●
3	(Røstvik, 2013)													●	
4	(Moschella et al., 2013)													●	
5	(C. S. P. López & Frontini, 2014)													●	
6	(Imenes, 2016)											●		●	
7	(Borda & Bowen, 2017)													●	●
8	(Tzetzi, 2019)									●				●	●
9	(Sesana et al., 2019)					○							●	●	●
10	(Thebault et al., 2020)		○							●		●		●	●
11	(Sudimac et al., 2020)				○						●	●			
12	(Pelle et al., 2020)				○	○		○						●	●
13	(Rosa, 2020)				○			○		●				●	●
14	(Lucchi et al., 2020)													●	
15	(P. López, 2020)					○						●	●		
16	(Jackson Inderberg et al., 2020)									●		●		●	●
17	(Roosmalen & Gritzki, 2020)											●		●	●
18	(Gholami et al., 2020)									●					
19	(Durante et al., 2021)			○					○			●		●	
20	(De Medici, 2021)						○		○					●	
21	(Polo López, Lucchi, et al., 2021)	○			○	○		○	○	●		●	●	●	●
22	(Polo López, Troia, et al., 2021)			○		○		○					●	●	●
23	(Ibrahim et al., 2021)										●	●	●	●	●
24	(Xue et al., 2021)									●					●
25	(Roszczynska-Kurasinska et al.,												●	●	●
26	(Sánchez-Pantoja et al., 2021)										●			●	
27	(Tsoumanis et al., 2021)											●	●	●	
28	(Shuldan & Al-Akhmmadi, 2021)												●		●
29	(Kalliopi et al., 2022)							○				●		●	●
30	(Lucchi et al., 2022)									●		●			
31	(Lucchi et al., 2022)													●	●
32	(Cumo et al., 2022)													●	
33	(Badawy et al., 2022)											●			
34	(Mete Basar Baypinar, et al)									●		●		●	●
		1	1	2	5	5	1	5	3	10	3	15	9	27	20

The review reveals that the integration of solar technology in historical buildings presents multifaceted challenges and barriers that should be overcome for their successful implementation and there is lack of solution or a variety of approaches able to effectively address the various aspects simultaneously. In the second step, these articles are organized based on the conservation criteria including viability, feasibility, integration, reversibility, compatibility, reliability & safety, non-invasiveness, acceptability which considered challenges and economic, geographical, technical, conservation, legislation, and social barriers and sorted by time of the publication. A frequency in the last line of the chart reveals that between conservation criteria reversibility, compatibility and non-invasiveness are more mentioned (5 times each)References to challenges and barriers retrieved in literature.. In addition, among barriers, legislation is the most frequented cited, appearing 27 times, followed by social consideration, cited 20 times and technical limitations 15 times. These findings provide an overview of the predominant and pressing issues that need consideration for the successful implementation of solar technology in historical building and illustrated by red dash color Fig 4 step 2.

In the step 3, Considering the findings from the review, while general challenges and barriers are discussed in a broader context, a more local analysis on case studies is necessary. In this paper, such analysis has been conducted on the area of Møllenberg, renowned for its historical richness and architectural values (Sandvik, 2006). Reviewing internal reports in Norway(*Photovoltaic Systems at Møllenberg*, n.d.; *Solar | Helios | Norway*, n.d.) prove that the challenges encountered in Møllenberg are the ones carried out from the literature review as well.

- **Non-Invasiveness:** Trondheim's historical buildings require that any technological incorporation be non-invasive both structurally and visually. To enable non-invasive solar technology in historical buildings, various methods can be employed. Strategic placement of solar panels (Al-Ahmmadi Saer & Larisa, 2021) (*Photovoltaic Systems at Møllenberg*, n.d.) with samples of solar tiles in the market to minimize the visual impact and preserving the aesthetic and historical values (Špaček et al., 2020). Removable mounting systems preserve structural integrity (Kandt et al., 2011b). BIPV offer aesthetic compatibility (Polo López, Troia, et al., 2021; Rosa, 2020). Furthermore, consultation with heritage experts and regulatory approvals are essential (Kandt et al., 2011).
- **Compatibility:** One of the main concerns of residents and municipality in Møllenberg is keeping the identity of this area as it is. Therefore, the use of compatible solar technology in historical buildings like those in Møllenberg refers to the idea that solar installations should align well with the building's architectural style, materials, and historical value (Cabeza et al., 2018). Customized designs, such as BIPVs, can mimic traditional materials to maintain aesthetic harmony (Li, 2021) in terms of architectural and technological compatibility (Fedorova et al., 2020). Strategic placement and color matching of BIPV further help in minimizing visual impact (Lee, 2021). Consultation with heritage conservation experts can help to maintain architectural integrity (Hmood, 2019). This consideration shows that collaboration between architects and conservation experts and BIPV advisors and community ensures the solar installations uphold the building's historical integrity.
- **Reversibility:** In conservation, reversibility means that any changes or additions to a structure can be reverted, allowing them to be removed or altered in the future without permanently damaging the structure. In Møllenberg, the principle of reversibility in conservation can be upheld through the use of removable mounting systems, modular plug-and-play solar components, and temporary structures that are aesthetically aligned with the area's historic architecture as presented in (Shuldan & Al-Akhmmadi, 2021). Transparent PV panels which can be used in windows, roofs, or facades with a potential of changing could be a solution. Same as other challenges collaborative planning with heritage organizations ensures compliance with conservation guidelines, making reversibility achievable (Gigliarelli & Quattrone, 2014).

Fig 3 Part of the Møllenberg area (on the left), the application of the solar roof tiles (in the middle) and transparent PV (om the right).

Besides challenges, it is crucial to address barriers on the integration of solar technology into historical setting. In that regard, legislation procedure is the most frequented cited barriers in the literature.

From the review of some reports in Norway, it can be noticed that the lack of social acceptance is another relevant barrier to be addressed Fig 4 step 4 which illustrated by red full line box.

- **Legislative:** The Møllenberg neighborhood in Trondheim is protected by heritage regulations, with Byantikvaren playing a pivotal role in advising on the cultural monuments and environments (*Byantikvaren*, n.d.). The main obstacles are the complication of the authorization process and the lack of clear legal guidelines. More than Byantikvaren's value, fire and safety, construction, and safety in Møllenberg can effectively stymie the adoption of RES solutions, requiring prolonged negotiations and adjustments to develop.
- **Social barriers**: In Møllenberg, stakeholders including owners, tenants, the municipality, consultants, and Antikvaren encounter significant barriers due to a lack of awareness and communication regarding the implementation of Building Integrated Photovoltaics (BIPV). This lack of interdisciplinary collaboration and knowledge-sharing works as a barrier to utilizing solar technology with the respect to conservation within the area.

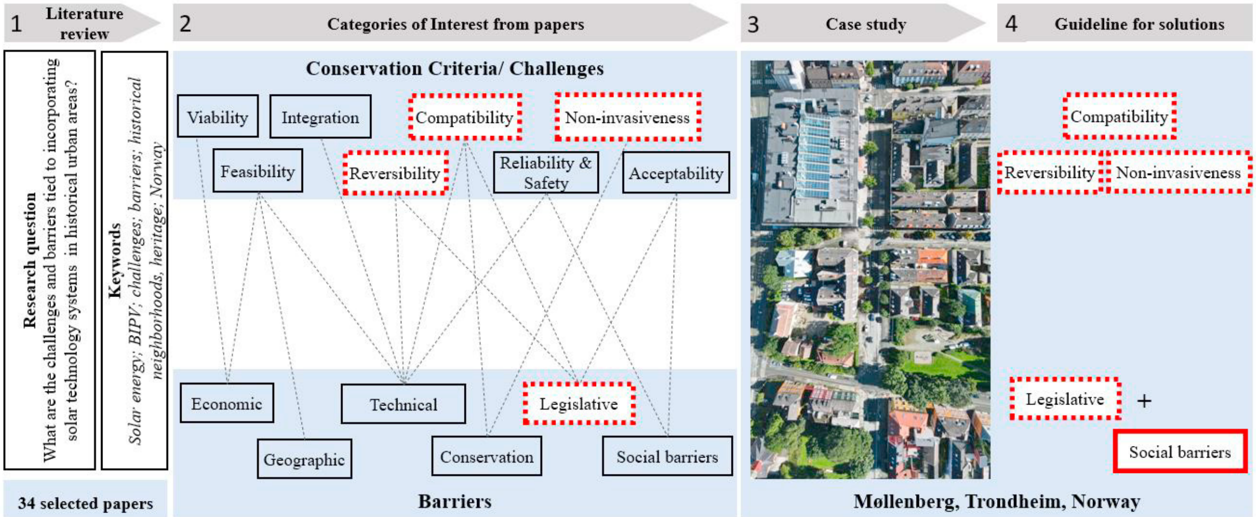

Fig 4 Summary of the workflow from the literature review to the analysis of challenges and barriers in the case study of Møllenberg.

The study's limitations may include a narrow geographical scope (Møllenberg, Norway) that limits the generalization of its findings to other historical areas with different cultural, social, or regulatory contexts. This could also restrict its broader applicability, as the legislative and technical challenges identified might not be globally applicable. Additionally, the paper does not fully capture the complexity of stakeholder's perspectives, such as local authorities or residents, which could provide additional considerations to the challenges, barriers, and opportunities.

4. Conclusion and further developments

The increasing technical feasibility and economic viability deployment of RES systems, particularly on solar energy, make them suitable solutions to achieve net-zero emissions by 2050 towards a sustainable and low-energy transition process. However, their integration into urban built environment, especially historical neighborhoods, and buildings, is fraught with challenges and barriers. The hereby study explored these challenges and barriers in the context of Norway, with a specific focus on the neighborhood of Møllenberg in Trondheim. The literature review highlighted a range of conservation criteria/challenges and barriers that should be considered for the successful integration of solar technology systems into historical settings. Among these, reversibility, compatibility, and non-invasiveness emerged as pressing challenges and legislative procedure appeared most frequently barriers, suggesting a need for targeted intervention. The Møllenberg case study serves to evaluate the extent to which the identified challenges and barriers apply to this specific neighborhood. The results indicate that Møllenberg faces similar challenges as those detected from literature, with the added complexity of social barriers due to a lack of public acceptance for solar energy solutions. These findings offer valuable insights for policymakers to develop strategic plans to meet global sustainability goals in historical areas, which represents one of the most relevant concerns considering the high prevalence of historical areas across Europe.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Improvement in the Energy Efficiency Label level – PBE Edifica: Case Study of the Community Library of the Federal University of São Carlos (UFSCar) – São Paulo - Brazil

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Abstract

This article describes the application of a method of environmental certification of buildings used in Brazil and named as Brazilian Labelling Program PBE–Edifica. The method was developed by Procel, National Electric Energy Conservation Program, which confers, four Labels of the Energy Efficiency levels of a building, covering the Envelope; the Lighting System; the Indoor Air Conditioning; and the building Overall, which includes all previous levels and bonuses. The levels and scope of the Label apply both in the design phase and after construction or existing building in accordance with the Technical Quality Regulation for the Level of Energy Efficiency for Commercial, Service and Public Buildings, RTQ-C. The efficiency level ranges from A to E, where A is the most efficient and E the least efficient. The method also considers Bonuses that allow improvements in the Overall Classification efficiency. Thus, the objective of the research carried out was to identify the classification of the level of energy efficiency of an existing building on the campus of the Federal University of São Carlos, the Community Library, called BCo, Brazil built in 1995 with an area of 6,947.48 m^2. The guidelines of the PBE Edifica using the prescriptive method were applied, and the characterization of the level of energy efficiency was carried out based on data obtained from plans and technical drawings of the building, and through a technical visit to obtain the data for entry into an application, WebPrescriptive. To obtain specific information about the wall's thermal transmittance and roof solar absorbance the PROJETEE application was used. All information processed so the building obtained an Overall classification C. For envelope and lighting level E, and air conditioning level B. To improve the level of efficiency, through bonuses, improvements in the lighting system and the elevator were suggested, resulting in level B for both Lighting and Overall efficiency. Notice that the building, due to its design and construction system does not have the conditions to reach level A of efficiency. In conclusion, we would like to point out that it is feasible to submit the building to the formal labelling process, since the proposed improvements

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resulted in an Overall Energy Efficiency Rating B. As a contribution for EFFICACY Project, some guidelines to be considered for buildings rehabilitation will be stated, as simulation of thermal insulation in facades and others improvements.

Keywords: Energy Efficiency; Energy Labelling; Procel-EDIFICA; RTQ-C; WebPrescritivo; PROJETEE

1. Introduction

In Brazil, buildings are responsible for the consumption of 48% of electricity in the country, in addition most of the energy is used by the commercial sector (90% of electricity use), with little participation from other sources (BOERGSTEIN, LAMBERTS, 2014).

Therefore public sector is responsible for a large part of Brazilian energy consumption. The consumption of this sector in 2010 was 36,919 GWh, according to data from the Ministry of Mines and Energy, in addition it increased consumption by more than 25% when compared to 2003. According to PROCEL, technical and managerial measures, low investment would be enough to reduce energy costs in the public sector by 15% to 20% (MME, 2021).

In Brazil, there are already guidelines that regulate the processes of determining energy efficiency and energy conservation since the 1980s, called Procel (ISSA, BRIANTI, ZUCCHI, 2020).

In 2003 the Procel Edifica program was implemented and in 2005 the Technical Requirements for the Quality of the Level of Energy Efficiency of Commercial, Service and Public Buildings (RTQ-C) and the Technical Regulation for the Quality of the Level of Energy Efficiency of Residential Buildings were established (RTQ-R). Both establishing the requirements, parameters, and methods for evaluating a building (ELETROBRAS, 2013).

The objective of this article is to present in detail the process of determining the level of energy efficiency, in accordance with the RTQ-C, in the case study of the Community Library of the Federal University of São Carlos, and based on this level of energy efficiency, propose actions that result better energy performance of the building.

Considering that the thermal insulation of external wall coverings contributes significantly to improving the energy performance of buildings, this article is also a contribution to the EEA Financing Project (EFFICACY, 2023), which aims to develop guidelines to systematize relevant criteria for solutions thermal insulation in existing buildings, in rehabilitation and/or in new constructions.

2. Labelling

The PBE Edifica label, , developed in partnership between Inmetro and Eletrobras/PROCEL Edifica (ELETROBRAS, 2013). evaluates and classifies the energy performance of buildings as a whole

In Brazil, manuals that detail and organize topics related to the building labeling stage are the following:

- Technical Quality Regulation for the Energy Efficiency Level of Commercial, Service and Public Buildings **(RTQ-C**) and
- Technical Quality Regulation for the Level Energy Efficiency of Residential Buildings **(RTQ-R);**

The RTQ-C, like the RTQ-R, brings concepts and definitions, in addition to presenting procedures to establish the levels of energy efficiency in buildings (ELETROBRAS, 2013). At the end of the labeling process, the building obtains a label with a classification ranging from A (maximum factor – most efficient) to E (minimum factor – least efficient). The labelling can be applied in two circumstances: design stage; and in existing building.

Evaluation of efficiency level can be carried out by the following methods:

- **prescriptive method:** surveys of a set of characteristics of the building and, through calculations, it can be obtained the partial level of efficiency for building envelope, lighting, air conditioning systems, and the overall building;

- **simulation method:** more complex, it uses software that allows the incorporation of new technologies in terms of materials (construction and thermal insulation), and passive and active conditioning strategies, among others.

At the end of the evaluation process the building labelling (design or existing) receives a Label as showed in Fig. 1.

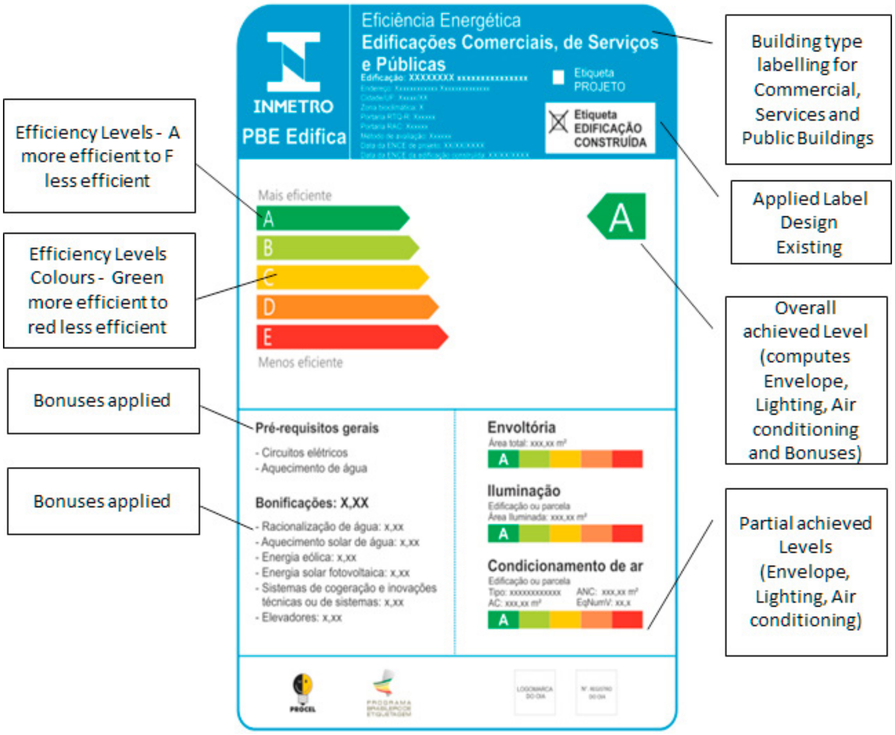

Fig. 1. Label indicating the efficiency level (ELETROBRAS, 2013).

3. Material and Method

3.1 Labeling process analysis

The methodological procedure for assessing the level of energy efficiency for Building Labeling is contained in the RTQ-C Manual (PROCEL, 2017). As preliminary analysis, it should be stated if a building (design or existing) attends some prerequisites related with electrical circuits and hot water systems, that allow to establish if the overall label can reach level A or not. From this point, the analysis can proceed to find out the partial Efficiency level for: Envelope, Lighting and Air Conditioning. In addition to these, Bonuses could be considered for the upgrade of the Overall Efficiency Level of the building.

The labeling is composed of steps for the analysis of three separated system (Partial) and for the entire building (Overall):

- **Envelope:** made with the determination of a set of indices referring to the physical characteristics of the building.
- **Lighting System:** determined by calculating the power density installed by the internal lighting, taking into account the activities carried out inside of building.
- **Air Conditioning System**: divided into two classes: the first is the one that makes up the individual and split components that are already classified by INMETRO (National Institute of Metrology, Quality and

Technology), while the second is related to air conditioning systems not yet classified by, such as the central ones.

For the systems and the partial or overall classification of the building, the prescriptive method apply the following Equation 1, in which a weighted efficiency classification resulted from weights applied to each system.

$$PT = 0.30\left[\left(EqNumEnv\,x\,\frac{AC}{AU}\right)+\left(\frac{APT}{AU}x5+\frac{ANC}{AU}xEqNumV\right)\right]+0.3\,x\left(EqNumDPI\right)+0.4x\left[\left(EqNumCA\,x\,\frac{AC}{AU}\right)+\left(\frac{APT}{AU}x5+\frac{ANC}{AU}xEqNumV\right)\right]+b_0^1 \quad (1)$$

Where:

PT: Overall efficiency level;

EqNumEnv: numerical equivalent of the Envelope;

EqNumDPI: numerical equivalent of the Lighting system, identified by the acronym DPI (Lighting Power Density);

EqNumCA: numerical equivalent of the Air Conditioning system;

EqNumV: numerical equivalent of non-conditioned and/or naturally ventilated environments;

APT: useful area of transitory stay, with no air conditioning system;

ANC: useful area of unconditioned environments for prolonged stay, with proof of percentage of occupied hours of comfort by natural ventilation (POC) through the simulation method;

AC: useful area with air conditioning system;

AU: useful area;

b: score obtained by the bonuses, which varies from zero to 1.

Partial and overall efficiency level calculations can be improved in illumination and air conditioning systems. Also the last term Eq.1, b (Bonuses), is considered can increase the overall efficiency level. Should be since it is an added parameter in (last term). It should be noted that there are mandatory compliance conditions that, if not met, may limit the maximum level of efficiency of the building. For instance, external coverings or roofing that do not have thermal characteristics suitable for the climatic region in which building is located, so it cannot achieve a level A in the label's classification (PROCEL, 2017).

3.2 Tools used

Two online tools were used to determine the level of efficiency according to the RTQ-C (PROCEL, 2017):

- WebPrescriptivo (LABEEE, 2023) i.e., an online application created using the concepts contained in the RTQ-C. It calculates the label values of commercial and public buildings using the prescriptive method, where all the information necessary for the labelling process of the buildings is inserted. It automatically determines the value of some factors, in addition to the fact that it calculates values for label level thresholds and the partial and overall rating of the building. It should be noted that there are some prerequisites that must be met, which may limit the maximum level of efficiency if they are not achieved.
- ProjetEEE - Designing Energy Efficient Buildings (MME, 2023) i.e., an application that provides several solutions for more efficient projects. The platform is based on climate data from different locations, bioclimatic strategies, as well as building components and energy-saving equipment. ProjetEEE is a great help in processes related to energy efficiency and it is used in this work to obtain thermal data of envelope (wall composition and insulation components) since it has a great influence in defining envelope and overall energy efficiency levels.

3.3 Case Study

The case study presented in this contribution is the Community Library - BCo located in São Carlos campus of UFSCar, located at Sao Carlos, Sao Paulo State, Brazil (22° 0′ 55″ S; 47° 53′ 28″ W). The building is part of a complex consisting of the Library, Auditoriums and Theatre, with a construction of more than nine thousand square meters, inaugurated on December 16, 1994, and started its activities on August 17, 1995. Fig. 2 shows the library front facade.

Fig. 2. Library – Case Study (BCo, 2023)

3.4 Data entry settings

Below are described the conditions and values defined for the simulation in WebPresctivo, taking into account the current conditions of the BCo Library building.

- General requirements

The following conditions have been taken into account for the general requirements:

- The building has an electrical circuit that allows centralized metering, separated by single circuit for each electricity use;
- Water heating characteristics do not apply to the building.

The BCo Library has an electrical circuit with the possibility of centralized measurement by electricity use and the water heating criterion does not apply. In this way, the building can be classified up to level A according to the general requirements, depending only on whether it meets environment, lighting and air conditioning requirements.

- \- Envelope

The first information refers to the bioclimatic zone, and according to NBR 15.220-3: Brazilian Bioclimatic Zoning (ABNT, 2005), São Carlos is located in ZB-4, with subtropical (type Cfa according to the Köppen-Geiger climate classification). The average annual temperature is 21 °C; the summer is warm with precipitation and the winter is cool with little precipitation (CLIMATE-DATA, 2023).

For the envelope requirements, the thermal transmittance for the roof was defined for conditioned and unconditioned environments (U_{COB-AC}=$U_{COB-ANC}$=2.06 W/(m^2K)) and for the wall (U_{PAR}=1.83 W/(m^2K)), determined using ProjetEEE based on the materials used in the construction of the BCo.

The values for solar absorption (σ_{COB}=65%) and wall absorption (σ_{PAR}=68.1%) were obtained from RTQ-C (PROCEL, 2017), based on the colours of the facades on the site.

The percentage of zenith opening (PAZ=0) was taken as there are no openings with an inclination less than 60°. The solar factor (FS=0) was taken as the worst case, as there was no information on the glass used in the openings.

The drawings of the building to obtain the values related to the dimensional characteristics were used. The values of the total area (A_{TOT}= 6,947.48 m^2), the projection area of the roof (A_{PCOB}= 2,962.64 m^2), the projection area of the building (A_{PE}= 2,962.64 m^2), the total volume (V_{TOT}= 31,815.53 m^3) and the envelope area (A_{ENV}= 3,385.21 m^2) were obtained.

The values for the percentage of opening of the total façade (PAF_T = 25%) and of the façade to the west (PAF_O = 20%) were taken from photographs and a visit to the site. For the solar factor (FS = 0.635) and the values of the shading angles, vertical and horizontal (AVS=45º and AHS=45º) inclination angles were defined as the most critical according to the RTQ-C (PROCEL, 2017).

- - Lighting system

In order to simulate the efficiency of the current lighting system, the activity method was used, which takes into account, for each environment, the distribution of circuits, the contribution of natural light, and automatic switch-off. The area of each environment and the installed power (lamps) were also taken into account, and for this purpose, technical visits were made to 46 BCo environments for a detailed survey.

- - Air conditioning

The technical visits on site identified 12 rooms with 22 air conditioning units, “split floor-ceiling” model. According to the equipment manufacturer, the cooling capacity is 60,000 BTUs, with an INMETRO efficiency level B label (MMEa, 2023).

In addition to the useful area (AU = 6,706.23 m^2) and the conditioned area (AC = 938 m^2), the pipe insulation requirement was considered to be met.

4. Results

Three simulations were carried out on the basis of the input data in WebPrescritivo. The first simulation refers to the current state of the building in order to find out the partial and overall efficiency levels; the second simulation takes into account the improvement of the lighting system, and third the application of a bonus provided for energy efficiency enhancement in the RTQ-C (PROCEL, 2017).

4.1 Simulation results for Partial Efficiency Systems levels

Based on the input data described, a simulation was carried out for the partial Efficiency levels (Envelope, Lighting and Air Conditioning Systems). The simulation results obtained are presented in Table 1.

Table 1. Partial efficiency systems levels.

Partial evaluation	Level obtained
Envelope	**E**
Lighting	**E**
Air conditioning	**B**

4.2 Simulation result for the Overall Building Efficiency level

In addition to the results obtained for each of the systems presented above, it was necessary to determine two other values in order to represent the overall energy level of the building. The area of permanent transit (APT= 492. 04 m^2), which corresponds to the circulation areas of the building. And the numerical equivalent value of unconditioned and/or naturally ventilated environments (EqNumV = 4), which varies from 1 to 5 according to the thermal comfort of the place, with 1 being the most uncomfortable and 5 being the least uncomfortable, adopting the value of 4 for the building, based on consultation with library users during technical visits.

Thus, with these new input, it was possible to determine the overall classification of the studied building, which reached the level of overall efficiency and a score (PT) presented in Table 2.

Table 2. Overall efficiency level.

Evaluation	Level obtained
Overall (PT = 3.07)	**C**

4.3 Simulation considering improvements and bonuses

An improvement to the lighting system can be a future replacement of the 1.20m long, 40W fluorescent tubular lamps by lamps of the same size but with a 20W output, LED type (ALUMBRA,2019). In addition to this is also proposed to install an automatic switch-off system (presence sensor in the surroundings).

Although there are several bonus alternatives to improve the overall rating, in order to meet the demand of users who need to use an existing lift (old with no efficiency classification) was taking in account a future replacement of this lift by a new model that has “A” efficiency level according to VDI 4707(AGE,2017).

Considering both the bonuses 0.5 points resulted in the overall rating of the building. The other bonuses allowed in RTQ-C were not considered in this work.

4.3.1 Result for the partial level of improvement in the Lighting System

The new input data for the lighting system improvement were introduced and the simulation is presented in Table 3.

Table 3. Partial efficiency systems levels (improvement in Light System).

Partial evaluation	Level obtained
Envelope	**E**
Lighting System	**B**
Air conditioning S	**B**

This change was made in WebPrescritvo and the result was that the classification resulted in an upgrade level from E to B, reflecting an improvement in the overall classification, which went from C to B.

4.3.2 Result for Overall Efficiency level with improvement in the Lighting System and Bonus

The results for the overall energy efficiency label level of the building considering the proposed improvements and bonuses is showed in Table 4 resulted in the following:

Table 4. Overall efficiency level (improvement and bonus).

Evaluation	Level obtained
Overall (PT = 3.93) for lamps replacement	**B**
Overall (PT = 3.57) for lift replacement	**B**

This lighting improvement and bonuses affected the Overall Efficiency Level resulting an upgrade form C to B efficiency level.

5. Discussion

The overall classification obtained by the BCo was therefore level C, which is in line with expectations given the uncertainties in the process, the age of the building and the characteristics of the building itself, which, due to the date of construction, did not include guidelines that would provide the best form of energy performance for the building. However, it is worth highlighting the low ratings obtained by the building's envelope and lighting systems.

The envelope finally received an E label due to the thermal system requirements of the envelope. If the BCo structure is evaluated without the prerequisites, the building achieves efficiency level C. It should be noted that the assumed transmittance values of the envelope (2.06 W/(m²K) are very close to the limit required to obtain the C classification, which is 2.0 W/(m²K).

With regard to lighting, the performance is due to the large number of luminaires with high energy consumption lamps, as an old BCo project from 2009 was used to determine the classification of the label.

As for the air-conditioning system, it achieved good results, so that although it is not in Level A, it still shows good energy efficiency.

Although BCo is defined by the C energy efficiency label, the measures taken to improve the lighting system and the bonus generated by the replacement of the lift led to a partial increase in the level of the lighting system from E to B, which is reflected in the level of overall efficiency, which went from C to B.

When considering the replacement of the lift, the resulting bonus is 0.5 (points) in Eq1, resulting in a direct improvement in the overall level and efficiency, which goes from C to B, as in the case of changing the light bulbs.

It should be noted that changing the light lamps affects the part related to the lighting system in Eq1, while the bonus is an increase in Equation 1 (PT).

As a contribution for EFFICACY Project guidelines development, from the results of this work can be stated the following:

- Labelling system can be a useful tool to find out the efficiency level of existing buildings,
- the simulations tools used (WebPrescritivo and ProjetEEE) allows the simulations with insulation materials that can be applied at building envelope making possible to find out which one results in a better efficiency level;
- these simulations are useful to stablish the guidelines for building rehabilitation using thermal insulation materials;
- the simulations results can point out if the proposed rehabilitation strategies and material for thermal insulation are adequate and able to fulfill any financial incentives proposed by governmental agencies.

6. Conclusion

It can be concluded that the use of the energy efficiency level simulation software allowed the evaluation of the BCo building at UFSCar. The results were better than expected, being an old building with an overall label of level C, and level E envelope. However, as the roof transmittance values are just above the limit, the level C label is restricted to be achieved. For the lighting system, a level E represents the reality of the system, as fluorescent lamps are still in use. For the air-conditioning system, a level B was a good result, as the equipment is more modern and has a high level of efficiency.

In addition, to the lighting system improvements were proposed, which resulted in a specific B label (before E) for the lighting system, resulting in an overall B label, improving the rating not only of the lighting system but also of the whole building. The lift bonus also improved the overall rating from C to B.

Another important point to highlight is that although the financial savings that could be made by improving the lighting were not foreseen in this work, it can be observed that it is possible to reduce the installed power by half, a significant reduction in consumption that is reflected in the energy bill.

Although the proposed improvements were not sufficient to achieve an A rating, they still provide significant benefits and a higher level of energy efficiency encouraging to apply similar solutions in others University buildings

The simulations, also, pointed out some guidelines useful for evaluating existing buildings for rehabilitation purpose, since various thermals insulation materials in the facade, and others improvements, to increase the efficiency level of the buildings, can be propose to meet as well the financial incentives requirements.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Improving energy efficiency in Portuguese buildings: Retrofitting façades with high reflectance finishing coat

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Abstract

The European Union must enhance energy efficiency in its building stock, given that buildings account for up to 40% of the EU's energy consumption. Currently, more than 85% of buildings have been in use for over two decades, with at least 75% lacking energy efficiency. Only 10% of the building stock achieves ‘A’ or ‘B’ ratings in energy performance certificates. To meet energy efficiency standards, retrofitting exterior walls with passive techniques, such as enhancing optical properties, proves highly effective. Employing high reflectance surfaces reduces solar heat absorption, thereby lowering cooling energy use. This study examines the impact of reducing surface temperature through an external thermal insulation system with a high reflectance finishing coat during building envelope renovation in various climatic zones in Portugal. Preliminary findings indicate that high reflectance has a more substantial effect on annual heat gain for moderately insulated walls than well-insulated ones. The effect varies with maximum air temperature, especially in hot summers. A change in reflectance can improve heat gain reduction, especially considering the cost of retrofitting with insulation materials. An optimal balance between reflectance and thermal resistance is key to achieving lower surface temperatures and reducing cooling energy demands for Portuguese climates.

Keywords: Reflectance; Finishing Coat; Surface Temperature; Heat Flux; Portugal Climate.

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1. Introduction

Climate change will increase air and surface temperatures and change the urban climate, affecting the thermal performance of buildings and, consequently, energy consumption due to the urban overheating effect (Nazarian et al. 2022). Nowadays, the impact of buildings on greenhouse gas (GHG) emissions is well known, and some reports from the Intergovernmental Panel on Climate Change (IPCC) show that 33% of worldwide energy-related GHG emissions are due to building use (Robert & Kummert 2012). Therefore, in this scenario, it is essential to design and maintain the building with a strategy for lower energy consumption. The Building Performance Institute Europe (BPIE) estimates that about 97% of the European building stock is not classified as 'A' in the Energy Performance Certificate (EPC) and that at least 75% of the EU building stock should be renovated by 2050 to achieve decarbonisation of buildings (BPIE 2017).

The building envelope plays a crucial role in improving the energy efficiency of buildings by regulating heat transfer between the external and internal environments, especially to maintain indoor comfort (Stocker & Koch 2017). External thermal insulation composite systems (ETICS), which consist of insulation boards and thin reinforced plaster, are often used in the building envelope, especially in facades, to solve heat transfer problems. Nonetheless, the effects of weathering lead to physical and aesthetic irregularities (Parracha et al. 2021). To mitigate the effects of thermal stress on ETICS, the European Association for External Thermal Insulation Composite Systems (EAE 2011) recommends a finishing coat with a solar absorption rate below 70% and surface temperatures not exceeding 80ºC.

Surface temperature (ST) is strongly influenced by solar reflectance and infrared emittance from surfaces. In general, surfaces with low solar reflectance, such as dark colours like black, have higher ST than surfaces with high solar reflectance, such as light colours (Nazarian et al. 2022). Therefore, maintaining the reflectance of the surface is crucial to reducing thermal load and extending the durability of the building envelope once weathering changes the reflectance over the life cycle of the coating (Hradil et al. 2014). The use of light colours, which are considered high-reflectance materials, reduces thermal stress. Nonetheless, reflectance often decreases rapidly in the first months of exposure due to the deposition of soot, dust or biomass associated with soiling and photodegradation (Santamouris et al. 2011).

Dark colours might be better suited to resist such weathering and soiling effects, as noted by Revel et al. (2014). Nevertheless, maintaining dark surfaces while keeping them cool under solar radiation remains a significant technical challenge. Changes in near-infrared (NIR) reflectance for dark colours can significantly reduce surface temperatures compared to standard reflective coatings (Mourou et al. 2022). Some results show a reduction of peak temperatures by at least 5ºC and a reduction of surface temperatures above 50ºC by up to 10% (Ramos et al. 2021) when dark NIR ETICS facades are used. Furthermore, using dark NIR paints can improve the durability of ETICS, as shown in Dantas et al. (2022) and keep the aesthetic colour of the façade, as in Ramos et al. (2020).

This study aims to determine the feasibility of using dark paints with high near-infrared (NIR) reflectance as an energy-efficient retrofit solution for building facades. It investigates the impact of high-reflectance dark colour paints on reducing the surface temperature of ETICS facades in different climatic regions of Portugal. The analysis includes estimating the surface temperature distribution with a steady-state calculation method under different reflectance conditions (aged, new, and retrofitted) for the same system. It is also investigated, the influence of climatic parameters such as solar radiation and air temperature on the surface temperature values.

2. Materials Description and Temperature Calculation

2.1. Façade system characterisation

The performance of the retrofit was evaluated using an original ETICS sample (1 m^2) that was naturally aged for three years in a horizontal position on the roof of the Department of Civil Engineering of the University of Porto, with the thermal performance of the original system described in Ramos et al. (2021). The aged sample after 3 years of natural exposition (Fig. 1a) was removed from the roof. A 10 x 10 cm piece was cut from the original 1-metre square panel, washed with water, air dried (24 ºC) for 48 hours and renovated with black paint with high reflectance in the near-infrared range (Fig. 1b). The composition of the samples is listed in Table 1.

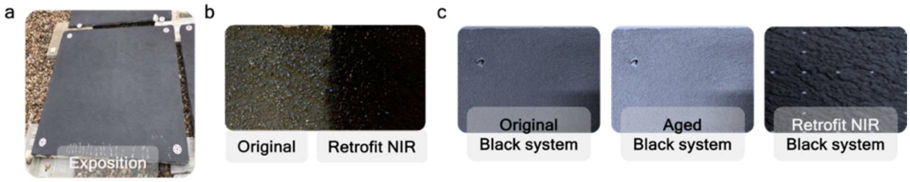

Fig. 1. Appearance of surfaces in the evaluated conditions: (a) Exposition configuration; (b) Retrofit process; (c) Final samples aspect.

Table 1. Façade system characterisation.

Sample ID	Composition	Condition
New	Insulation slab: EPS (40 mm); Base coat: commercial cementitious mortar; Finishing coat: commercial organic coating composted of mineral filer, resins in aqueous dispersion black pigment (PBk11) and specific additives.	Original 0 year
Aged		Natural aged 3 years
Res	Insulation slab: EPS (40 mm); Base coat: commercial cementitious mortar; Finishing coat: commercial organic coating composted of mineral filer, resins in aqueous dispersion black pigment (PBk11) and specific additives; Retrofit layer: commercial NIR black paint with pigment PBk29.	Paint renovation

The effects of age and renovation method on the surface temperature were defined considering experimental values for reflectance. In this work, a modular spectrophotometer (FLAME-T and FLAME-NIR Ocean Optics – 200 nm to 1650 nm) with a 30 mm diameter integrating sphere and a Spectralon® reference disc were used to measure the total reflectance (ρ) of the samples in their original state, aged state and renovation. The reflectance was calculated based on the 100 selected ordinates by:

$$\rho = \frac{1}{100}\sum_{i=1}^{100}\rho(\lambda_i) \tag{1}$$

where ρ is the total reflectance of the sample and λ is the wavelength weight in nanometres according to ASTM E903 (2020). The measurements were carried out in six different points for each sample. The average was used to calculate the surface temperature.

2.2. Numerical modelling

In order to evaluate the thermal effect of reflectance variation for the three conditions studied, the distribution of surface temperature (ST) was calculated considering the steady state condition. For a dry surface under solar radiation, the steady-state surface temperature can be estimated as follows:

$$\frac{T_s - T_i}{R} = (1-\rho)I - \varepsilon\sigma\left(T_s^4 - T_{sky}^4\right) + h(T_s - T_a) \tag{2}$$

where T_s is the surface temperature (K), T_i is the internal temperature (K), R is the thermal resistance of the façade (m^2K/W), ρ is the solar reflectance, I is the solar flux incident on the surface (W/m^2), ε corresponds to the emittance, T_{sky} is the sky temperature (K), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4), h is the external convective heat transfer coefficient and T_a is the air temperature (K).

For the purposes of this calculation, the following definitions were adopted:

- T_s should be calculated considering an algorithm to solve a quartic equation.
- R assumes two conditions, R1 = 3.03 m^2K/W and R2 = 7.14 m^2K/W, the maximum and minimum thermal transmittance values according to the Portuguese Regulation on Thermal Properties of the Building Envelope (RCCTE, 2016).
- T_i is defined as 25 ºC by the RCCTE (2016).
- ρ is the average value calculated from the experimental measurements (New, Aged and Res).

- ε is constant for all conditions, defined as 0.90, an average value for the ETICS system (Alonso et al. 2017).
- T_{sky} is calculated according to the procedures of Costanzo et al. (2014), considering Brunt's equation.
- The external convective heat transfer coefficient is 25 W/m^2K (WUFIPro value).
- The climate data, i.e., air temperature, irradiation, and humidity, were taken from the EnergyPlus Weather Format – EPW (Climate.OneBuilding 2023).

The ST value was calculated for different Portuguese climatic zones using the numerical model for 17 Portuguese cities, with climate variables in Table 2. In addition, the impact of retrofitting was estimated considering two different expositions, horizontal (roofs) and vertical (façades), in four orientations (west, east, south, and north).

Table 2. Distribution of used cities for each climate (IPMA 2011).

City	Climate classification	Annual Average Ta(ºC)	Annual Cumulative Horizontal Irradiation (Wh/m^2)	City	Climate classification	Annual Average Ta(ºC)	Annual Cumulative Horizontal Irradiation (Wh/m^2)
Funchal	Csb	19.7	1836.64	Castelo Branco	Csa	16.3	1719.06
Pico	Cfa	18.0	1578.54	Porto Alegre	Csa	15.3	1710.64
Flores	Cfb	17.9	1488.21	Coimbra	Csb	15.4	1610.90
Beja	Csa	16.2	1789.12	Viseu	Csb	13.4	1619.66
Faro	Csa	17.8	1843.08	Porto	Csb	15.1	1654.06
Sagres	Csa	25.4	1762.7	Vila Real	Csb	13.6	1593.63
Lisboa	Csa	17.1	1771.56	Bragançca	Csb	12.5	1612.39
Sintra	Csa	15.8	1753.39	Viana do Castelo	Csb	14.3	1645.02
Peniche	Csb	15.4	1619.09				

3. Results and Discussion

3.1. Experimental reflectance measurements

The average and standard deviation of the reflectance measurements are listed in Table 3.

Table 3. Reflectance results.

Sample ID	Condition	Reflectance
New	Original 0 year	0.120 ± 0.009
Aged	Natural aged 3 years	0.076 ± 0.007
Res	Restored	0.250 ± 0.003

The 3-year aged reflectance value is 36% lower than the original value. This reflectance loss is below the expectations of the Cool Roof Rating Council (CRRC), which estimates a threshold of 23% loss after three years of natural degradation (CRRC 2019). However, the reflectance variation in time will result from chemical and physical stress in combination with matter depositions (Shi et al. 2019). In some cases, dark surfaces with low initial reflectance can increase aged reflectance, as demonstrated by Sleiman et al. (2011). Furthermore, the increase in reflectance due to the use of a paint with high NIR reflectance as a retrofit solution was 108% compared to the initial condition and 228% compared to the aged condition. The change in reflectance due to NIR reflectance was also demonstrated in Mazhar et al. (2020) and Ramos et al. (2021).

3.2. Calculation algorithm

The ST is calculated by a quartic equation for which an algorithm had to be developed to solve the equation 2. In this study, a root algorithm was created in the free software R. The algorithm is based on the equations described in Akbari et al. (1996) and Costanzo et al. (2014). The numerical values calculated by the R algorithm were validated by comparison with the values simulated by WufiPro®.

Hence, to evaluate the effects of the three reflectance conditions (New, Aged, and Rest), the ST was calculated considering a fixed emissivity value (0.90), two thermal resistance values (R1 and R2), four Portuguese climates (Csa, Cfa, Cfb and Csa) and six envelope orientation expositions (Horizontal, Vertical/west-east-south-north).The advantage of the algorithm is that it allows the calculation of ST in a steady state with annual distribution, considering any climatic data or characterisation of the material in an accessible form. The result of the algorithm is a file with comma-separated values (.csv) that can be processed in any analysis software. The algorithm can be requested by contacting the authors.

3.3. Estimated surface temperature

The surface temperature (ST) of External Thermal Insulation Composite Systems (ETICS) is significantly affected by both radiative properties and thermal resistance. Fig. 2 presents the boxplot distribution of average annual surface temperature, considering three different reflectance values (Table 3) and the two thermal resistance (R1 = 3.03 m^2K/W and R2 = 7.14 m^2K/W, item 2.2)**Error! Reference source not found.**.

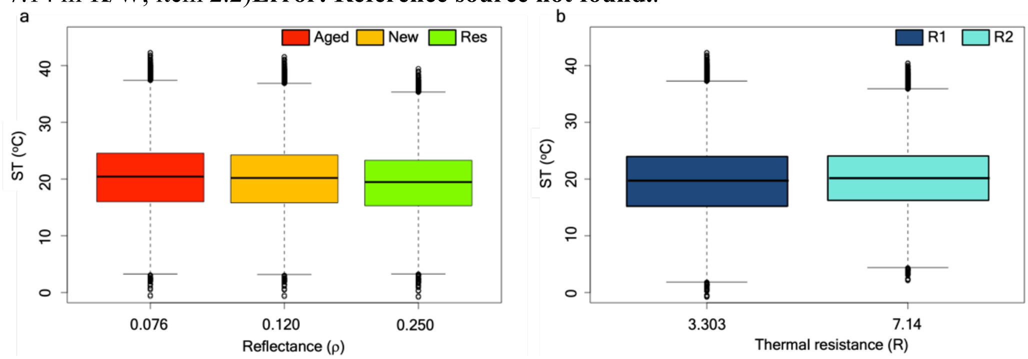

Fig. 2. Influence of materials properties annual average values: (a) Reflectance; (b) Thermal resistance.

The ST for the restore conditions (green boxplot, Fig. 2a) and the higher R-value (light blue boxplot, Fig. 2b) have lower dispersion than the other conditions. Meanwhile, in all cases, the ST shows a symmetrical distribution with some outliers, which can be attributed to the influence of the environmental distribution over the year, in particular the fluctuations in air temperature.

In Fig. 2a, the annual average surface temperature of the aged condition (red boxplot) is 5% higher than the retrofitted conditions (green boxplot), where the lower reflectance resulting in a TS of 20.41 ºC against 19.37 ºC for the restored reflectance. When compare the aged condition (red boxplot) to the original condition (yellow boxplot), the surface temperature increases by 1.5%. Fig. 2b highlights the impact of changes in thermal resistance, showing that as thermal resistance change from 3.303 m^2K/W to 7.14 m^2K/W, surface temperature increases by 3% from 19.68 ºC to 20.27 ºC. This observation suggests that, considering material properties, enhancing reflectance can be more effective in reducing surface temperature than improving the thermal resistance of the building envelope.

Fig. 3 presents the boxplot distribution of average annual surface temperature, considering the environmental variables of climate zone and envelope orientation.

Fig. 3a shows the effects of climate classification on surface temperature using the radiation and air temperature. The different climate zones exhibit varying surface temperature distribution. For instance, climate zone Cfa displays a higher average ST of 21.62 ºC and an average annual cumulative horizontal radiation of 1764 Wh/m^2, whereas climate zone Csb presents a ST of 19.14 ºC and an average annual cumulative horizontal radiation of 1648 Wh/m^2.

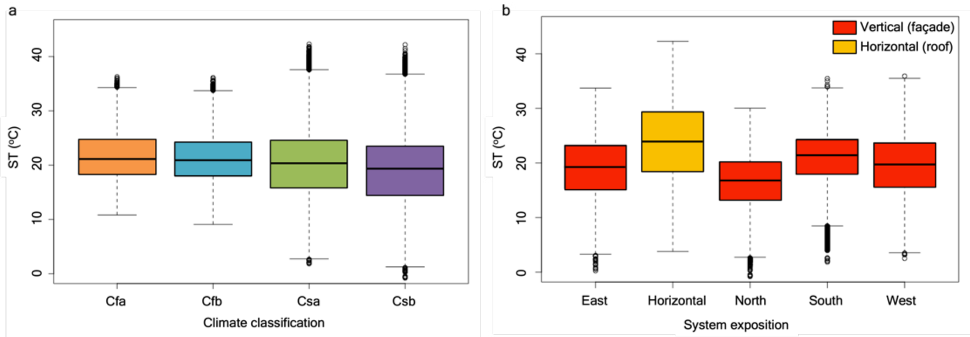

Fig. 3. Environmental variables annual average values: (a) Climate classification; (b) Envelope system exposition.

The impact of the radiation is also notable in the system orientation, where the north facade has an annual average ST of 16.52 ºC, while the south facade registers 20.84 ºC, a difference of 4.3 ºC. Additionally, horizontal surfaces (roofs) exhibit the highest ST at 23.79 ºC. Especially, for the evaluated Portuguese cities, roofs have a surface temperature that is 14% higher than that of north facades and 44% higher than that of south facades.

The use of dark colours in envelopes can have adverse effects on thermal stress, particularly in hot climates and summer season (Sghiouri et al. 2020). Therefore, the study explores scenarios that combine reflectance and thermal resistance (listed in **Error! Reference source not found.**) for both roof and west facade applications, as detailed in Fig. 4 and Fig. 5.

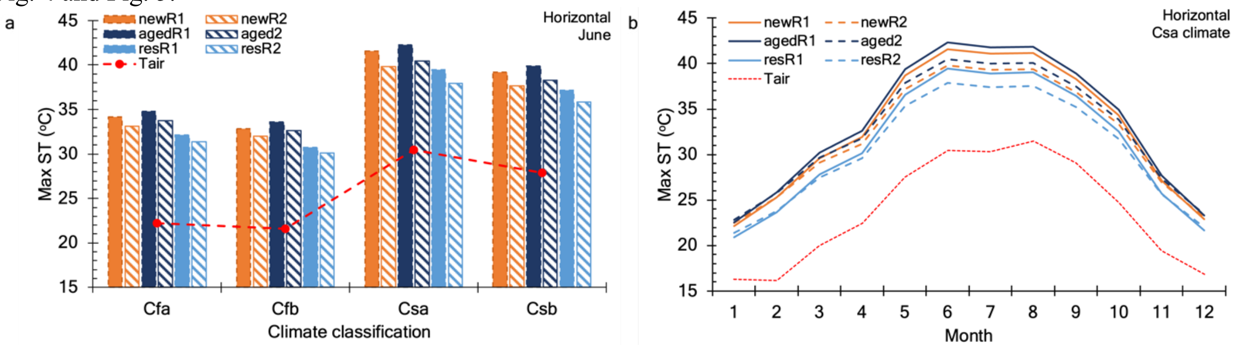

Fig. 4. Surface temperature for horizontal orientation (roofs): (a) Climate classification for June; (b) Year distribution for climate zone Csa.

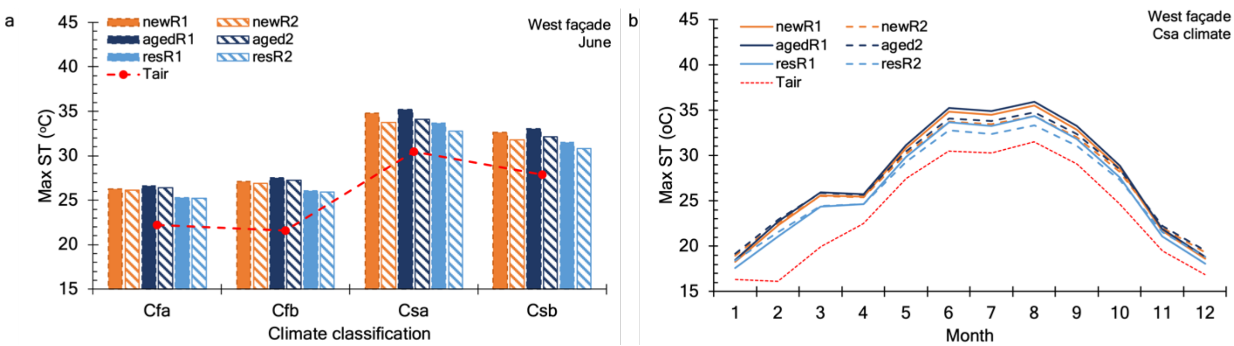

Fig. 5. Surface temperature for the vertical west orientation: (a) Climate classification for month of June; (b) Year distribution for climate zone Csa.

The maximum surface temperature for the roof and west orientation in the month of June for the four different climate zones is exhibited in Fig. 4a and Fig. 5a, respectively. Fig. 4b, shows an annual distribution of the maximum temperature for climate zone Csa on roofs and Fig. 5b for the west orientations.

The retrofit of roofs can reduce summer peak temperatures by 7%, irrespective of the R-value, when comparing the aged (agedR1/R2) condition with the retrofit (resR1/R2). However, when considering the Csa climate zone, as depicted in the annual distribution of the maximum ST (Fig. 4b), the influence of the R-value is nearly insignificant (1%) during the winter season, while reflectance maintains its reduction effect (6%).

Similar to the roof application, the west façade is exposed to higher ST in the Csa zone in summer. Retrofitting the west façade reduces peak summer temperatures by 4%, regardless of R-value, when comparing the aged condition (agedR1/R2) with the retrofit (resR1/R2). However, as can be seen from the annual distribution of maximum ST in Fig. 5 the influence of the R-value during the winter season in climate zone Csa is almost negligible (2 %), while reflection continues to have a reducing effect (4 %). The numerical results are similar to Souza et al. (2023) for Portuguese simulations that the reduced ST for the city of Porto (Csb climate) achieved 3% when using NIR black coatings.

Therefore, Fig. 6 present the correlation between the reflectance and the maximum surface temperature for the two configurations of R-value.

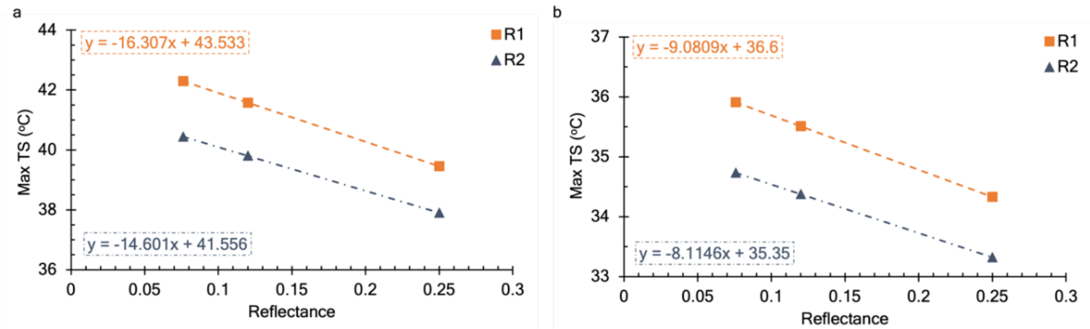

Fig. 6 Correlations between reflectance and maximum surface temperature for Csa zone: (a) Horizontal orientation; (b) Vertical west orientation.

As expected, the reduction of the surface reflectance due to the reflectance increment is more effective in the roof (Fig. 6a) than in the west façade (Fig. 6b) as verify in Alonso et al. (2017) and Dias et al. (2014). This effectiveness is related to the higher absolute value of surface temperature result from the solar irradiation, although is worth highlighting that the in both cases, the increment on R-value reduces the influence of the reflectance.

4. Conclusions

The study highlights the promising potential of NIR black paints as a cost-effective retrofit solution for Portuguese buildings. The effectiveness of these paints depends on several factors, such as the climate zone and the orientation of the building envelope. The results show the expected thermal behaviour of the NIR reflective materials on the experimental campaign and the numerical simulation for the surface temperature, where the NIR paint could be used as a quick retrofit method, listing:

- The NIR dark paints can reduce the surface temperature and the cooling/heating demand of Portuguese buildings.
- The use of NIR dark paints on roofs could be more effective than on façades due to the radiant energy received.
- There is an optimal design value between the U-value and the reflectance.

In addition, it is worth noting that using black NIR paints impacts surface temperatures in both summer and winter. Therefore, further assessment of the risk of condensation on building facades in different climates is needed. Comprehensive assessments should also be carried out to quantify the reduction in cooling and heating degree-days through energy simulations. These considerations will help us better understand the practical implications and long-term benefits of using NIR black paints as part of a building's energy retrofit strategy.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Intervention in Portuguese Historic Villages Facing Desertification and Climate Change

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Abstract

The 12 Historical Villages of Portugal, located on the border between Serra da Estrela and Spain, are a remarkable piece of Portuguese history. However, these villages have been deeply impacted by the increasing issue of depopulation, aging, and abandonment. While this phenomenon is not limited to these villages, there are certainly unique factors that contribute to the tension between maintaining the historical significance of the villages and addressing the everyday needs of the local. In the particular context of the buildings that still withstand, mostly in the central areas of the villages, many of those who insist on remaining in this territory end up abandoning the stone houses inside the villages and migrating to new buildings built in their surroundings.
Despite its valuable symbolic capital (for its environmental, landscape and heritage potential), the tourism sector is clearly not the sole answer as its revenue to the local economy proves to be insufficient for the essential material, social and economic balance that attracts and fixes the population.
The issue of unattractiveness in these villages is multifaceted. A key factor contributing to this problem is poor housing conditions, which fail to provide residents with the comfort they deserve. This lack of comfort also results in misguided interventions that mischaracterize the existing heritage, leading to a further devaluation of the symbolic capital of these communities.
Considering this context and in articulation with the SDG11, it is imperative to establish solid bases for interventions in existing buildings that allow reconciling the need for adequate comfort levels with the protection of the landscape and heritage legacy, which incorporate innovation in terms of sustainability of materials and energy expenditure, with an alliance of ancestral knowledge with innovation in efficient water management, but also that pay attention to environmental, social, economic sustainability with beneficial impact on society and territory. These bases must also incorporate an adaptation to climate change that affects both the landscape and the comfort conditions inside the existent buildings.

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Keywords: heritage; vernacular architecture; sustainability; climate change.

1. Introduction

Central Portugal's rural landscape is characterized by a series of small villages that have maintained their traditional characteristics. Twelve of these communities have the denomination of "Historic Villages" (DN2/1995) and have been the subject of renovation actions in the1990s following Decreto 23/1996 (D 23/1996). "In fact, the improvements carried out in the 15 Churches, in the 8 Castles and fortress walls and in the 24 buildings, of recognized architectural value, illustrate the various changes undertaken: along with pure actions of enhancement and restoration of monuments, with or without the introduction of modern components and materials, to the simple conservation of the ruins, with the aim of creating symbolic and/or fantastic scenic ensembles, There are initiatives for the restoration/modernization of buildings with the incorporation of new functionalities, allowing, at the same time, to value, reuse, enliven, give life and monetize a heritage that belongs to everyone's history" (Boura, 2004). According to Boura (Boura, 2004) and taking into account the associated legal basis (D 23/1996) together with available information regarding the various projects that were implemented in these villages (Lousada, 2008; Rapagão & Fernandes, 2000), there was a first phase regarding direct intervention in the urban context and in the existent buildings, creating a uniformity within each village. These interventions were led by Portuguese architects and performed on the façades and roofs (including windows and doors) and also on the context of electrical and water systems and external pavements.

However, most of the traditional building materials are still in place and a current reflexion taking into account conservation/rehabilitation of these villages with a focus on sustainability aspects is now being undertaken. Looking at sustainability in a holistic way, encompassing the use of buildings and public participation, this paper will focus on the sustainable aspects linked to traditional building materials. Sourcing of local materials was a basis for vernacular architecture, meaning that local available stone was used for building structures, pavements and, sometimes, roofs. Materials of natural origin such as wood or vegetable fibres were also employed, due to easy availability. The intervention that will take place in these villages will take into account the preservation and/or reuse of these materials, highlighting the importance of conservation/rehabilitation actions as sustainable procedures in themselves. Energy incorporation in these materials, CO_2 incorporation, thermal behaviour (inertia and transmission) and effect on indoor air quality are some of the main parameters that will be taken into account in the analysis of existent materials. For the choice of new materials, further factors such as LCA, ecological footprint and local provenience will be incorporated in the decision-making process.

2. Characterization of the actual state

2.1. Location

As pictured in Figure 1, the Historic Villages are located between the Spanish border and one of the main mountain ranges in Portugal, Serra da Estrela. This gives these villages specific characteristics, as they had to adapt to a difficult landscape with a significant temperature variation and a certain level of isolation due to the difficulty in surpassing the mountains, despite their proximity to Spain.

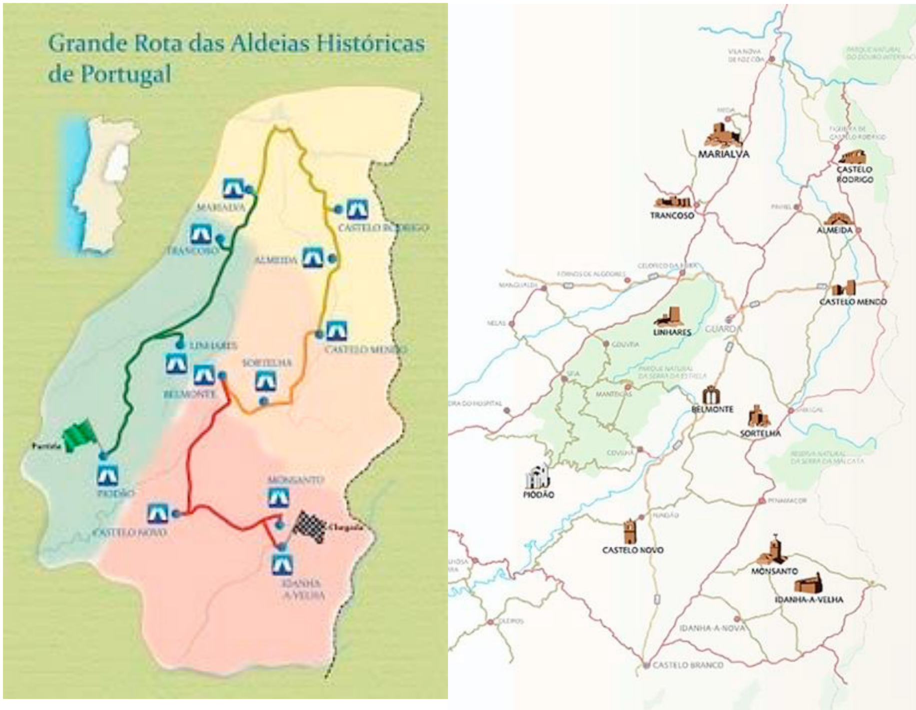

Fig. 1. Location of Historic Villages a) in Portugal b) in the region of interior Central Portugal
(a) http://floradaserra.blogspot.com/2010/08/aldeias-historicas-de-portugal.html, b)https://www.amazonasemais.com.br/outros-destinos/portugal/aldeias-historicas-de-portugal/attachment/mapa-aldeias-historicas-portugal/)

2.2. Building materials

Village houses (Figure 2) in this area are usually built with local stone (mainly granite and sometimes schist) for external walls and timber in roof structure, partitions, flooring and door and window frames. Lime and/or earth mortars (Figure 3) were commonly used for rendering of external and internal surfaces, depending very much on economic possibilities of the house owners, and other materials such as corn stalks, hay and canes were also used for partition structures in many cases.

Fig. 2. Typical street with original elements (Castelo Novo, Portugal)
Fig. 3. Traditional building materials (external earth mortar)

2.3. Heritage - monuments and conurbations

This area, with innumerous fortresses (Figure 4), religious monuments and preserved villages is rich in heritage buildings and conurbations. In this context, there has been an increase in terms of the classified heritage in the Historic Villages (AHP).

Fig. 4. An example of classified heritage in Almeida (fortress) in Portugal.

While the classification status of a building, its inclusion within a designated heritage area, or its ongoing classification process should not act as a hindrance to initiating modifications, it is essential that any alterations are carried out with utmost consideration for preserving its original essence. The execution of any construction, regardless of its perceived scale, should be undertaken in collaboration with architectural, engineering, and archaeological experts. Their specialized insight is vital in recommending techniques that harmonize with the existing structure and promote its long-term sustainability. In addition, professionals should prioritize the use of locally sourced materials and skilled labor proficient in working with traditional construction elements. This approach may ensure that when new materials or construction methods are required, they seamlessly blend with the historical aspects of the building.

3. Historic Villages and Desertification

Demographic dynamics of the last decades have proven hard for this geographic area. Since the 1950s, the territories farthest from the cities and the Portuguese coast lost population consistently, as a result of migration to other countries or to urban centers in the national territory. This migration, in addition to an inevitable impact on demography, compromises the existence of the villages, as well as the transmission of knowledge related to the construction and maintenance of built spaces, through traditional techniques.

From the analysis of the population data of the parishes in which the AHPs are inserted (Table 1), it can be seen that all of them show a decrease in population in the last decade, with the populations of Piódão and Sortelha being the ones that suffered the highest impact, 33% and 28% of decrease, respectively. The parishes that decreased their population the least were the Union of Parishes of Trancoso and Souto, Maio and Marialva, with a reduction of 6.7% and 5%, respectively. This trend reflects a regional pattern, as all municipalities also showed a reduction in their population, with an average reduction of 13.3%. However, the population reduction of some parishes is even more accentuated than that of the respective municipalities, with the greatest reduction being observed in the municipalities of Almeida (19%) and Figueira de Castelo Rodrigo (18%).

Table 1. Population evolution in AHP (INE 2021)

Village	Demographic trends at parish level
Almeida	Almeida lost 13% of its population. The age groups that decreased the most were between 0 and 14 and 15 and 25 years old (25%). In the parish, the population over 65 decreased by 13%.
Belmonte	Belmonte lost 9.4% of its population compared to 2011. The age group that decreased the most was 15 – 25 years old, with a decrease of 26%; the population over 65 increased by 8.7%.
Castelo Mendo	The parish lost 21% of its population. The age groups that decreased the most were between 0 and 14 years old (75%) and 15 and 25 years old (46%); The population over 65 has not increased.
Castelo Novo	Loss of 21% of its population. The age groups that decreased the most were 0 to 14 years (75%) and 15 to 25 years (46%); The population over 65 has not increased.
Castelo Rodrigo	The population of the parish decreased by 9.5%. The age group that decreased the most was from 14 to 25 years old, with 33.7%, while the one that decreased the least was over 65 (4,5%).
Idanha-a-Velha	The population decreased by 14%. The population from 0 to 14 years old increased by 56% while in the municipality it decreased by 14%. The population over 65 years old decreased 23%.
Linhares da Beira	The population decreased 18%. The population groups that decreased the most were between 15 and 24 (53%) and between 0 and 14 (50%), while the population over 65 decreased 19%.
Marialva	The population decreased by 5.5% that of the county decreased by 11%. The population group that decreased the most was from 15 to 24 years old, (81%). The group over 65 remained static.
Piódão	The population decreased by 33%; the group that decreased the most was that over 65 (46%).
Sortelha	The population decreased by 28%; the group that decreased the most was between 15 and 14 with 60%, followed by the group of 25 – 65, with 28%.
Monsanto	The population decreased by 14%. The group that decreased the most was between 15 and 24 years old with 44%, while the population between 0 and 14 years old increased 56%.
Trancoso	The population decreased by 6.7%. The group that decreased the most was from 0 to 14 years (28)%. The population group over 65 increased by 17%.

This critical situation of demographic loss greatly contributes to the degradation of the built heritage that is mostly uninhabited and abandoned, steadily leading to a its loss. Although some villages are used for touristic purposes, this is not extensive to all, nor does it solve the problem at its core. According to World Heritage Site Managers, preservation of both tangible and intangible heritage implies a sustainable balance with tourism without neglecting in any way their heritage´s original function (Durrant et al, 2023).

4. Historic Villages and Climate Change

4.1. Energy Poverty

Vulnerability to energetic poverty is a problem affecting buildings throughout the totality of the Portuguese territory (Horta et al, 2019). As reported in Figure 5 (Gouveia et al, 2019), it is clear that energy poverty greatly affects the region under focus in this study (as per Figure 1). Dwellings with a historical and architectural heritage, in this context, find themselves in a state of heightened vulnerability. Within the AHP context, this contextual consideration extends beyond the historical town centers, encompassing newly developed residential areas. The relatively compact dimensions of vernacular structures and their high thermal mass represent favorable factors in addressing energy poverty, provided these attributes are coupled with effective heating solutions.

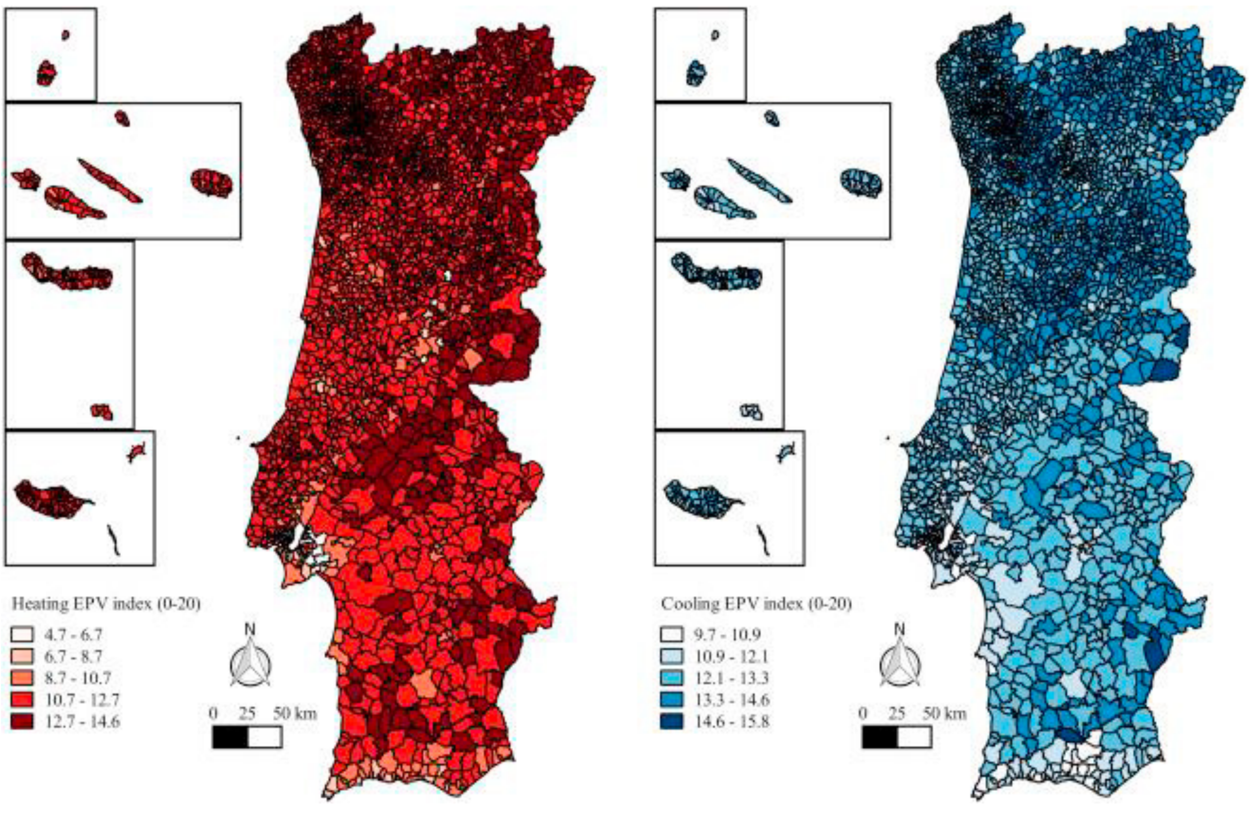

Figure 5 – Vulnerability to energy poverty (Gouveia et al., 2019)

4.2. Climate Change

The effect of climate change is and will be felt in the region of Central Portugal. This influence, following the European Environmental Agency´s projected impacts, consists of a multitude of effects upon this region, among which:

- Higher temperatures and heat waves;
- Drought and extensive impact on biodiversity;
- Increased Wildfires;
- Subsequently issues of territorial and populational relevance, such as:
- Increase in water demand for agricultural use
- Increase in energy demand for cooling

This prospect will definitely impact actual and future users of the existent buildings and, in this context, the anticipation of possible effects together with the new notions of comfort are crucial for an adequate intervention outcome. This point of view has been recently dealt with by the scientific community (Blavier et al, 2023, Sesana et al, 2020) but needs to be specifically addressed in the context of AHP. This will imply a careful balance between preservation and innovative adaptative measures, that must incorporate energetic behaviour of these buildings intertwined with a sustainable approach.

5. Intervention aspects

It is clear that a rehabilitation action in itself is a sustainable process as it does not create additional expenditure of resources (both in terms of extensive use of materials and consumption of energy for demolition and new construction). Additionally, it promotes the maintenance of functional materials and architectural elements that can meet the necessary performance requirements; it is also a cultural action encompassing the relevant aspect of valuing endogenous heritage. In this framework, it is essential to privilege maintenance actions that increase the useful life of buildings in parallel with the implementation of improvements to ensure interior comfort in order to guarantee occupants' quality of life.

Comfort is a vast concept that encompasses indoor temperature and humidity, absence of noise, and air quality, among others. However, it has been mostly treated in terms of thermal conditions, linked to energetic efficiency solutions (Jiang et al, 2023; Stanojević et al, 2021), hindering a more holistic approach that may actually tackle these issues whilst respecting a built value. The materials and construction solutions used in intervention situations contribute to these factors in a determinant fashion. Building ventilation solutions, the thermal conductivity of materials, their heat storage capacity and delay in heat dissipation, the permeability of materials to water vapour, their impact on air quality, among other factors, are technical characteristics of materials that need to be taken into account and their juxtapositions should be the basis for sustained choices. Definitely, the determination of solutions for an adequate intervention is a task with multiple aspects, involving technical criteria, sustainability assessment, heritage preservation incorporation as a basic need and, very importantly, the input of the resident population.

6. Conclusion

The AHP have a strong presence in Central Portugal. Their monumental and vernacular heritage as well as the heritage value of the conurbations is undoubtful. There has been a strong depopulation trend in the area, which is situated between the mountains of Serra da Estrela and the Spanish border especially felt by the small villages and there are recent interactions due to a possible increase in tourism, creating a double-sided impact, as well as further strain brought about by the prospect of climatic change.

It is fundamental that the intervention that will take place in these villages will take into account the preservation and/or reuse of existent materials, highlighting the importance of conservation/rehabilitation actions as sustainable procedures in themselves. Only through physical intervention procedures can a greater attractiveness of this territory be achieved, reversing the strong depopulation trend that is an actual reality. The focus on sustainability in these interventions should occur in a holistic way, including the (re)use of buildings and the need of public participation, but also, and fundamentally, encompassing the sustainable aspects linked to traditional building materials.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Key Performance Indicators: their use in the energy efficiency retrofit for historic buildings

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Abstract

Energy efficiency in the built environment is gaining ground due to policies to mitigate climate change impact. This contribution focuses on investigating the role of Key Performance Indicators (KPIs) that can be useful for the energy retrofit of historic buildings. The KPIs were hinged upon PESTEL domains (Political, Economic, Social, Technological, Environmental, and Legislative) in order to define objective and measurable criteria that allow for a comprehensive evaluation of an energy retrofit performance. A literature review carried out through the PRISMA flow chart allowed to select 59 papers, subsequently analyzed to investigate the occurrences of the selected KPIs. The findings showed that the political domain is the less considered, differently from the legislative one, whose KPI highlighted the importance of being compliant with regulations. The domains representing economic, social, technological, and environmental KPIs are mostly present together in the scientific literature, underlining the importance of a holistic and multidisciplinary approach. Future research should be oriented towards delineation of best practices to meet sustainability and conservation needs, and to better integrate current policies and international requirements.

Peer-review under responsibility of the ESICC 2023 Organizers

Keywords: Key Performance Indicators; Energy Efficiency; Historic Buildings; PESTEL Analysis.

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1. Introduction

The building sector is responsible for approximately 40% of European Union (EU) energy consumption and 36% of carbon dioxide equivalent (CO_{2eq}) emissions. About 50% of all the EU-28 buildings are estimated to be not energy efficient and the 95% of the building stock needs to be renovated and decarbonized for achieving the goal of EU Green Deal, i.e., the climate neutrality and reduction of CO_{2eq} emissions by 2050 (International Renewable Energy Agency and European Commission (2018)). Therefore, the EU has promoted research focused on increasing energy sustainability while reducing the carbon footprint. In recent years, many governmental energy grants and new loan programs have been activated in the EU countries to support the retrofit of buildings, which include all interventions aimed at both improving the energy performance and the thermal comfort for occupants (Mazzarella (2015), and Posani et al. (2021)). Other aspects should be considered such as the building age, the climate zone, the thermal and physical properties of building materials (e.g., thermal transmittance, water vapor absorption), and the building use. In case of historic buildings, an energy retrofit is a challenging task since it has to combine the conservation requirements of the building, its aesthetics, and the surrounding cultural environment according to EN 16883:2017. In this framework, any energy retrofit should be addressed through a systematic approach to facilitate the proper improvements. In the last decades, building energy simulation is used to evaluate in advance the effectiveness and suitability of interventions (Lo Faro et al. (2021)). More recently, this tool is used to assess the impact of interventions from both conservation perspective and thermal comfort of the users (Coelho et al. (2019); Frasca et al. (2019a, 2019b, 2021); Mancini et al. (2016)). As the environmental impact due to the emission of CO_2 is a core topic for the building sector, the Life Cycle Assessment (LCA), standardized in the framework of UNI EN ISO 14040:2021 and UNI EN ISO 14044:2021, is used to evaluate the retrofitting interventions in terms of environmental sustainability and circular economy. LCA can be used in parallel with the Life Cycle Cost (LCC) to simultaneously assess the economic impact during the life cycle.

The present work aims to outline the state of the art related to case studies focused on energy retrofit of historic buildings, considering the impact of climate change, and the use of innovative methodologies such as LCA to make more efficient and sustainable the refurbishment process for those buildings. Then, quantitative, and measurable criteria (i.e., Key Performance Indicators, KPIs) underlying the choice of the suitable energy retrofit will be searched within the content of the selected papers, by structuring them in the framework of the PESTEL domains (Political, Economic, Social, Technological, Environmental, Legislative) (Rothaermel (2015)).

2. Materials and Methods

2.1. Selection of scientific papers

Scientific papers dealing with energy retrofit in historic buildings were identified via *Scopus* and *Web of Science* (WoS) databases without setting a starting year and stopping the search at the end of 2022. The systematic literature review was performed through the three-steps process “PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow diagram” (Page et al. (2021)). The query strategies involved ten combinations of ten keywords, with the Boolean operators “AND” and “OR” in the field “titles, abstracts, and keywords”: “zero emission”, “refurbishment”, “retrofit”, “intervention”, “building”, “historic* building”, “neighborhoods”, “conservation”, “climat* change”, “LCA”. The asterisk has been used on some words to include the various forms in which they can be found in the literature (e.g., historic/al) thus avoiding many duplicates. In the first step, 1194 papers were extracted from both databases. Then, after the merge, duplicates were removed. The 621 remaining papers were further screened to exclude the ones with no authors (7 papers), no English language (18 papers), no full text (25 papers), and out of scope (240 papers). In the end, 59 papers were critically reviewed, (Agliata et al. (2020) - Zazzini and Capone (2018)).

2.2. Definition of Key Performance Indicators (KPIs)

Key Performance Indicators (KPIs) are objective and measurable criteria commonly used in the corporate/business sector. This contribution aims at extending the use of KPIs to the field of historic building retrofit. KPIs were retrieved through a critical reading of the case studies present in the reviewed papers and then clustered in the six domains of the PESTEL Analysis (Rothaermel (2015)), i.e., the Political (P), Economic (Ec), Social (S), Technological (T), Environmental (En), and Legislative (L) domains. The KPIs are listed in Fig. 1, reported by number in each PESTEL domain.

	Key Performance Indicators
P	**1**. Government Influence; **2**. Government Policy
Ec	**1**. Investment costs; **2.** Operating and Maintenance costs; **3**. Pay-back period; 4. Economic savings
S	**1**. Change in health & well-being; **2**. Social awareness; **3**. Change in intended use; **4**. Heritage significance; **5**. Visual impact
T	**1**. Retrofitting materials; **2**. Energy consumption savings; **3**. Historic materials risk; **4**. Compatibility of materials
En	**1.** Change in IEQ; **2**. Change in EPC; **3**. CO_{2eq} emission savings; **4**. Impact on the outdoor environment; **5**. CC impact
L	**1**. Compliance with current legislations

Fig. 1. KPIs clustered in PESTEL domains (IEQ = Indoor Environmental Quality, EPC = Energy Performance Certificate, CC = Climate Change)

Once all the criteria were outlined, the number of KPIs per paper were counted to define which KPI is actually the most considered in the reviewed scientific literature. Then, the KPIs' occurrences were also transposed into "PESTEL units" through Equation 1. This proposed equation allows to determine the occurrences of PESTEL domains by normalizing them based on the number of categories per domain.

$$\%_{PESTEL} = \frac{n}{\Sigma n} \cdot 100 \qquad (n = n_{KPI}/n_{cat}) \tag{1}$$

Where n_{KPI} are the occurrences of KPI in each domain and n_{cat} is the number of categories of KPIs per each domain (e.g., political domain has two criteria, so $n_{cat} = 2$, with 16 occurrences for P1 and 13 occurrences for P2).

3. Results and discussion

3.1. Historic buildings retrofit in scientific literature

The Journal Citation Report categories via Web of Science has provided information about the most occurring subject areas associated with the selected papers, i.e., "Environmental Science", "Energy & Fuels", "General Energy", "Green & Sustainable Science & Technology", "Environmental studies", and "Construction & Building Technologies". Journals dealing with heritage and conservation are two, with one publication each: "Journal of Cultural Heritage" and "Journal of Architectural Conservation", highlighting as this topic is mostly linked to engineering and architecture disciplines, in particular to those involved in energy studies. The reviewed papers describe the retrofit in 62 case studies: 54 are located in Europe (33 in Italy), and eight in non-European countries, and this suggests that European culture is paying more attention to this type of issues. Most of the case studies are historic buildings built in 18th, 19th, and 20th centuries mainly located in urban contexts (57 sites), three in rural, and two in not defined sites. Specifically, 16 places are residential buildings, and 37 are non-residential, divided into the following categories: schools and universities (11), museums and galleries (8), workplaces (8), industrial complexes (4), worship places (3), and hotels (3); the remaining nine sites are not defined. The review papers showed that a major simulation contribution is perceived: 57 out of 59 papers use building simulation tools (with BIM and/or BEM software) sometimes combined with LCA. As for this latter, the most used impact assessment methods are Impact 2002+, ReCiPe, EDIP 2003, Ecoinvent V.3 database, ECO Indicator 99. Moreover, the case studies treating environmental impacts are not using the same approach concerning the LCA stages considered in the analysis of materials and processes. Actually, four case studies are approaching the "Cradle to Gate" stage (A1-A3 phases), i.e., they only assess the impact of the materials production, two of which are also measuring the "transport to site" stage (A4 phase); 17 case studies treat the LCA as "Cradle to Grave" stage (A1-C4 phases), which include the materials production (A1-A3), the construction process (A4-A5), the Use stage (B1-B7), and the End of Life stage (C1-C4); finally, only one case study treats the "Cradle to Cradle" stage, where the LCA is assessed beyond the system boundary (A1-D Phases, all LCA stages). Since the energy/environmental field is prevalent in this research, information was sought on how energy consumption and CO_{2eq} emissions have changed from "*pre-*" to "*post-*" retrofit. Table 1 presents papers considering energy consumption and CO_{2eq} emission savings simultaneously, both expressed in percentage (%). Retrofit where both passive (e.g., application of thermal insulation) and active (e.g., replace of air conditioning systems) approaches are used lead to greater savings.

Table 1. List of case studies, i.e., the reference (1st column) with building type (2nd column) and construction year (3rd column), containing both energy consumption and CO_{2eq} emissions savings (last two columns) both measured in percentage, after the retrofit intervention (4th column).

Reference	Building type	Year	Retrofit intervention	Energy Consumption Savings	CO_{2eq} Emissions Savings
Bennadji et al. (2022)	Building stock	Pre 1945	Replacement of windows Installation of mechanical ventilation with heat recovery	87 %	76 %
Ascione et al. (2022)	University	1224	Insulation of external vertical wall and roof (PUR) Replacement of windows New heat pump Installation of PhotoVoltaic	55.8 %	46 %
Ascione et al. (2017)	University	1513	Replacement of windows Replacement of the boiler	59%	57%
Dalla Mora et al. (2015)	Residence	1894	Insulation of internal and external (inner part) walls (EPS + MW) and roof (WF) New insulated windows New mechanical ventilation Installation of PhotoVoltaic New heat pumps and chiller	92.5 %	81 %
Knox (2015)	Residence	1933	Replacement of HVAC Setting of solar hot water Installation of PhotoVoltaic	65 %	32 %

3.2. Analysis through the Key Performance Indicators

Figure 2a shows the number of papers considering a specific KPI. It was found that the most used KPIs in the literature review are:

- T2, "Energy Consumption Savings", cited by 53 papers, confirming that the design of the retrofit mainly aims at improving the energy consumption of the building.
- S4, "Heritage significance", considered by 49 papers, meaning that declarations of interest as well as protection and conservation of historical buildings by law play a key role in designing the retrofit project.
- En3, "CO_{2eq} emission savings", considered by 38 papers. This KPI considers both the emissions of CO_{2eq} and other harmful substances in the environment. This aspect is usually considered in LCA.
- L1, "Compliance with current legislations", 44 papers referred to the legislations in use, highlighting the importance of strictly follow the regulations.

The other KPIs have been considered by several papers ranging from six to 28 (Figure 2a). The social domain is the least explored: S2 (Social Awareness, six papers), and S3 (Change in intended use, seven papers). En2 (Change in Energy Performance Certificate) reach at least 10 papers and it starts appearing from 2015, testifying as the energy issue has been more recently studied in the scientific literature about the retrofit in historical buildings.

Figures 2b and 2c were plotted taking as reference values the "$\%_{PESTEL\ units}$" (from the proposed Eq. 1). This analysis confirms that the legislative domain is mandatory to be compliant with the regulations during a retrofit intervention. Comparing the two different periods (Figure 2c), the economic domain seems to have had a slight decrease in interest in papers (from 19% to 12%), while the technological and environmental domains had a slight increase of 3% and 4%, respectively, as if to demonstrate a greater tendency to activate interest in issues related to environmental protection and climate change.

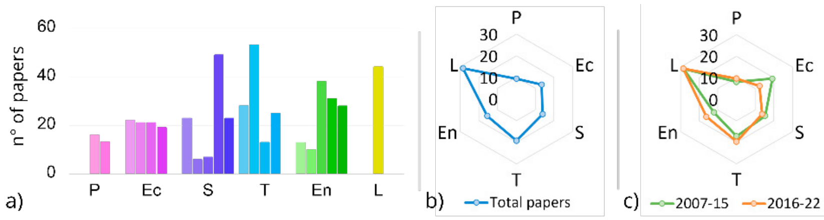

Fig. 2. a) Column plot showing the most impactful Key Performance Indicators. b-c) Radar plots showing the "%$_{PESTEL\ units}$" considering the whole number of analyzed papers (b) and the number of papers split over two periods: 2007-2015 (green line) and 2016-2022 (orange line) (c).

Figure 3 shows how a combination of KPIs occurs in the reviewed papers. The social and technological domains are presented coupled in about 90% of the cases (15 groups out of 17) emphasizing great attention to users and conservation aspects (social field) together with material and structural aspects (technological field). Moreover, a great correlation between Social, Technological, Environmental and Legislative domains is perceived, and the number of papers increases when these domains are considered in conjunction with the economic field. These articles deal with the topic of energy retrofitting in a holistic way, in some cases even making it explicit in the title, although the main focus is related to the technological and environmental domains (i.e., energy consumption and related environmental impacts). These "EcStEnL" articles are all very recent, (from 2017 onwards), and this demonstrates the importance of new policies and legislation, such as the EBPD 2018/844 on the energy performance of buildings that amended already existing European directives (Ogut, O. et al (2023)), or such as the Paris Agreement, which promotes economic growth and sustainable development.

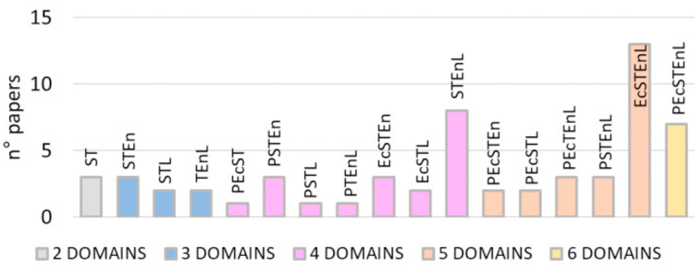

Fig. 3. Combination of PESTEL domains per number of papers.

4. Conclusions

A retrofit intervention on the historical building sector means focusing attention on recent legislation aimed at a "green transition" by 2050 (i.e., Green Deal). This paper aimed at determining the criteria (Key Performance Indicators, KPIs) underlying the choice of the retrofit for historical buildings. First, we explored 59 papers and a total of 62 case studies on the retrofit of historical buildings. Then, the reviewed case studies were critically analyzed considering KPIs categorized in the six domains of the PESTEL Analysis. It emerges that the political domain is the less considered in scientific literature, probably due to the near lack of real retrofit scenarios with respect to the simulated ones. The interest towards the economic domain has tended to decrease in the most recent papers, but it's still taken into account as it allows to estimate the cost feasibility of the energy retrofit. The social domain is related to two main categories, concerning the impact of the retrofit on: 1) the society, paying attention to KPIs related to users' well-being (i.e., quantifying thermal comfort with indices), and 2) the heritage building, with great attention paid to the cultural value significance (i.e., citing the historical value to be maintained on a visual level). The technological domain seems to be closely related to the field of application to which the papers of this review mostly belong, i.e., energy and environmental science/engineering studies. The environmental domain is mainly explored through the LCA and global warming calculation. Although a high quantity of papers is linked to these aspects, no unique calculation methodologies or impact assessment methods are used. Finally, the legislative is the most considered domain, pointing out it is mandatory to strictly follow the regulations when retrofitting historical buildings, both during a simulation scenario and a real retrofit case study.

The PESTEL Analysis can be a useful tool in retrofitting historical building to outline a holistic approach methodology that considers both the heritage significance and the environmental related impacts within the mitigation and CO_{2eq} emission reduction perspective. For this reason, KPIs were hinged upon PESTEL domains to define objective and measurable criteria that allow for a comprehensive evaluation of an energy retrofit performance. Further research is still needed to better integrate all these domains, especially the political one, thus directing future research in the perspective of implementation on real case studies.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Life Cycle Assessment and Maintenance Planning of an Innovative Flat Roof Solution

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Abstract

This study analyses the potential of a high-energy efficient flat roof, relating sustainability to its costs, and, in conjunction, develops its maintenance strategy. Considering the common energy deficiency of flat roofs, the Smart Roofs System (SRS) project developed a new solution to the market. It combines traditional and innovative thermal insulation and waterproofing layers, to achieve a roof that provides thermal comfort to building users. This paper presents an analysis focusing on the maintenance needs and on the environmental impacts - based on a Life Cycle Assessment (LCA) approach - of fifteen different combinations for this SRS. The sustainability assessment of the roof analysed combines cost data and environmental impacts, considering categories such as non-renewable primary consumption (PE-NRe) and global warming potential (GWP), in a cradle-to-gate analysis. The strategy used for the maintenance plan is proactive, focused on defining inspections, cleanings, repairs, and substitution actions, with their periodicity based on the prognosis process. The aim of this plan is the possibility of improving product quality in the long term, reducing expenses, and maximizing its efficiency over the time. Given the information and analysis presented, it is possible to make a holistic evaluation of the solution and deliver important data to decision-making, where the decision-maker can choose the most suitable combination taking into account the prioritized factors, such as environmental impact, expenses, and maintenance efforts.

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Keywords: Roofs; Sustainability; Life Cycle Assessment; Maintenance; Performance; Service Life

1. Introduction

Currently, traditional flat roofs are a more frequent choice than pitched roofs in Portugal, despite the lack of information correlating the economic and energy performance (Marrana, 2017). They play an essential role in

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protecting buildings, influencing in thermal comfort, affecting the behaviour of the building and providing safe access to maintenance actions (Botejara-Antúnez, 2022). When a flat roof has a poor thermal comfort, this is a result of a bad use of this key element that contributes to thermal exchanges with the exterior. In winter, thermal comfort depends on some characteristics of the roof, such as the horizontal envelope area. However, in summer, there is a tendency for the internal building temperature to rise if the thermal insulation of the roof is not effective (Gomes. 2014). Flat roofs can also suffer significantly in the absence of proper maintenance as compromised water and moisture sealings, for instance, become pivotal weak points in the roof structure, disrupting thermal comfort. These issues extend by impacting environmental and economic variables. Over the building's lifecycle, rising energy consumption becomes apparent (Jo, 2010), leading to substantially higher operational costs due to increased maintenance demands.

Despite increased emphasis on retrofitting in the past two decades, driven by guidelines, decrees, legislation, and government programs, there remains a noticeable gap in the effective thermal comfort of building occupants. This challenge also needs to be faced with innovative market solutions for flat roofs, such as the one studied in this research.

The Smart Roofs System project aimed to create an improved thermal comfort solution using traditional flat roofs. They comprise the following layers: bonding material, thermal insulation, basecoat reinforced with glass fiber, liquid waterproofing membrane, and an additional reinforcement layer. The common layers are the same in all possible combinations, and they are: bonding material and basecoat reinforced with glass fiber.

Beyond the focus on thermal comfort, concerns related to economic, environmental, and long-term performance aspects of the roof hold significant importance and constitute the primary subject of analysis of this paper. This article proposes to estimate the environmental impacts of the materials used through Life Cycle Assessment (LCA), its associated costs, as the demand of this process is increasing in Portugal (Marrana, 2017) and the necessary proactive maintenance, which also helps with the energy consumption of the building (Jo, 2010). This paper promotes a discussion of these aspects regarding the studied flat roof.

This paper is organized in four sections, including this one. In Section 2, the methodology used in this research will be presented by discussing about the methods and data collected to the development of the LCA, the costs of each solution and the process to do the data normalization and comparison between economic and environmental aspects of the 15 different combinations of the flat roof solution. Then, the description of the approach used to determine the proactive maintenance plan will be presented. In Section 3, the data generated in the LCA and the economic aspect will be reported. Also, the normalization of the data of environmental and economic impacts will be discussed for different scenarios with different priorities. The final result presented will be the main anomalies and suggested actions to avoid and treat them in the Proactive Maintenance Plan. Section 4 presents the main conclusions of this discussion and analysis.

2. Methodology

Considering the various layer configurations available for this roofing system, encompassing a total of fifteen potential combinations, we will conduct a comprehensive analysis focusing on three pivotal factors that play a significant role in shaping customers' decision-making processes: environmental impact, economic considerations, and maintenance factors.

The combinations were labelled based on abbreviations representing the materials used, following the order: thermal insulation material, waterproofing layer and reinforcement. The abbreviations representing materials are going to be, respectively: MW (Mineral Wool with Primary), ICB (Insulation Cork Board) and XPS (Extruded Polystyrene); PU (Polyurethane Membrane with Water Soluble Basis) and PUD (Polyurethane Membrane in Dispersion with White Pigment); R22R (Textile Structure R22 V2: 100% Polystyrene Recycled); R23R (Textile Structure R22 V3: 100% Polystyrene Recycled), FV (Glass Fiber), R22PP (Textile Structure R22 V2: 100% Polypropylene) and NT (Non-Textile). During the conceptualization phase, the development team established the potential combinations as follows: (1) MW-PUD-R22R; (2) MW-PUD-R23R; (3) MW-PUD-FV; (4) MW-PUD-R22PP; (5) MW-PU-NT; (6) ICB-PUD-R22R; (7) ICB-PUD-R23R; (8) ICB-PUD-FV; (9) ICB-PUD-R22PP; (10) ICB-PU-NT; (11) XPS-PUD-R22R; (12) XPS-PUD-R23R; (13) XPS-PUD-FV; (14) XPS-PUD-R22PP and (15) XPS-PU-NT. The methodology employed was replicated for every roof combination studied.

2.1. Environmental Dimension

The environmental dimension was developed by conducting a Life Cycle Assessment (LCA), considering global and local environmental impact categories. The LCA stands as a pivotal tool for evaluating the environmental impact of this product. Its significance lies in understanding the embodied impact, providing insights toward achieving a more sustainable solution. One of its fundamental roles is to support decision-makers through the comparative analysis of alternatives.

In accordance with EN 14040 (2006), a four-step methodology must be completed when conducting LCA. These steps follow a sequential order, beginning with goal and scope definition, going to life cycle inventory, continue with the evaluation of environmental impacts, and concluding with the interpretation of the results.

The scope of the LCA was defined during collaborative sessions with the product development team. It was determined that the primary focus of this LCA would be to understand the embodied impact in the product stage, falling under the *cradle-to-gate* approach. Therefore, in this environmental analysis, the focus is to comprehend the product stage by the evaluation of phases A1 to A3 (CEN. 2019.). In phase A1, the supply chain of raw materials is studied. Phase A2 is centred on the transportation-related impacts. Lastly, in phase A3, the manufacturing processes involved are investigated, as illustrated in Fig. 1.

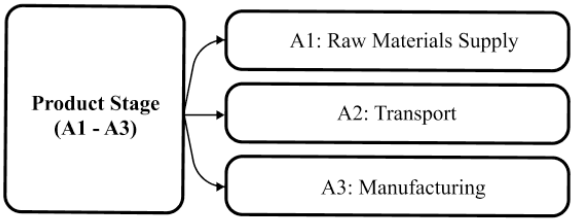

Fig. 1. Product Stage from A1 to A3 in LCA

The inventory step was initiated by collecting data related to the raw materials, production, recycling and waste generation processes, as well as other inputs and outputs associated with the final product. For the materials used in each layer of the roof, a bibliographic study was conducted to identify the ones for which an LCA had already been completed. These materials included MW (Pedroso. 2019. and Volcalis. 2016.), ICB (Amorim. 2016.), XPS (Silvestre. 2012.), bonding material and basecoat (Pedroso. 2019.), and Polyurethane Membranes (Gomes. 2019., Maris Saint-Gobain. 2023., Tecnopol. 2023., and Weber Saint-Gobain. 2023.). Continuing with this process, the software SimaPro 9.4.0.2 was utilized to model the remaining inputs of the product. The software's database was sourced from Ecoinvent 3, and the calculation method employed was based on EN 15804 + A2, CML-IA baseline V3.08 and CED – Cumulative Energy Demand for PE-NRe.

For a more comprehensive understanding of the product's sustainable behaviour, and in alignment with the iterative process of LCA, at the evaluation of environmental impacts step it was determined that five categories of environmental impacts would be thoroughly studied. Among these, two are of global significance: Global Warming Potential (GWP) and Primary Energy - Non-Renewable Energy (PE-NRe). The remaining three impact categories exert a local influence, namely Acidification Potential (AP), Eutrophication Potential (EP), and Potential Photochemical Oxidation (POCP).

2.2. Economical Aspect

The costs calculation of the roof's solution stands as an important factor in ensuring the project's economic feasibility. Apart from securing affordability for the client, achieving a balance between costs and the integration of robust and sustainable materials hold paramount importance. This equilibrium not only guarantees accessibility but also the project's commitment to durability and sustainable practices. Such an approach not only aligns with financial prudence but also influence responsible and sustainable choices.

The roof's costs were computed based on information supplied by the development team, defining the value associated with each layer in all the combinations considered. This comprehensive data not only facilitated the determination of the total cost but also enabled a thorough comparison of values across the 15 potential combinations.

2.3. Multi-criteria Scenarios application

While identifying environmentally favourable combinations, it became evident that no singular solution stood out prominently. At the same time, absolute cost does not offer a complete and nuanced evaluation of the solutions. Recognizing this, it was decided to develop a weighting process, that started by a normalization of the environmental impacts and costs, to enhance the depth of the analysis. This process involved establishing a given ratio where the highest value of each variable was standardized to 1, with other values adjusted proportionally by dividing per that highest value.

In order to gain a deeper understanding of the options and identify solutions that strike a balance between costs and sustainability, four distinct multi-criteria scenarios were applied to the normalized data:

- Scenario 01:
  Costs: 70%; Environmental: 30% (GWP: 15% and PE-NRe: 15%)
- Scenario 02:
  Costs: 50%; Environmental: 50% (GWP: 25% and PE-NRe: 25%)
- Scenario 03:
  Costs: 34%; Environmental: 66% (GWP: 33% and PE-NRe: 33%)
- Scenario 04:
  Costs: 34%; Environmental: 66% (GWP: 50% and PE-NRe: 16%)

By aligning priorities within these scenarios, it is possible to anticipate that decision-makers have the data to make more informed, responsible decisions that align with their sustainability objectives. These scenarios provide a framework for evaluating options, ensuring that the final choice not only meets financial considerations but also aligns with environmental responsibility, fostering a balanced and conscientious approach.

2.4. Maintenance planning

Proactive Maintenance Plan is a tool to improve longevity and the performance of the roof. Through regular inspections and preventive measures, it identifies and resolves potential issues before they burgeon into major problems. By aiming to prevent breakdowns and minimize downtime, proactive maintenance ensures optimal performance of the property's components. Beyond these immediate benefits, this approach also plays a pivotal role in preserving the property's aesthetics and functionality.

Defining maintenance source elements is essential and requires understanding of the flat roof system. In the context of this study, this involves dissecting the flat roof system into two distinct layers, thermal insulation and waterproofing, as it shows in Table 1. By considering these layers, it is possible to understand their unique maintenance needs, and enable a comprehensive approach to roof maintenance.

Table 1. Definition of the maintenance source elements.

Layer	Maintenance Source Element
Reinforcement (R22R/R23R/FV/R22PP/NT) Polyurethane Membrane (PU/PUD)	Waterproofing Layer (Layer A)
Basecoat reinforced with Glass Fiber	Thermal Insulation Layer

Thermal Insulation (MW/ICB/XPS)	(Layer B)
Bonding Material	

Following the implementation of the roof solution, the attention was focused on critical constructive aspects of the roof. These considerations are fundamental for shaping the Proactive Maintenance Plan, and they were identified through on-site inspections, as illustrated in Fig. 2. Additionally, an internal research initiative involving collaboration with the product development team was conducted. This internal research aimed to discern vulnerable points, potential anomalies, and to understand the expectation of the lifespan of each layer within the system, providing valuable insights for proactive maintenance strategies.

Fig. 2. Simulating a retrofitting scenario with solution in Carregado, Portugal. 2023.

With the gathered data, it was possible to start the literature review. This iterative process involved collaboration with the development team, aiming to anticipated the behaviour of the innovative roofing systems, that doesn't have historical application data. Through extensive literature studies, it was identified potential roof anomalies. These insights were pivotal in formulating proactive maintenance actions and determining their necessary frequencies. With all these components, and recursive analysis, it was possible to develop the Proactive Maintenance Plan.

3. Results and Discussion

The GWP refers to the total amount of greenhouse gases emitted directly or indirectly by the product. It serves as a metric for assessing contributions to global warming. Reducing the carbon footprint is crucial in combating climate change and promoting environmental sustainability. The standard unit of measurement for the carbon footprint is kg CO_2 eq and was calculated for each square meter of every roof combination.

Upon analysing each combination results, it is evident that solutions incorporating ICB as thermal insulation yield a lower carbon footprint compared to other alternatives. From an environmental perspective, these solutions prove to be more advantageous. Additionally, the thermal insulation layer emerges as a significantly influential factor in the Carbon Footprint, surpassing the impact of the waterproofing membrane and reinforcements.

PE-NRe refers to the total amount of non-renewable energy used during the manufacture of a product, including raw material extraction, transportation, and production. It stands as a vital metric for assessing the environmental impact associated with the production of goods and services. Reducing primary energy in products and processes is a key-factor for promoting sustainability and minimizing the consumption of natural resources. In this context, the focus is primarily on reducing the use of non-renewable energy sources.

When examining the results for PE-NRe , both the thermal insulation layer, the waterproofing membrane, and the reinforcements can have significant impacts on the ranking of solutions. The solutions with lower PE-NRe do not necessarily align with those having a smaller GWP. This disparity is because, among the evaluated thermal insulation solutions, ICB has the smallest GWP, while MW stood out for having the lowest PE-NRe , and XPS does not performs well in either of these 2 environmental impact categories.

POCP refers to the ability to create tropospheric ozone, affecting air quality and human health. AP results from the release of gases that acidify soils and waters, damaging ecosystems. EP stems from an excess of nutrients in water bodies, leading to excessive algae growth and biodiversity impacts. Understanding these environmental impacts helps mitigate their negative effects, promoting a healthier environment for all. On assessing these 3 variables, the evaluation focused on the waterproofing membrane. Across local impact variables, the PUD demonstrated superior performance, exhibiting lower environmental impacts.

From cost analysis, it can be stated that the total cost of the Smart Roofs System is primarily influenced by thermal insulation and the waterproofing membrane. However, in terms of costs, the pricing spotlight shifts towards MW for thermal insulation, followed by XPS. Meanwhile, ICB, which proved to be among the top environmentally friendly solutions, does not stand out in terms of costs.

Understanding the complexity of data analysis, multi-criteria scenarios become indispensable to facilitate a holistic evaluation of the situation. In Table 2, data normalization (column 2) for costs, (column 3) GWP, and (column 4) PE-NRe is shown. Subsequently, various scenarios were applied: (Scenario 01) costs: 70%, GWP: 15%, PE-NRe : 15%, (Scenario 02) costs: 50%, GWP: 25%, PE-NRe : 25%, (Scenario 03) costs: 34%, GWP: 33%, PE-NRe : 33%, and (Scenario 04) costs: 34%, GWP: 50%, PE-NRe : 16%. Then the bests combination for each scenario is highlighted in bold.

Table 2. Normalized data and combinations for costs, GWP and PE-NRe .

Combination	Cost	GWP	PE-NRe	Scenario 01	Scenario 02	Scenario 03	Scenario 04
MW-PUD-R22R	0.48	0.46	0.45	0.47	0.47	**0.46**	0.47
ICB-PUD-R22R	1.00	-0.18	0.58	0.76	0.60	0.47	**0.34**
XPS-PUD-R22R	0.91	0.99	0.98	0.93	0.95	0.96	0.96
MW-PUD-R23R	0.47	0.46	0.45	0.46	**0.46**	**0.46**	0.46
ICB-PUD-R23R	1.00	-0.18	0.58	0.76	0.60	0.47	**0.34**
XPS-PUD-R23R	0.91	0.99	0.98	0.93	0.95	0.96	0.96
MW-PUD-FV	0.45	0.47	0.46	**0.45**	**0.46**	**0.46**	0.46
ICB-PUD-FV	0.97	-0.18	0.59	0.74	0.59	0.47	**0.34**
XPS-PUD-FV	0.88	1.00	0.99	0.91	0.94	0.96	0.96
MW-PUD-R22PP	0.48	0.47	0.47	0.48	0.47	0.47	0.47
ICB-PUD-R22PP	1.00	-0.18	0.60	0.76	0.61	0.48	0.35
XPS-PUD-R22PP	0.91	1.00	1.00	0.94	0.95	0.97	0.97
MW-PU-NT	0.19	0.43	0.47	**0.26**	**0.32**	**0.36**	0.35
ICB-PU-NT	0.54	-0.22	0.60	**0.43**	**0.36**	**0.31**	**0.17**
XPS-PU-NT	0.46	0.96	1.00	0.62	0.72	0.80	0.79

It is evident that the alternatives lacking prominence either utilized XPS as thermal insulation material or incorporated a textile structure with 100% polypropylene reinforcement. It is noted that, even when costs carry significant weight, solutions featuring ICB emerge as highly viable. This indicates that, despite the relatively higher costs associated with ICB, its environmental advantages render it a compelling and sustainable choice. Similarly, MW stands out prominently across various scenarios, even when the GWP values are the focus and considering that the absolute value of MW's GWP is not the best. This underscores the synergy between cost and PE-NRe values, making these combinations worthy.

The Proactive Maintenance Plan is based on three key factors: the service life, the considered pathology, and, consequently, the corresponding actions to maintain the roof and their frequencies. Each outcome was derived from the discussion, analysis and combination of the data obtained through a literature review (Monteiro. 2022., Perret.

2019. and Flores. 2022.), collaborative research with the development team, and on-site observations during technical visits in Carregado, Portugal, where the roofing solution was applied.

Table 3. Definition of the service life of each layer.

Layer	Service Life expected	Service life in literature review
Reinforcement		20 years
Waterproofing Membrane		25 years
Basecoat reinforced with Glass Fiber	25 years	5 years
Thermal Insulation		35 years
Bonding Material		20 years
Bearing Structure	35 years	35 years

The analysis of the flat roof system's lifespan encompasses a range of anomalies or pathologies, including localized or generalized cracking, blistering, perforations, detachment, corrosion, debris accumulation, ponding water, biological growth, decay, infiltration, and condensation. Additionally, deficiencies in coping, fasteners, or downpipes are considered. These defects help for defining the third key factor i.e., the proactive maintenance actions and their required frequencies.

The actions are divided by inspection and cleaning, minor interventions and major interventions. Following inspections on the applied roofing solution, the need for targeted repair actions has become evident. These actions encompass repairing cracks, conducting thorough cleanings, applying treatments to prevent and eliminate biological colonization, addressing blistering issues, and rectifying problems in the roofs' expansion joints, among others. Additionally, the plan outlines significant interventions, which occur towards the end of the estimated lifecycle of the coating system, involving the replacement of more extensive areas. Inspections and cleanings are scheduled every 1 to 2 years to ensure regular maintenance. Minor interventions, ranging from 2 to 10 years, address specific issues, maintaining the roofing system's integrity. Major interventions, involving replacements and extensive repairs, are planned at intervals of 25 to 50 years, aligning with the system's estimated lifespan.

4. Conclusion

The primary goal of the research, conducting a comprehensive Life Cycle Assessment (LCA) for all Smart Roofs System (SRS) combinations, has been achieved. This analysis encompassed 5 key environmental variables, both local and global in scope. Notably, the waterproofing layer exhibited varied impacts across categories, with Polyurethane Membrane with soluble basis (PU) showing a smaller global impact, and Polyurethane Membrane with water-based solution in Dispersion (PUD) demonstrating reduced impacts in local ecosystem as in Acidification (AP), Eutrophication (EP) and Photochemical Oxidation Potential (POCP). Although the focus centred on Global Warming Potential (GWP) and Primary Energy – Non-Renewable Energy (PE-NRe) as main influence factors, it is challenging to definitively label one membrane superior to the other. Looking ahead, a strategy to minimize global variables involves reducing resin and titanium dioxide percentages, as these layers significantly influence the final outcome.

In this analysis, economic impacts needed to be associated with the sustainability assessment, necessitating the application of multiple scenarios. This approach enabled a multi-criteria evaluation of each solution, merging global environmental variables with cost data. Through the definition of the four distinct scenarios (from 1 to 4), certain combinations consistently emerged as optimal choices, while others felling below. Notably, combinations involving Mineral Wool with Primary (MW) and Insulation Cork Board (ICB) consistently stood out positively across all scenarios. Conversely, Extruded Polystyrene (XPS) combinations tended to be less favoured. This insight underscores the need for market research to assess the viability and demand for combinations containing XPS, ensuring a well-informed decision-making process in sustainable roofing solutions.

Also achieving the objective of the research, a tailored Proactive Maintenance Plan was created. Besides the service life, the plan considers the potential pathology and outlines specific actions and their frequencies. Despite the plan is ready, its efficacy depends on real-time observations of the roof's condition, specially to compare with the suggested maintenance and anticipated anomalies. Given that there is not a historical background yet, the plan is predominantly derived from literature reviews, collaborative research with the development team, and on-site observations during the solution's application on the roof. This approach can have necessary adaptations, ensuring the maintenance strategy aligns with the real-world scenarios, making proactive maintenance efforts agile, adaptive, and effective. This methodology should be followed when a new constructive solution is designed and contributes to enhance long-term performance with minor environmental impacts over time.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Mechanical behavior of recyclable polymeric specimens made by additive manufacturing

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Abstract

Additive Manufacturing (AM) has seen a massive growth in engineering applications in recent years. Fused Filament Fabrication (FFF), probably the most widespread technology, is nowadays capable of producing polymeric components for all kinds of need: from common use to advanced engineering applications, thanks to the usage of a wide range of polymer materials. Some of them (such as PEEK, PEI and others so-called ultra-polymers) offer very good mechanical properties and sometimes can be even capable of replacing metals. In addition, they are stable at relatively high temperatures and thermally re-processable and recyclable, showing good biocompatibility in most of cases. The distinct advantages of AM have facilitated the rapid development of polymer products with complex customized structures and functionalities, thereby enhancing their applications in various fields. In this work, the mechanical behaviors of FFF manufactured polycarbonate (PC) and Polymethyl methacrylate (PMMA) coupons, both suitable for building construction applications thanks to their good mechanical strength, thermal insulation capability and resistance to ultraviolet (UV) rays, were preliminarily investigated. The aim was to assess the durability of such materials in order to possibly exploit their potential in substitution to conventional ones, in light of their recyclability, so as to eventually promote circularity.

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Keywords: additive manufacturing; fused filament fabrication; PMMA; PC

1. Introduction

Additive Manufacturing (AM) production technologies are now quite widespread in many industrial settings to create physical prototypes as well as end-use parts. The construction sector is still lagging behind about the use of AM,

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although in recent years this trend is changing. First construction projects have been implemented by using AM processes, especially based on the use of large-manufactured products technologies (Gardner (2023), Paolini et al. (2019)). These developments can be attributed to the distinctive features that AM offers, mainly related to geometrical complexity freedom, wide range of material that can be used and the automation of the process. Interesting advancements in this field include the use of Fused Filament Fabrication (FFF) technology for the production of plastic parts. The possibility to easily produce parts that are structurally strong, UV-resistant and recyclable would ensure not only the design of futuristic forms but also processes that are sustainable in every aspect (Gopal et al. (2023)). Among the wide range of plastic materials, particularly interesting for construction engineering applications appear to be PolyMethylMethAcrylate (PMMA) and PolyCarbonate (PC).

PMMA is a transparent polymer with excellent weathering and UV resistance. Its transparency and ability to be easily fabricated make it perfect for windows, lights, and transparent panels. On the other hand, PC is known for its outstanding resistance to impact and breakage. It is a lightweight material, tinted or transparent, that can be used for partition walls, roofing, or skylights. The performances of AMed parts are highly dependent on the setting of numerous process parameters. Thus, knowledge of their influence on mechanical properties and geometric stability is crucial to produce satisfactory AM parts (Alfieri et al. (2022), Sepe et al. (2022)). The literature reports research that involved the study of the mechanical properties of Additively Manufactured (AMed) PMMA and PC by considering different technologies. Petersmann et al. (2023) investigated the effect of some post-treatments on the mechanical properties of PMMA-based materials produced by FFF. In (Petersmann et al. (2020)), PMMA mechanical properties for dental implant applications were investigated, finding that they hardly depend on the temperature changes inside the human body. The literature is more substantial concerning the study of the performance of AMed PC. In (Cole et al. (2020)) the physical properties, including tensile ones, of AM PC were studied, observing that tensile properties degraded in presence of pore networks and poor interfacial bonding. Furthermore, Reich et al. (2019) studied the tensile properties of recycled PC produced by material extrusion. They achieved interesting results demonstrating that recycled PC can be 3D printed and guarantees high-strength and heat-resistant products at low cost.

This study reports an experimental investigation about the effect of raster angle variations on both tensile and flexural properties of transparent PMMA and white PC samples. The results showed high repeatability of the process and satisfactory performances achieved for both materials, in some cases even comparable with those shown by their moulded versions. This document marks represents an advancement in the existing literature by contributing to a more comprehensive understanding of the mechanical behavior of these two materials with a glimpse to their use in the field of construction engineering.

2. Materials and Methods

Specimens made of PMMA and PC were obtained through the FFF technology, particularly by means of a Ultimaker s5 Pro Printer. The related setting of printing parameters is listed in Table 1 for both materials. Both dog-bone and rectangular specimens were printed according to ASTM E8 and ASTM D790 Standards respectively. The dimensions of specimens are reported in Figure 1. Five printing cycles were carried out for each considered material; each cycle led to the printing of six specimens (Figure 2a): three dog-bone ones (with printing patterns: 0°, ± 45°, and 90°) and three rectangular ones (with printing patterns: 0°, ± 45°, and 90°) (Figure 2b). Therefore, a total of 30 specimens for each material was printed.

Table 1. FFF printing parameters.

	PMMA	PC
Nozzle temperature	250°C	260°c
Bed temperature	110°C	110°C
Layer height	0.1 mm	0.1 mm
Wall number	1	1

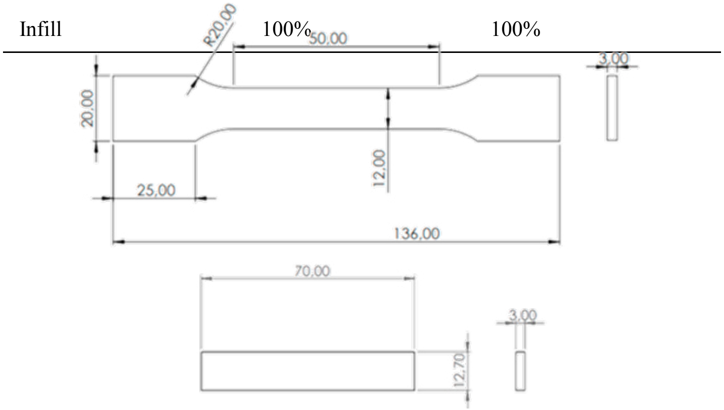

Fig. 1. Main dimensions (in mm) of the printed dog-bone and rectangular specimens

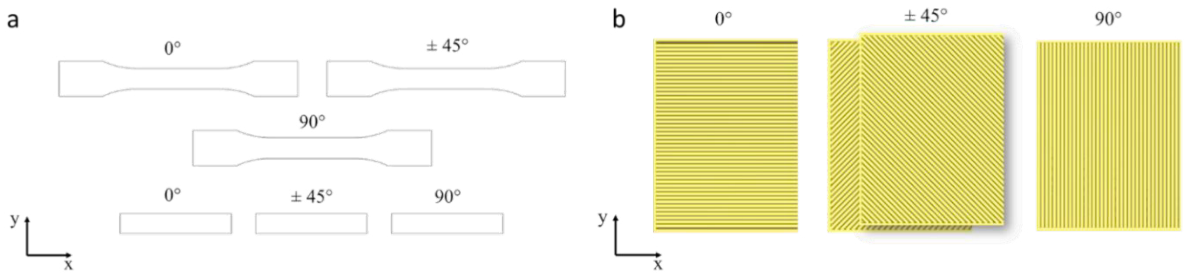

Fig. 2. (a) Specimens printed at each printing cycle and their position on the printing plate; (b) printing patterns for each printing cycle.

3. Results and Discussion

Results were compared among specimens of the same AMed material but characterized by different printing patterns in such a way to highlight the influence of the printing patterns on the mechanical properties. Figures 3 shows some of the tensile stress/strain curves for (a) three PMMA and (b) PC dog-bone specimens, whereas Figure 4 shows the flexural stress-strain curves for the three rectangular specimens. In general, it can be noticed that, both for tensile and flexural behaviours, the elastic moduli and the strengths are almost completely independent from the printing pattern, for both materials. However, the biggest difference can be noticed in the maximum strain to failure. As a matter of fact, in almost all cases the specimens with the 90° printing pattern failed earlier than the other ones. Tables 2 and 3 report the mean values and the standard deviations for the elastic moduli E and the maximum stress S_{max}, for the tensile and the flexural tests, respectively.

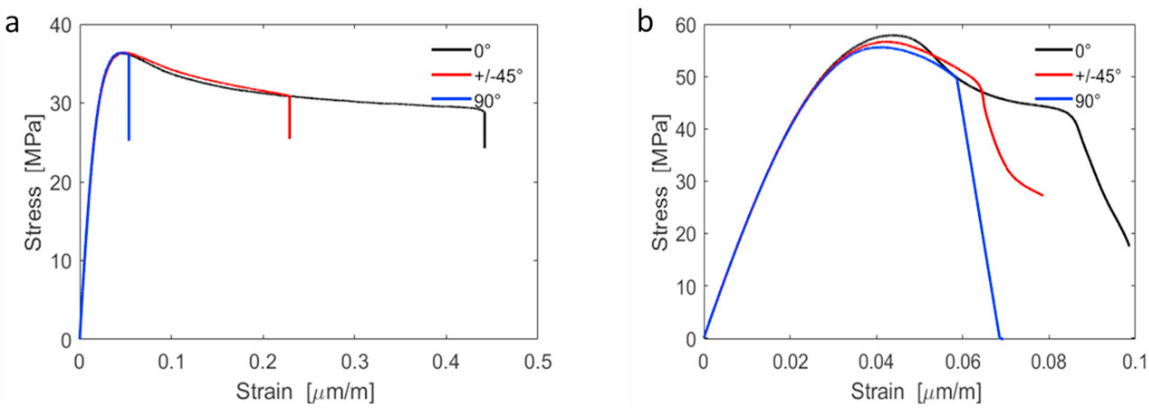

Fig. 3. Tensile stress vs. strain curves for PMMA (a) and PC (b) dog-bone specimens printed with 0°, ± 45° and 90° printing patterns respectively.

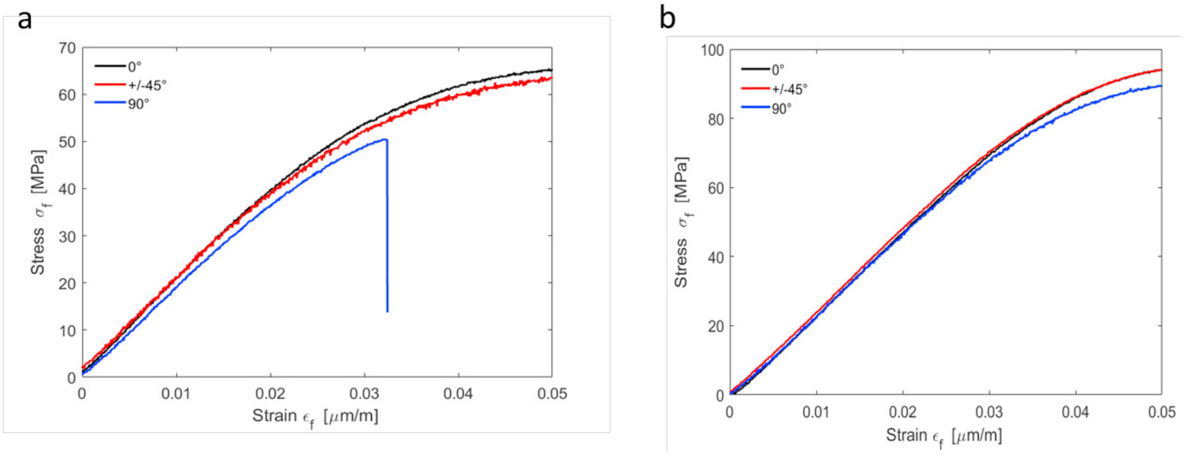

Fig. 4. Flexural stress vs. strain curves for PMMA (a) and PC (b) rectangular specimens printed with 0°, ± 45° and 90° printing patterns respectively

Analysing the data from Tables 2 and 3 it can be noticed that the specimens characterized by the 90° printing pattern showed, in most cases, the highest standard deviation for all the considered mechanical properties. However, in general, it can be appreciated that the standard deviation for each mechanical property, for each printing setup and for each material was limited, thus witnessing the repeatability and the reliability of the printing process. Finally, it can be highlighted that the PC specimens had strengths that were almost 35% higher than the PMMA ones.

Table 2. Mean value and standard deviation for the Young's modulus *E* and the maximum stress S_{max} obtained from the tensile tests of PMMA and PC specimens.

	Printing patterns	E [MPa]		S_{max} [MPa]	
		Mean	Standard deviation	Mean	Standard deviation
PMMA	0°	1977.8	72.84	37.5	1.19
	90°	1910	39.5	35.52	1.96
	+/- 45°	1931.2	33.2	36.45	0.46
PC	0°	1977.8	72.84	37.5	1.19
	90°	1910	39.5	35.52	1.96
	+/- 45°	1931.2	33.2	36.45	0.46

Table 3 – Mean value and standard deviation for the flexural modulus E_f and the maximum stress S_{max} obtained from the flexural tests of PMMA and PC specimens.

	Printing pattern	E [MPa]		S_{max} [MPa]	
		Mean	Standard deviation	Mean	Standard deviation
PMMA	0°	2104.6	46.68	65.65	0.76
	90°	1977.3	65.23	50.75	10.84
	+/- 45°	2033.6	79.22	64.68	0.59
PC	0°	2332.1	60.16	95.51	0.87
	90°	2229.6	32.23	88.76	6.76
	+/- 45°	2350.3	81.67	95.1	0.8714

4. Conclusions

The mechanical behaviours of AMed polycarbonate (PC) and Polymethyl methacrylate (PMMA) coupons were preliminarily investigated in this work. Dog-bone and rectangular specimens were printed by means of the FFF manufacturing technique by using three different printing setups and subsequently subjected to tensile and flexural mechanical tests. The stress vs. strain curves were obtained for the two considered materials, and the mean value and the standard deviation for the tensile and flexural mechanical properties were calculated. It was found out that, in general, the specimens obtained with the 90° printing setup were less resistant and characterised by a slightly higher variability in the mechanical properties. However, the obtained results are repeatable and therefore they witness the reliability of the printing process. Future investigations could deal with the comparison of results with those obtained testing the traditional moulded materials even under fatigue loadings.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

NETOBRA: Boosting Urban Resilience through a digital platform for the construction ecosystem

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Abstract

In the face of escalating climate change and increased frequency of natural and man-made hazards, there is a pressing need for a robust, data-oriented approach in the construction industry. This study proposes an innovative platform designed to connect professionals across the industry, integrating risk and asset management strategies with data-driven decision-making.
The platform, based on the principles of Multi-Criteria Decision Analysis (MDCA) and the Analytic Hierarchy Process (AHP), facilitates the creation of interactive maps that combine different geographic data based on subjective judgment. Furthermore, the platform allows for the calculation of map indicators as variables, considering cities as alternatives or options, which facilitates comprehensive, visually intuitive representations of potential scenarios.
This advanced decision-support system streamlines risk and asset management in the face of potential hazards, empowering industry professionals to make strategic, data-driven decisions that enhance urban resilience. Utilizing Portugal's 308 municipalities as a case study, we demonstrate the platform's potential to strengthen urban resilience, provide insightful risk assessments, and effectively manage assets amidst an ever-changing climate and increasing threats.
This innovative approach not only offers an advanced tool for risk and asset management but also contributes significantly to the broader discourse on sustainable urban development and resilience in the face of climate change.

Keywords: Climate change; Data oriented approach; Risk management; Urban resilience; Sustainable urban development

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1. Introduction

Considering escalating climate change effects, and heightened disaster occurrences, there is an urgent need for sustainable and resilient infrastructure, aligning with various United Nations Sustainable Development Goals (SDGs) (Hendricks et al., 2018; Yigitcanlar & Dur, 2017). This study's relevance is underscored by its alignment with SDGs (Boakye et al., 2018; United Nations, 2015), especially SDG 9 (focusing on resilient infrastructure and innovation), SDG 11 (emphasizing sustainable urban spaces) (*Goal 11 | Department of Economic and Social Affairs*, n.d.), and SDG 13 (addressing climate change) (National Infrastructure Advisory Council, 2010) and (Griggs et al., 2013).

Globally, there is a spotlight on infrastructure resilience. Initiatives like Canada's Action Plan for Critical Infrastructure (2021-2023), the EU's Critical Entities Resilience Directive (2022), and Australia's Security of Critical Infrastructure Act (2018, amended in 2022) recognize and stress the importance of resilience across sectors. Our study integrates into this global conversation, aiming to elevate urban ecosystem resilience through the NETOBRA platform (Rezvani et al., 2021, 2022).The notion of resilience, defined as a system's ability to endure, recover, and adapt to shocks, has gained prominence, especially in urban planning and construction sectors due to rising climate challenges. Urban resilience is categorized into four phases: Avoidance (proactively minimizing threats using climate projections in planning (Rezvani & Gomes, 2021), Endurance (building capacity to face shocks), Recovery (swift post-shock recovery (Rezvani, 2021), and Adaptability (learning and adapting post-event).

International standards, ISO 31000:2018 (Risk Management) and ISO 55000:2014 series (Asset Management), offer guidance for resilience enhancement. The former focuses on systematic risk management (ISO 31000:2018; ISO 55000:2014; Rezvani et al., 2023) while the latter emphasizes efficient asset management to meet performance standards. In addition, Geographic Information System (GIS) stands out as an essential tool for urban resilience, providing spatial vulnerability insights (Gerges et al., 2022), integrating diverse data, and enabling risk visualization (Narjabadifam et al., 2021; Parizi et al., 2022). Given climate complexities, a data-driven approach, like integrating GIS with ISO standards, is imperative for concrete urban resilience measures (Limones et al., 2020; Oliazadeh et al., 2021; S. M. H. S. Rezvani, Almeida, & Falcão, 2023).

GIS's role in consolidating diverse data sources enhances urban resilience visualization (Schaefer et al., 2020) and helps planners comprehend vulnerabilities and strategies effectively (Narjabadifam et al., 2021; Rezvani, Almeida, et al., 2023). All these insights lay the groundwork for understanding NETOBRA's approach in enhancing urban resilience (Rezvani, 2023).

2. Materials and Methods

2.1 Literature Review: Scopus Advanced Search Strategy and Rationale

The Scopus advanced search string filters research articles related to urban resilience and climate change, focusing on those using GIS and mapping, relevant to the construction industry, and specific to Portugal or municipalities. The search also ensures the articles are in English, published in academic journals, and excludes those from agriculture, biochemistry, and medicine. The Scopus advanced search string is as follows:

(TITLE-ABS-KEY ("urban resilience" OR "climate change") AND ("GIS" OR "Geographic Information System*" OR "GIS Analysis" OR "Mapping") AND ("construction industry" OR "AECO" OR "Architecture, Engineering, Construction, and Operations" OR "data-driven decision making" OR "risk management" OR "asset management") AND ("Portugal" OR "municipalities")) AND (EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))

Data from 2008 to 2023 reveals a rising interest in urban resilience and climate change. Until 2015, publications were limited, but a notable increase began in 2019, highlighting the growing global awareness of climate change and the need for urban resilience (Duarte et al., 2022). Most published works are in the fields of Environmental Science, Social Sciences, and Earth and Planetary Sciences, showcasing a multidisciplinary approach to the subject.

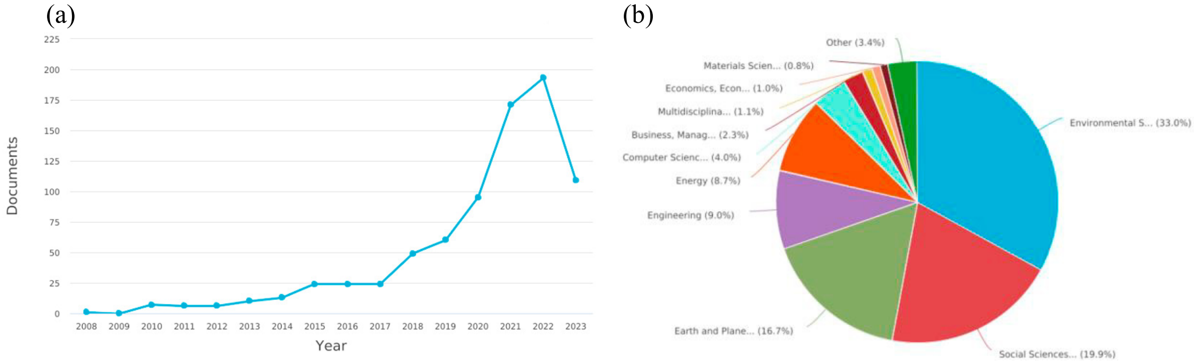

Fig 1. a) Yearly Publication Trend in Urban Resilience and Climate Change Research (2008-2023): An Increase in Scholarly Attention. b) Interdisciplinary Engagement in Urban Resilience and Climate Change Research: Document Distribution across Diverse Subject Areas

Various fields have contributed to the discourse on urban resilience and climate change. Engineering and Energy address technical and infrastructural perspectives, while Computer Science emphasizes the role of technology. Business, Management, and Accounting, alongside Economics, bring forward economic and financial considerations. Other areas like Arts, Mathematics, and Psychology showcase the issue's interdisciplinary nature. The literature review, while thorough, remains concise to maintain paper brevity. Having set the context on the field's current state, the paper's contribution will focus on innovative strategies for urban resilience.

2.2 NETOBRA: A Cutting-edge and Game-changing approach

2.2.1 NETOBRA technical features NETOBRA Technology is a cutting-edge platform developed using tools like server-side rendering, JavaScript, ReactJS, Remix Run, Prisma, and GIS tools like Leaflet and QGIS. It delivers superior web performance, dynamic content generation, and robust mapping capabilities for visualizing climate risks. Alongside Python integration and an in-house authentication system, NETOBRA is primed for expansion, with plans to add advanced analytics and machine learning. Designed to empower insurance firms with precise risk assessment, it addresses the challenges of climate change by linking professionals in the construction industry. NETOBRA champions resilience and sustainability, integrating risk management and data-driven insights for developing robust infrastructure *(Rezvani & Almeida, 2021; Rezvani, 2023)*.

2.2.2 Measuring the impact of NETOBRA on Urban Resilience

NETOBRA is an innovative tool designed to bolster urban resilience by offering a suite of advanced features. It delivers a thorough climate risk assessment, spots vulnerabilities in urban infrastructure, and assists in scenario planning. By aiding urban planners, insurers, and policymakers, NETOBRA streamlines informed decisions, disaster responses, and policy crafting, all underpinned by its data-driven core and visual aids. It paves the way for resilient, sustainable city planning in the face of climate threats.

In this section (2.2.3), the focus is on measuring resilience of vital assets through a 4-phase method detailed in Figure 2, emphasizing the cyclical nature of urban resilience. This method, which is aligned with the insights from Duarte et al., 2022, offers valuable guidance for entities like insurers and governments, enabling proactive measures like Early Warning Systems and efficient budgeting.

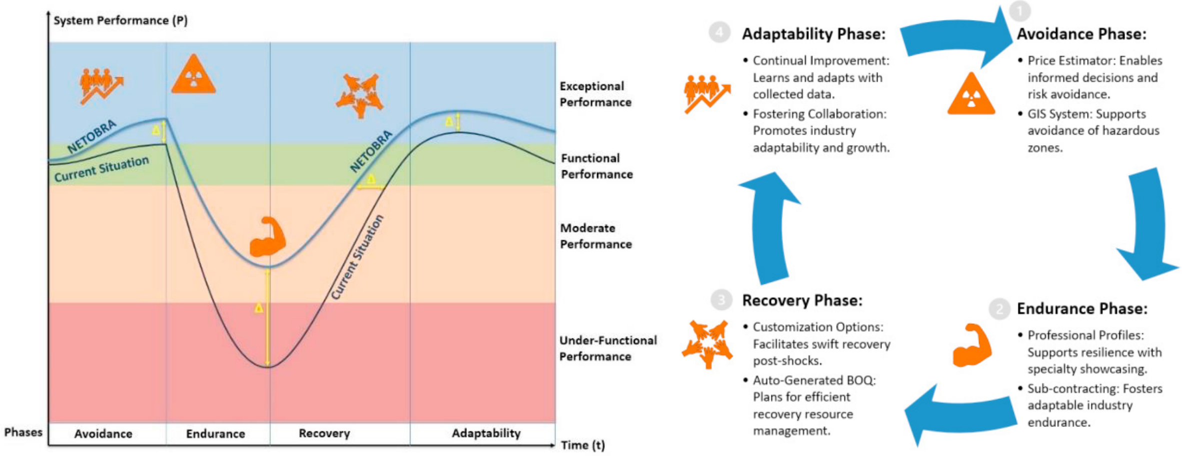

Fig 2. Four Phases of Urban Resilience where NETOBRA's Contributions to Enhance Urban Resilience (Seyed Rezvani, 2023)

2.2.3 NETOBRA Holistic Approach to Enhancing Urban Resilience

In the Avoidance Phase (first phase), preparedness is emphasized to prevent or lessen the brunt of looming threats. NETOBRA's Price Estimator and GIS visualization offer cost insights and demarcation of risk zones, ensuring readiness at the disaster's onset. During the Endurance (second phase), stability is paramount. NETOBRA fosters this through Professional Profiles, showcasing relevant expertise, and a Sub-contracting feature ensuring industry adaptability. These collectively ensure minimal performance degradation during crises. The Recovery (third phase) spotlights post-disaster rehabilitation. NETOBRA's Customization Options and Auto-Generated Bill of Quantities (BOQ) enable adaptive recovery and effective resource management, reducing the time to bounce back. In the Adaptability (fourth and last phase), NETOBRA promotes learning and strategy refinement. The Continual Improvement feature, along with Fostering Collaboration, champions knowledge sharing and joint efforts, fostering future resilience.

NETOBRA's phased strategy has profound implications for Early Warning Systems, offering predictive analysis, and Budget Allocation, backed by its BOQ and Price Estimator. Additionally, its data-driven approach spearheads System Optimization, refining efficiency, and overall output.

2.3 How NETOBRA Enhances Resilience

NETOBRA integrates a three-pronged approach to amplify urban resilience:

- **Enhancing Industry Cohesion**: NETOBRA serves as a connection for over 60,000 firms registered in Instituto dos Mercados Públicos, do Imobiliário e da Construção (IMPIC), facilitating streamlined communication and collaboration. By offering a platform for businesses to efficiently display their services and communicate project updates, it fortifies industry unity and strength (Rezvani, 2023).
- **Leveraging Data for Risk Management**: At NETOBRA's core is its commitment to data-driven decision-making. Its GIS feature pinpoints disaster risk zones, enabling pre-emptive planning. This capacity to pinpoint and assess assets in disaster-prone areas fosters informed preventive measures, bolstering resilience.
- **Optimizing Resource Management**: With tools like the Auto-Generated BOQ and Advanced Price Estimator, NETOBRA champions efficiency in resource allocation, ensuring preparedness not just after, but before potential calamities strike, ultimately solidifying resilience (Rezvani, 2023).

3. Results

3.1 Case Study: Portugal's 308 municipalities

The choice of Portugal's 308 municipalities as the basis for our case studies was strategic and essential for multiple reasons. Portugal's municipalities represent a diverse mix of urban and rural settings, geographical features, population densities, economic conditions, and climate vulnerabilities. This range of characteristics provides an expansive ground to apply, test, and validate our proposed resilience model: NETOBRA.

Portugal also has a robust administrative and geographical dataset available for all its municipalities, facilitating an in-depth and comprehensive GIS analysis. Moreover, the country has been facing significant challenges in the face of climate change, with increased instances of extreme weather events such as heatwaves, droughts, and floods. Therefore, exploring how resilience can be enhanced in regions affected differently by climate change and hazards using NETOBRA becomes significantly important. Studying all 308 municipalities provides a holistic understanding of the effectiveness and potential of NETOBRA, encompassing its performance across varied contexts, and not just limiting to selecting few urban centers or specific regions. This enables us to make conclusions and recommendations that are more universally applicable and insightful for different municipalities around the world with similar characteristics and challenges.

3.1.1 Spatial Distribution and Capacity Analysis of Companies Across Portugal

In our endeavor to build a comprehensive understanding of Portugal's economic landscape, particularly within the context of urban resilience, we turn our attention to an examination of the country's business distribution and capacity. This section offers a detailed analysis of companies spread across various Portuguese districts, categorized by their capacity classes for taking on the work. These capacity classes, ranging from class 1 (least capable) to class 9 (most capable) in terms of contract amount, serve as a pivotal metric in our study. Our analysis of these datasets offers critical insights into the country's economic planning, resource allocation strategies, and risk management approaches. We aim to provide valuable input for policy makers, urban planners, and business leaders, thereby contributing to a resilient, sustainable, and robust economic framework for Portugal (See Table 1 and Figure 3).

Table 1. The number of Portuguese IMPIC approved construction companies in various cities clustered by capacity (1 to 9).

Count of Distrito Main City Name	1	2	3	4	5	6	7	8	9	Grand Total
Aveiro	625	890	154	119	79	35	11	2	0	1915
Azores	279	261	29	26	25	6	0	1	3	630
Beja	163	135	17	13	11	3	0	0	0	342
Braga	895	1361	214	186	144	42	21	9	11	2883
Bragança	172	157	27	34	22	2	0	1	0	415
Castelo Branco	265	230	55	31	19	10	1	0	0	611
Coimbra	376	509	86	83	49	15	7	4	0	1129
Évora	243	213	25	14	9	2	0	0	0	506
Faro	664	1145	129	114	80	24	9	0	1	2166
Guarda	240	206	29	27	17	5	5	0	0	529
Leiria	712	963	147	135	93	34	14	1	6	2105
Lisboa	2352	3085	487	457	353	112	57	18	42	6963
Madeira	214	342	52	47	45	17	6	1	3	727
Portalegre	150	94	8	15	6	5	0	0	0	278
Porto	1388	2346	330	317	240	91	46	14	19	4791

Santarém	570	614	92	66	51	6	4	2	2	1407
Setúbal	896	1234	147	132	92	14	4	2	3	2524
Viana do Castelo	270	422	57	53	27	15	1	0	0	845
Vila Real	241	332	36	36	29	3	2	2	2	683
Viseu	482	754	73	70	50	6	4	1	6	1446

Here are observations based on the company data: Lisbon (Lisboa) and Porto, the two largest cities in Portugal, have the highest number of companies across all the capacity classes. This suggests the two cities as significant hubs of economic activity in the country. A significant proportion of construction companies are categorized at class 1 and 2, underscoring a diverse economic fabric where smaller-scale companies coexist alongside larger entities. The noticeable decrease in the number of firms from class 3 upwards suggests that while smaller enterprises are prevalent, there is a comparative rarity of larger-scale operations. Districts such as Aveiro, Braga, Faro, Leiria, and Setúbal demonstrate a significant number of companies in higher capacity classes, with Braga and Leiria notably hosting over 200 companies in class 3 and 4, indicative of their capability to undertake sizable projects.

Figure 3 illustrates the total number of construction companies operating within Portugal, providing a comprehensive overview of the sector's size and distribution across the country. This visual representation serves as a quantitative benchmark for the construction industry's scale, potentially reflecting economic vitality and informing policy development and market analysis.

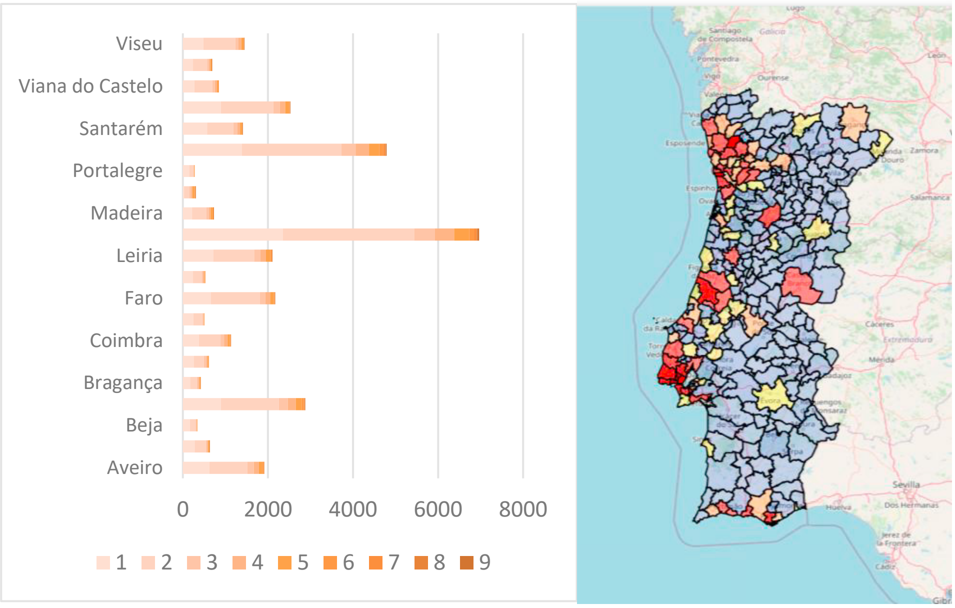

Fig 3. Distribution of IMPIC Certified Companies in Portugal

From a decision analysis perspective, these observations could be useful in several ways: Economic Planning: Identifying areas with a high concentration of low-capacity companies could indicate where more support is needed to enhance economic performance. Resource Allocation: The data can assist in decisions regarding the distribution of resources, such as funding for business support programs or infrastructure development. Risk Management: Understanding the concentration and capacity of companies across different regions can help in managing risks related to economic downturns or crises. The next steps could involve a more in-depth analysis of the data, including statistical analysis to identify significant patterns or trends and the application of decision analysis models to support specific decision-making processes.

3.1.2 Companies/population and companies/Area

The assessment of the number of companies possessing an IMPIC certificate per 1000 population across various Portuguese districts provides us with an in-depth understanding of regional economic robustness as this is an extension to the Figure 3. It showcases the spatial distribution of certified firms in the country, shedding light on both the industrial commitment to standardization and regional variations in compliance levels. This analysis can help us understand the potential capacity for urban resilience initiatives in different regions and inform strategies for better resource distribution and risk management at both regional and national levels.

3.2. Discussions

Our comprehensive study encompassing Portugal's 308 municipalities showing part of the economic landscape and underscoring the potent applicability of the NETOBRA platform. By analyzing the spatial distribution and capacities of companies, we discerned economic hubs in Lisbon and Porto and identified a decline in firms beyond capacity class 3, suggesting potential areas needing support. Through this analysis, not only did we understand the regional economic resilience and compliance by evaluating the number of certified companies as well as the number of certified companies per 1000 population which are shown respectively in Figure 3, but we also gained insights for future economic planning, resource allocation, and risk strategies.

While our research leveraged NETOBRA's GIS capabilities to analyze data from municipalities, it is important to note that the interactive maps generated—synthesizing various geographic data—are not included within this manuscript. These maps, which employ the Analytical Hierarchy Process (AHP) within a Multi-Criteria Decision Analysis (MCDA) framework, are crucial in identifying areas at risk of disasters and pinpointing essential assets. Although these weighted maps based on subjective judgment are central to our findings, they are hosted exclusively on the NETOBRA web application due to their interactive nature and the volume of data they encompass. For comprehensive access and further information, stakeholders and decision-makers are encouraged to consult the NETOBRA web application, where the full suite of GIS tools and maps are available to aid in the formulation of strategies for urban resilience.

4. Conclusions and Future Works

The construction industry and the property market face a myriad of challenges, from contractor selection and budgeting to sustainable practices and climate change implications. Issues like pricing discrepancies, labor shortfalls, and stakeholder miscommunication often lead to inefficiencies in the construction sector. In contrast, the property market grapples with steep property values, gentrification, and climate-related threats. NETOBRA emerges as a solution-oriented platform, bridging these gaps. Current tools like contractor profiles, price estimators, and sub-contracting options tackle fundamental industry concerns. Meanwhile, upcoming features, including the Auto Generated BOQ, Data Visualization Tool, and GIS system, target pricing ambiguities, labor challenges, and disaster-prone asset identification.

As we look ahead, NETOBRA is set to further expand its capabilities. Future tools like the Risk Analysis Tool and the Infrastructure Assessment and Upgrade Planning Tool will delve deeper into climate change concerns, infrastructure longevity, and sustainable practices. The anticipated Affordability Analysis Feature aims to address the property market's cost and gentrification challenges head-on. Ultimately, NETOBRA exemplifies a forward-thinking approach, committing to not just addressing the present challenges of the construction and property sectors but also shaping a resilient and sustainable future for them.

Acknowledgements

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Author Contributions

Intellectual property and ownership, conceptualization, investigation, source code, resources, data wrangling and curation, writing- original draft preparation, S.M.H.S.R.; methodology and visualization, S.M.H.S.R. and N.M.d.A.; writing-review and editing, S.M.H.S.R., N.M.d.A., and M.J.F. All authors have read and agreed to the published version of the manuscript.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

New perspectives in Structural Health Monitoring of restored elements of cultural heritage monuments

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Abstract

The acoustic activity generated in marble specimens under elementary loading schemes (direct tension and uniaxial compression) is studied in terms of the average energy of the acoustic signals recorded. It is highlighted that several seconds before the macroscopic disintegration of the specimens the temporal variation of the specific quantity exhibits a clear plateau, which is terminated just a few tenths of a second before fracture. The specific conclusion is verified by considering the temporal variation of the average energy of the acoustic events against the respective variation of the Pressure Stimulated Currents produced while a restored marble epistyle of the Parthenon Temple is loaded under multi-point bending. It is thus safely stated that the onset of the specific plateau can be considered as an interesting pre-failure signal warning about entrance of the system into its critical stage.

Keywords: Structural Health Monitoring; Cultural Heritage; Restoration and Conservation; Acoustic Emisions; Energy of the Acosutic Signals

1. Introduction

From the structural engineering point of view, the critical issue while restoring monuments of unique splendor of the cultural heritage is that of the structural integrity (keeping, of course, in mind that any intervention is to be restricted

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to the minimum possible level, and, also, that it should be of reversible nature) and, in addition, the Continuous Structural Health Monitoring of the restored elements. Nowadays, the No Destructive monitoring technique most widely used worldwide is that of the Acoustic Emissions (AE). An extremely wide variety of parameters, obtained from the analysis of raw data concerning the acoustic signals, are used in order to characterize the damage level of a given structural member and, most importantly, to quantify the proximity of the system (loaded structural member or loaded structure) to the entrance into its critical stage, namely the stage during which macroscopic catastrophic fracture is impending.

Among these parameters one could mention (indicatively only) some characteristics of the acoustic wave recorded, as it is, for example, the rise time (either its magnitude or normalized over the respective amplitude), the average frequency, the relation between the rise time per amplitude and the average frequency etc. In addition, one could mention the cumulative number of the counts recorded, the rate of production of acoustic signals (either hits or events), the *b*-value and the improved *b*-value (quantifying the relation between weak and strong events) etc. Recently, studies have been published which take advantage of additional parameters, namely, the interevent time intervals between any two successive acoustic signals (Triantis and Kourkoulis (2018)), the distance (Euclidean) between the sources of any two successive acoustic events, the average location of the acoustic sources and the energy (or the respective power) of the acoustic waves (Triantis et al. (2022a)) etc. In general, the analysis of the acoustic activity is implemented either in terms of the conventional time or in terms of the so-called Natural-Time Domain (Triantis et al. (2023)). Relatively recently, studies have been published attempting to analyze the data related to the acoustic activity using concepts based on the principles of Non-Extensive Statistical Mechanics (NESM), a scientific discipline that is found on the borderline between Physics and Applied Mechanics (Kourkoulis et al. (2023), Stavrakas et al. (2016)).

The temporal variations of the above parameters provided by the AE technique during the process of loading and fracture of brittle building materials (as, for example, concrete and rock-like materials) have been long ago studied by many researchers worldwide. It has been indicated that signs warning about upcoming fracture can be detected by proper analysis of the data. Indicatively, one could mention the sudden increase of the rate of generation of acoustic hits and counts (Li et al. (2019), Ohtsu et al. (2005), Rao et al. (2009), Triantis et al. (2021), Triantis and Kourkoulis (2018), Vidya Sagar et al. (2013), Yan et al. (2023)), the abrupt decrease of the *b*-value and that of the *Ib*-value (Aggelis et al. 2011, Loukidis et al. 2021, Meng et al. 2016, Rao et al. 2005), the decreasing trend of the average frequency of the acoustic signals (Aggelis et al. (2011), Sun et al. (2017), Triantis (2018), Tsangouri and Aggelis (2019)), the intensely increasing rate of the energy content of the AEs and the respective cumulative energy (Cai et al. (2007), He et al. (2010), Pasiou and Triantis (2017)) etc. The latter, i.e., the average energy content of the acoustic signals is the object of the present study. The temporal evolution of the specific quantity is explored in terms of the time-to-failure variable (in other words, along an inverse time arrow), in an attempt to detect characteristics that could provide information about the proximity of the loaded system to its critical stage.

The present analysis is based on experimental data gathered from previously implemented protocols, during which the acoustic activity generated while marble specimens were loaded either in direct tension or in uniaxial compression (until fracture) was recorded. The study indicates clearly that several seconds before the macroscopic fracture of the speimen the temporal evolution of the average energy of the acoustic events exhibits a clearly distinguishable plateau, which is terminated some tenths of a second before the final disintegration of the specimen. It is thus suggested that an additional pre-failure index is hidden in the AE data, an index that could be quite valuable in hands of structural engineers, especially if it is considered in parallel with already existing indices. The specific conclusion is verified by studying the temporal variation of the average energy of the acoustic events in juxtaposition to the respective variation of the Pressure Stimulated Currents produced while an accurate copy of a restored marble epistyle of the Parthenon Temple on the Athenian Acropolis (Athens, Greece) is loaded under multi-point bending.

2. Methods: the temporal variation of the average energy content of the acoustic events in the case of elementary tests

Consider a time series of N acoustic events, generated at the time instants t_1, t_2, …, $t_N = t_f$, where the instant t_f corresponds to the N^{th} event, namely the event recorded at the fracture instant. The respective energy contents, E_i, of each event form another time series E_1, E_2, …, E_N. The average energy content of n successive events, $\overline{E}(t_i)$, and the total average energy content of all the events, $\overline{E}(t_f)$, recorded up to the fracture instant, are defined, respectively, as:

$$\overline{E}(t_i) = \frac{\sum_{i=1}^{n} E_i}{n}, \quad \overline{E}(t_f) = \frac{\sum_{i=1}^{N} E_i}{N} \tag{1, 2}$$

The normalized average energy content, $\overline{E_i^*}$, is then defined as:

$$\overline{E_i^*} = \frac{\overline{E}(t_i)}{\overline{E}(t_f)}, \quad 0 < \overline{E_i^*} \leq 1 \tag{3}$$

3. Results: analysis of experimental data

Data from two experimental protocols are analyzed in this section. The first one included direct tension tests of wide plates made of Dionysos marble. The plates were shaped in the form of Double Edge Notched Tensile specimens. The load was applied quasi-statically and monotonically up to the fracture of the specimens. Details about the specific protocol are provided by Kourkoulis et al. (2018a, 2018b). The fracture force for the typical specimen that will be analyzed here was equal to 2.57 kN. A total of N=85 acoustic events were recorded during the whole duration of the test. Attention is here paid to the very last loading stages. As already mentioned in previous section the temporal evolution of the quantities studied is plotted versus the time-to-failure parameter, t_f-t, adopting a logarithmic scale, in order to shed light at the critical stages of the experiment, i.e., the stage during which the load tends to each maximum value, the stage during which the load is almost stabilized and, finally, the stage during which the load starts decreasing until the instant of fracture of the specimen. In this context, the temporal variation of the load applied during the last 250 seconds of the experiment is plotted in Fig.1a together with the energy of each one of the acoustic events recorded.

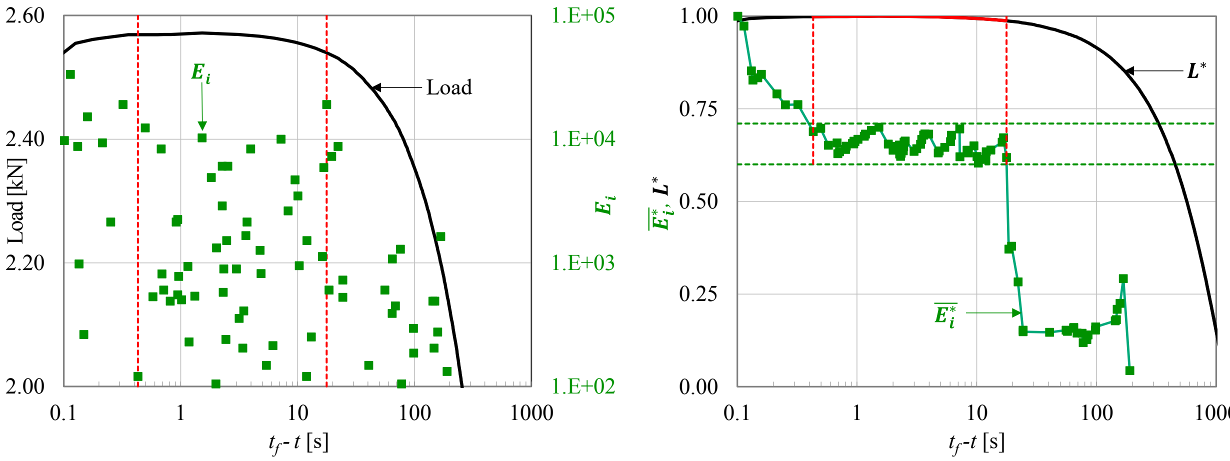

Fig. 1. Direct tension test of wide notched marble plates: (a) The temporal variation of the load applied during the last loading steps of a typical test of the first protocol, together with the energy of each one of the acoustic events recorded; (b) The temporal variation of the normalized load applied in juxtaposition to the respective one of the normalized average energy of the acoustic events.

As a next step, the temporal variation of the normalized average energy of the acoustic events is plotted in Fig.1b, together with the respective evolution of the normalized load applied (i.e., L*). It is clearly seen from Fig.1b that as the load tends to attain its maximum value (i.e., at the time instant t_f-t≈18 s, or, equivalently, about 18 seconds before the fracture of the specific specimen) the normalized average energy of the acoustic events exhibits an abrupt increase (from about 0.15 to about 0.60) and then it is trapped within a very narrow and stable "window" ranging in the 0.60< $\overline{E_i^*}$ <0.70 interval. In other words, it exhibits a clearly distinguishable plateau, which is terminated at the time instant t_f-t≈0.4 s, i.e., only four tenths of a second before the final catastrophic fracture of the specimen. All specimens of the specific protocol exhibited quite compatible response to that of the specimen just described.

The second protocol considered here included uniaxial compression tests of small intact prismatic specimens made again of Dionysos marble. As previously, the load was applied quasi-statically and monotonically up to the fracture of the specimens. The ultimate compressive strength (UCS) for the typical specimen that will be analyzed here was equal to 54 MPa. Additional details about the specific protocol are provided by Stavrakas et al. (2019). A total of N= 122 acoustic events were recorded during the specific experiment. Focusing again on the last loading stages, the temporal evolution of the load applied during the last 300 seconds of the experiment is plotted in Fig.2a together with the energy of each one of the acoustic events recorded.

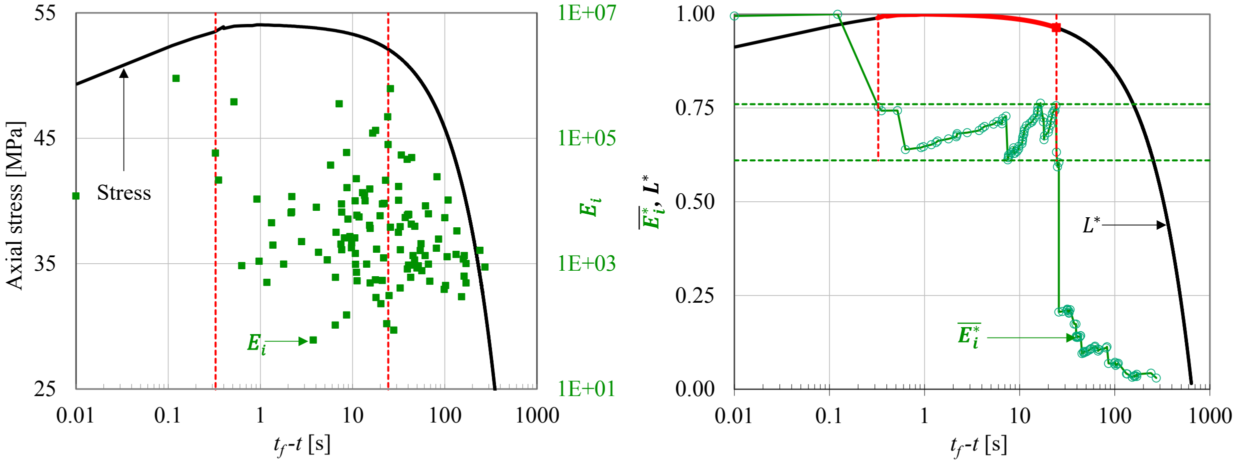

Fig. 2. Uniaxial compression of intact prismatic marble specimens: (a) The temporal variation of the load applied during the last loading steps of a typical test of the second protocol, together with the energy of each one of the acoustic events recorded; (b) The temporal variation of the normalized load applied in juxtaposition to the respective one of the normalized average energy of the acoustic events.

The temporal variation of the quantity of interest, i.e., of the normalized average energy of the acoustic events is plotted in Fig.2b, in juxtaposition to the respective evolution of the normalized load applied (L*). The similarity of the plots of this figure with the respective ones of Fig.1b is at least striking. Several seconds before the fracture of the specimen, and as the load approaches its maximum value (i.e., after the time instant t_f-t≈26 s, namely 26 seconds before the fracture of the specific specimen) the normalized average energy of the acoustic events exhibits again an abrupt increase (from about 0.20 to about 0.60) and afterwards it is trapped within a very narrow "window" ranging now in the interval 0.60< $\overline{E_i^*}$ <0.76. A clearly distinguishable plateau is again formed, which is now terminated at the time instant t_f-t≈0.3 s, namely three tenths of a second before the specimen's abrupt disintegration. The response of the remaining specimens of this protocol is quite compatible to the one just described.

Comparative consideration of the two protocols indicates interesting similarities between the temporal evolution of the average energy of the acoustic events. At the early loading steps, it is relatively low exhibiting either a slightly increasing trend or a stabilization tendency. Then, several seconds before the load attains its maximum value the average energy of the acoustic events exhibits a sudden jump to a quite higher level (in fact its value becomes almost three times higher) and it tends to be stabilized with some minor fluctuations. This stabilization tendency is terminated just a few tenths of a second before the fracture of the specimens.

4. Discussion: The case of structural tests

The applicability of the conclusions drawn in previous section (from the analysis of data recorded from experiments with small scale specimens) in case of large structural elements will be studied in this section. In this direction, the acoustic activity developed in an accurate copy (scale 1:3) of a restored epistyle of the Parthenon Temple is analyzed, in terms of the average energy of the acoustic events. The epistyle tested consists of two asymmetric marble fragments, joined together with the aid of three pairs of threaded titanium bars (shown schematically in Fig.3) and suitable cement paste. The epistyle was prepared by experienced technicians of the Acropolis worksite. It was submitted to monotonic ten-point bending under quasi-statical displacement-controlled conditions. Analytic description of the specific experimental protocol is given by Kourkoulis et al. (2017). The maximum overall bending load attained during the specific structural test was equal to about 33 kN. A total of N=951 acoustic events were recorded during the experiment, which was terminated at the instant of abrupt fracture of one of the corners of the restored epistyle. The temporal evolution of the load applied is plotted in Fig.4a together with the energy of each one of the acoustic events recorded.

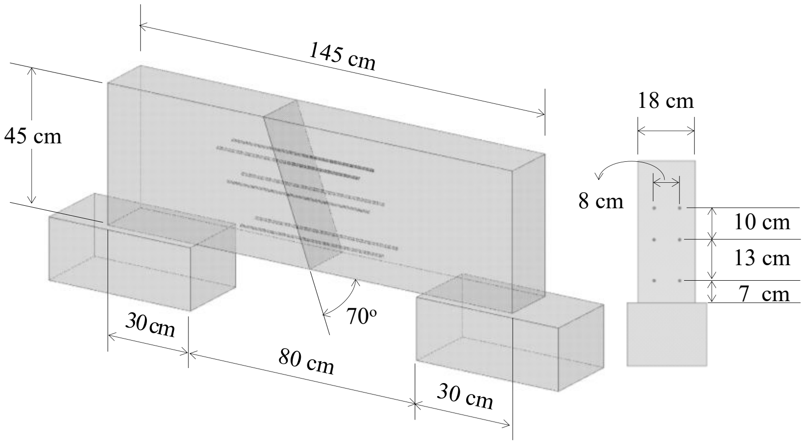

Fig. 3. The geometry and the dimensions of the restored epistyle. The two marble fragments and the position of the three pairs of reinforcing bars are shown. The restored epistyle rests on marble blocks simulating the capitals of the Temple and it is tested under ten-point bending.

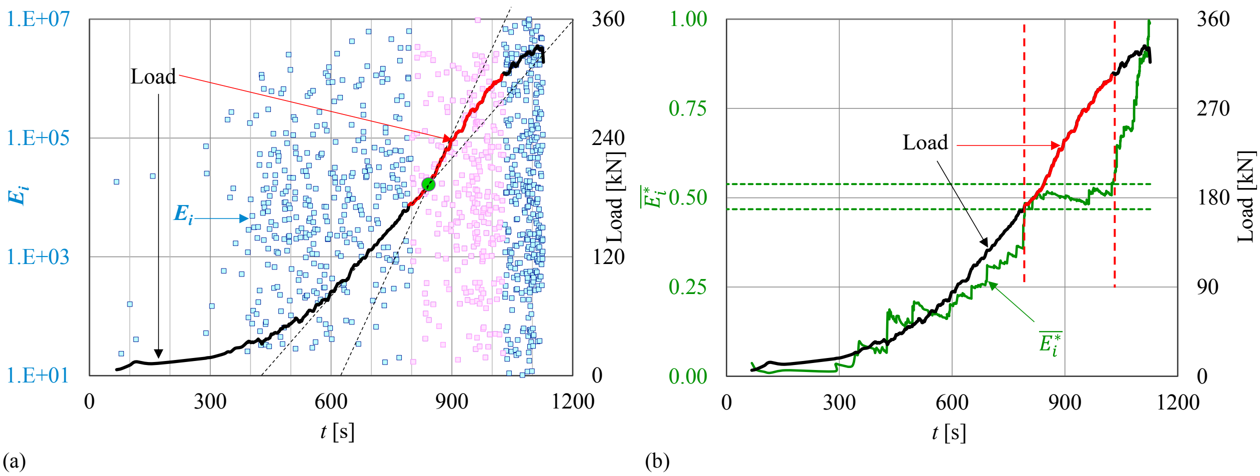

Fig. 4. Ten-point bending of a restored marble epistyle: (a) The temporal variation of the load applied, together with the energy of each one of the acoustic events recorded; (b) The temporal variation of the load applied in juxtaposition to the respective one of the normalized average energy of the acoustic events.

Thorough analysis of the mechanical response of the restored epistyle (by means of data provided by the 3D-Digital Image Correlation technique and with the additional aid of traditional clip gauges measuring the opening of the fault, i.e., the distance between the two constituent blocks of the specimen) has revealed that entrance of the specific system into its critical stage took place at the instant with t_{cr}≈830 s, namely the instant of the slope change of the load-time curve indicated by the green circle in Fig.4a (Kourkoulis et al. (2024)). At this instant the load applied was equal to about L_{cr}≈183 kN. It should be emphasized that this critical load does not indicate proximity to fracture of the marble blocks. The complicated nature of the specific structural member, which consists of three materials (marble, titanium and cement paste) with many interfaces, is responsible for a variety of failure mechanisms, including not only fracture of the marble, but, also, debonding of the reinforcing bars from the marble body, fracture of the cement paste surrounding the titanium bars and covering the faces of the blocks in contact and finally yielding or fracture of the reinforcing bars themselves. Therefore, entrance into the critical stage is to be here understood as proximity to activation of at least one of these failure mechanisms and not exclusively to proximity to macroscopic fracture of one of the two marble blocks (which, in fact, was observed at a much higher load, equal to about 330 kN).

Based on the above observation, attention is paid to the time interval around the critical instant corresponding to L_{cr}≈183 kN. The temporal variation of the normalized average energy of the acoustic events is plotted in Fig.4b, together with the respective evolution of the load applied. It is observed from this figure that several seconds before the bending load applied approaches the critical limit L_{cr} (more specifically at the instant t≈795 s) the normalized average energy of the acoustic events exhibits a rapid increase (from about 0.35 to about 0.47). From this instant on, its value tends to be stabilized (with minor fluctuations) in a narrow "window" in the interval $0.47<\overline{E_i^*}<0.53$, forming a plateau (as it was the case of the elementary tests described in previous section). The plateau is terminated at the instant t≈1025 s, namely the instant of the second slope change of the load-time plot. According to the analysis of the sets of all data available this instant corresponds to activation of an additional fracture mechanism (coalescence of micro-cracks within the marble blocks) indicating now proximity to the fracture of marble.

In an attempt to comparatively consider (and further validate) the above findings, the temporal evolution of the Pressure Stimulated Current (PSC), recorded during the specific experiment is plotted in Fig.5, in juxtaposition to the respective evolution of the bending load. The term PSC designates low-level electric signals (in the form of very weak electric currents of the order of pA), which are emitted during loading of brittle geomaterials. The temporal evolution of the PSC provides reliable information about the damage level of the material. It is experimentally verified that the PSC exhibits a smooth increasing tendency during the period of generation of the networks of micro-cracks and a quite rapid increase when the networks of microcracks start coalescing to each other, leading to the formation of fatal macro-cracks (Li et al. (2021), Stavrakas et al. (2004), Saltas et al. (2018), Triantis et al. (2022b)). As a result, the temporal evolution of the PSC is considered as providing reliable pre-failure indicators, which have been found to be in very satisfactory agreement with the respective ones provided by the AEs (Triantis et al. (2022b)).

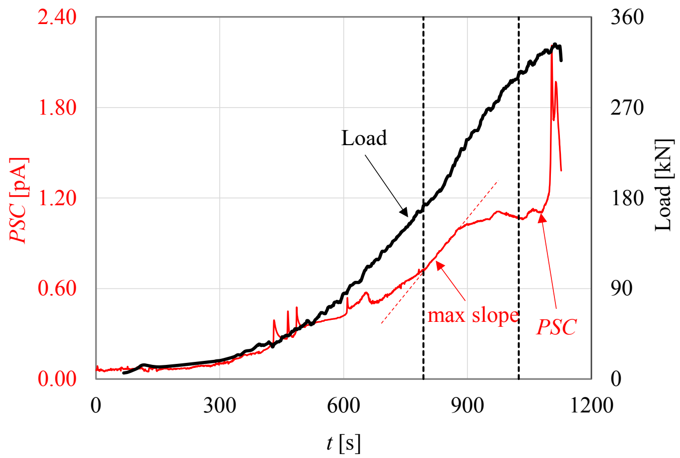

Fig. 5. The temporal evolution of the Pressure Stimulated Current in juxtaposition to the respective evolution of the bending load.

It can be seen from Fig.5, that at the time interval at which the normalized average energy of the acoustic events forms its plateau the PSC exhibits, also, a stabilization tendency (after a period of smooth, almost linear, increase). Moreover, it is to be emphasized that the plateau of the PSC is terminated abruptly at the instant t=1090 s and is followed by a quite abrupt increase, which is considered as a clear warning signal of upcoming macroscopic fracture (which was indeed observed about 40 seconds later, i.e., at the instant at t=1130 s).

3. Concluding remarks

The temporal evolution of the average energy content of the acoustic events recorded during loading and fracture of marble specimens subjected to either direct tension or uniaxial compression was studied. It was highlighted that while the load tends to attain its maximum value, the average energy exhibits a relatively sudden increase and then it tends to be stabilized within a rather narrow interval forming a kind of a plateau, which is terminated some tenths of a second before the fracture of the specimen tested.

Similar qualitative conclusions were drawn for the case of a structural test, namely an experiment during which a copy of a fractured and restored marble epistyle was tested under ten-point bending. In spite of the differences and the much more complex nature of the specific specimen (compared to the wide marble plates and the prismatic marble beams tested in tension and compression, respectively) the average energy content of the acoustic events exhibited a compatible behaviour to that of the elementary experiments. Indeed, at the critical time instant (corresponding now to the slope change of the load-time plot rather than to the maximum load) a plateau of the temporal evolution of the average energy was formed (after a relatively rapid increase), which was terminated at the instant of a second load-time slope change (designating activation of an additional damage mechanism). The temporal evolution of the average energy of the acoustic events recorded in the epistyle was studied in juxtaposition to that of the Pressure Stimulated Currents. Remarkable similarities were highlighted, validating somehow the conclusions drawn.

Recapitulating it can be stated that the onset of the plateau of the average energy constant may be well considered as a relatively early signal, warning about upcoming entrance of a system into its critical stage. Moreover, complementary use of more than one monitoring techniques (like, for example parallel use of the AEs technique and that of the PSCs) may be proven quite advantageous for practical engineering purposes.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Oyster shells' incorporation into mortar to achieve blue circular economy – LCA case study in Portugal

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Abstract

Currently, society's great challenge is to face climate change and mitigate environmental impacts. This study aims to identify the environmental impacts of recovering traditional construction techniques in coastal regions by incorporating oyster shells into mortar to achieve the objectives of the blue circular economy. The possible environmental impacts are measured using Life Cycle Assessment. Oyster shell is considered as a powder or an aggregate in construction, and comparison is made between mortars produced with percentages of substitutions of traditional materials by oyster shell incorporation. The case study was carried out in the Algarve region, in the south of Portugal. Consequently, the potential of circularity for a biomaterial derived from the aquaculture industry and its inclusion in different particle size in the construction industry is discussed. This work is part of the activities to be carried out within the scope of the EEA granted Shellter Project, which aims to explore the potential of incorporation of oyster shells in the production of construction materials within a circular economy model.

Keywords: Oyster shell; Mortar; Life Cycle Assessment; Blue Circular Economy

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1. Introduction

Aquaculture is an ancient practice that has evolved over the centuries according to the knowledge acquired by farmers based on needs and also on their positive and negative experiences. In 1950 the total production of fisheries and aquaculture reached 19 million tons; almost 70 years later, this value reached a historic record accomplishment of 179 million tons in 2018 with an annual growth of 3.3% (FAO. 2022).

In Portugal, the production of mollusks in aquaculture increased by 48% in 2020, representing 58% of the total aquaculture production. In 5 years (2015 to 2020) oyster production tripled in Portugal. Oysters were the most relevant species (3,838 tons), followed by clams (3,659 tons) and mussels (2,007 tons) in 2021 (DGRM. 2021).

From the perspective of aquaculture production, Algarve is the most representative region in Portugal, being responsible for 42% of the production sales volume and production value of around 157 M€ (2020). Most of the nurseries for the production of bivalves are located specifically in the Ria Formosa. The high production volume of this product is due to the good conditions for cultivation, such as the warmer water temperature (DGRM. 2021).

The consumption of bivalves is part of Portuguese gastronomy and its role in the national industry is considerable. This fact is due not only to the production of a high number of species, but also to the number of people who depend directly on this sector, through the harvesting and commercialization. The practice in this sector generates a large production of shellfish waste, and the slow process of shell degradation increases the volume of this waste, making reuse more important (Félix et al. 2018).

Based on the current reality, the final destination for oyster shells is incineration, which carries environmental impacts. Due to incineration high costs, often dead oysters are left in the nurseries or in surrounding areas: The accumulation of shells leads to unpleasant odors, reduces the quality of life for individuals (Mo et al., 2018), and increases oyster farmers concerns due to the occupation of space near fishing sheds and the lack of options for reuse. These reasons often lead to the inappropriate use of shells, or negative effects on local environment.

With the principle of safeguarding goods from the ocean, the blue economy concept surfaced in 2012, intertwined with the circular economy, which emphasizes sustainability and the recycling of waste, along with various other sustainable practices that utilize and preserve marine and coastal resources (Eikeset et al. 2017).

It is possible to find previous studies (Magalhães et al. 2024) that report the use of oyster shells in mortars hundreds of years ago in coastal regions (Razali et al. 2017). Laefer (2004) says that lime had to be produced using oyster shells, because limestone was scarce. Therefore, coastal regions took advantage of the availability of this material to incorporate it into mortars. The reports even claim that this mortar was more durable.

Historically, shells were used in mortar mixing to make a specific type of material, using local resources and part of the vernacular architecture of each place (Hodges. 2022). The addition of local products in mixtures for civil construction dates back to an ancient period (before Christ), and at that time the materials used were natural. Lime-based products have been used since very early times in the history of civilization. The type of lime varied according to the availability of materials in each region, with oyster shells being used in seaside places and calcium and magnesium rocks such as chalk, dolomite and limestone in other places (Guimarães. 2002; Chandra. 2003).

Guedes (2018) through a European vision, reports that the Portuguese adopted construction techniques originating from Indian culture, due to their trips to India in the 16th century. The Indian technique used to mix and grind ingredients to make the lime mortar known as *Chunam*. According to the author, the mixture might have a Greco-Roman origin as well and the use of softening lime mortar joining shells, sand and other materials has multiple origins in Europe and Asia. The recipe was well accepted at the time in places like Mozambique, Brazil and Macau.

Currently, society's great challenge is to face climate change and mitigate environmental impacts and the incorporation of shells is a promising sustainable solution of reusing waste while creating a durable product in the construction sector. The present work aims to identify the environmental impacts of recovering traditional construction techniques in coastal regions by incorporating oyster shells into mortar towards to a blue circular economy. The possible environmental impacts are measured using Life Cycle Assessment. Life Cycle Assessment (LCA) is a methodology that aims to identify the significance of the potential environmental impacts of a given product at various points in its life cycle, assisting in strategic planning, definition of priorities, project or design of products or processes. The LCA intends to analyze the product from the beginning to the end of life, starting from the acquisition of raw materials, production, use, end-of-life treatment, recycling and disposal (ISO 14040. 2006).

The LCA is an important tool in modern industrial environmental management (Löfgren et al. 2011). Increasingly, industries are using LCA to reduce overheads, consequence of the life cycle of goods and services, in addition to improving the competitiveness of the company's products. The LCA process is also used to improve product design for a better choice of materials, technologies, design criteria and to consider recycling (E.C. 2023). Based on the results generated by the LCA, it is possible to promote a more responsible project, mitigate environmental impacts, and reduce the use and release of toxic materials (EPA. 2023).

This paper studies oyster shell, in the form of powder or aggregate waste and it compares mortars made with varying percentages of traditional materials substituted by incorporated oyster shell. The case study was conducted in the Algarve region, located in southern Portugal.

This work is part of the activities to be carried out under the EEA granted Shellter project. The project intends to discuss the potential of incorporating oyster shells waste in the development of construction materials in a circular economy model, joining Nofima AS (Norway) and Instituto Superior Técnico, University of Lisbon (Portugal).

2. Study methodology – LCA case study

The methodology employed in this study is in line to the European Standard EN 14040 (2006), which outlines the principles and framework for a life cycle assessment. In the LCA study, oyster shell was considered as a component of the coating mortar, and was harvested on Culatra Island, Algarve, in the south of Portugal. Algarve region was chosen because it is the largest aquaculture producer in Portugal. The Global Warming Potential (GWP) was identified for three different types of oyster shell mortars produced in Faro, the capital of the Algarve region. The Life Cycle Assessment (LCA) modeling was conducted using SimaPro 9.4.0.2 software, and the Ecoinvent 3 database to create processes that are relative to the oyster shells treatment and sand. To understand the processes of Natural Hydraulic Lime, it was used a reference (Miniera. 2020). In this work, the life cycle covers from the cradle to the gate. The GWP were assessed from the extraction of necessary raw materials from their natural environment (except for the oyster shell) to the associated transportation and manufacturing processes. To address this, an approach was employed, involving a synthesis of the identified and treated impacts, which were then integrated in Excel to yield results that are both compatible and realistic.

With advances in research into the application of other biomaterials in the composition of mortar for civil construction, interest in the use of oyster shell as a substitute for binder or aggregate in the manufacture of mortar for civil construction has been awakened, in order to contribute to the reduction of environmental impacts (Bellei et al. 2023).

In the manufacturing stage, the objective was to produce coating mortars by replacing percentages of traditional materials with oyster shell. A conventional mortar was considered to be composed of: Natural Hydraulic Lime 3.5 (binder), Sand (aggregate), and Water (CONTROL). Three solutions were analyzed, each of them containing percentages of oyster shell in the composition, but varying these percentage in the production processes involved. In Solution 1: 24% of the hydraulic lime is replaced with oyster shell powder (24% NHL-OSP); in solution 2: 24% of the hydraulic lime is substituted with calcined oyster shell powder (24% NHL-COSP); and in solution 3: 30% of the sand is replacing by an oyster shell aggregate (30% S-OSA).

3. Results and discussions

3.1. Life cycle of oyster shell mortars

<u>*Extraction of raw materials*</u>: in this study the GWP of the production of natural hydraulic lime and the extraction of sand were considered according to the Section 2. The stage of raw material production from oyster shells was not considered in the LCA of this study. This is because its primary purpose is not construction but rather food consumption. Once the shell becomes a waste product for the environment, either through population consumption or mortality during harvesting by oyster farmers, it can potentially become an attractive biomaterial for other industries. Furthermore, after the oyster shell arrives at the laboratory, the cleaning and drying stages were not considered in this study. Currently, oyster farmers leave oyster shells near their sheds, and the shells are naturally cleaned and dried. These and other data were obtained from interviews conducted in the Algarve region. The interviews with

intermediaries (Oyster farmers, Association or Cooperative, Scrubbing Station or Distributor, Consumer, Hospitality, Restaurant, Supermarket/Hypermarket, Construction and Building Materials Company) were carried out within the framework of the Shellter project, together with a master's dissertation, and a Ph.D. thesis.

With the opportunity to recover traditional construction techniques, this biomaterial needs to be transported to a mortar production factory that explores its potential. In the study a possible location of such factory was considered in Faro.

Transportation: at this stage, the transportation of natural hydraulic lime and sand were considered as mentioned in Section 2. The environmental impacts of shells were considered in terms of transportation from a fishing shed on Culatra Island in the Algarve region to a possible company facility located in the city of Faro. The distance was obtained from Google Maps (5 km by boat and 10 km by truck weighing up to 32 tons). After arriving at the facilities, the shells need to be prepared for use in construction.

Manufacturing: the oyster shell was used to replace percentages of traditional materials in the composition of the coating mortar. The shell powder was obtained by using a cutting mill (for an initial reduction in shell particle size) and a centrifuge mill (so that all particles are < 150 μm). For the use of shell as aggregate, only the cutting mill was needed. The mills are shown in Fig. 1. In addition, one of the mortars was produced with calcined shell powder. In this case, the oyster shell powder still underwent a calcination process, requiring an oven that reaches high temperatures, such as 1000 °C.

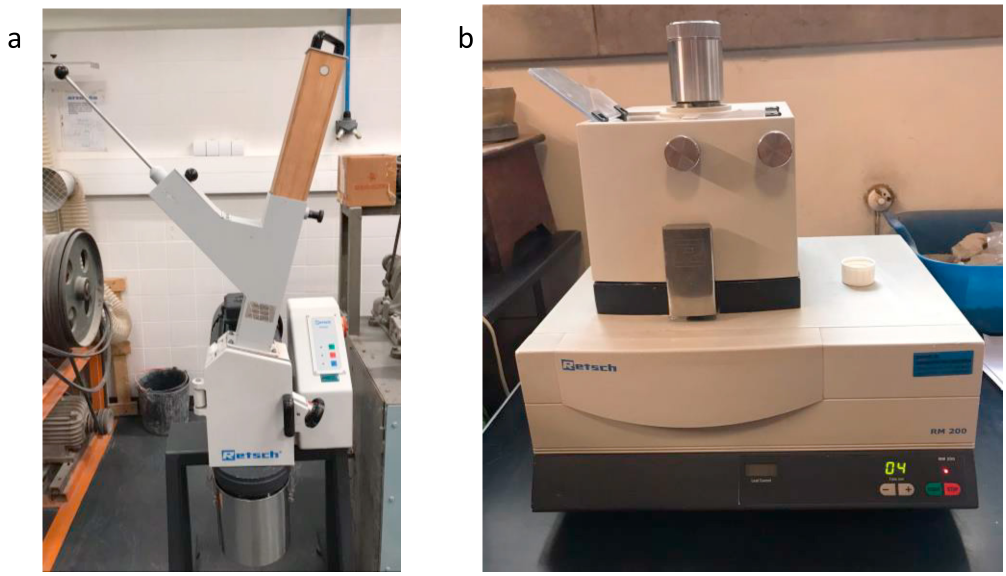

Fig. 1. (a) cutting mill; (a) centrifuge mill.

3.2. Environmental impacts

In this endeavor, our focus centered on the analysis of the environmental variable Global Warming Potential (GWP). All the environmental impacts values were weighting to the ratio of the mortar mix. The components and processes of LCA in GWP per kilograms are seen in the Fig. 2. The total GWP of each mortar is shown in Fig. 3.

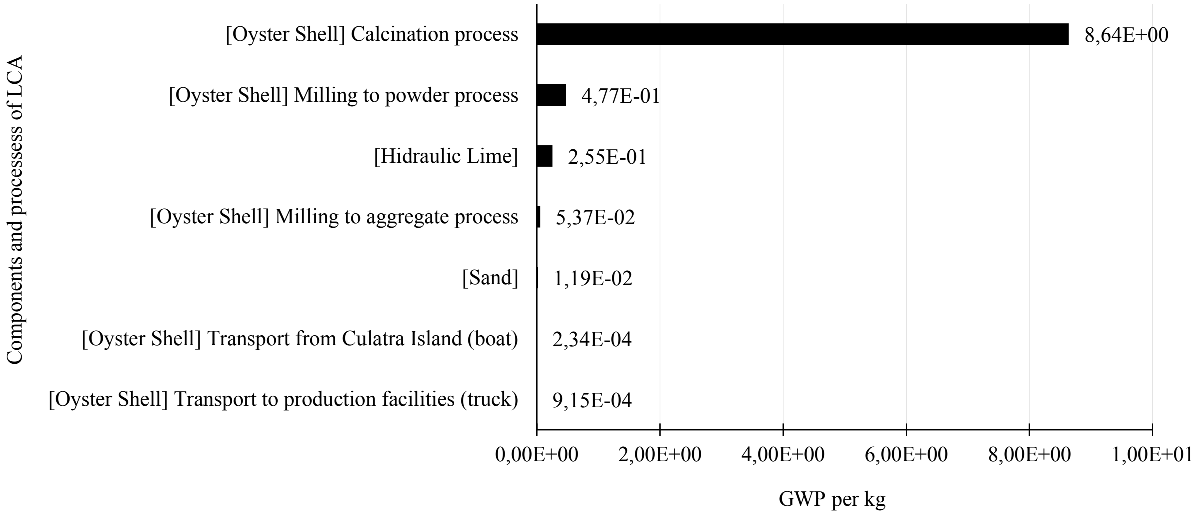

Fig. 2. Components and processes of LCA in GWP per kilograms

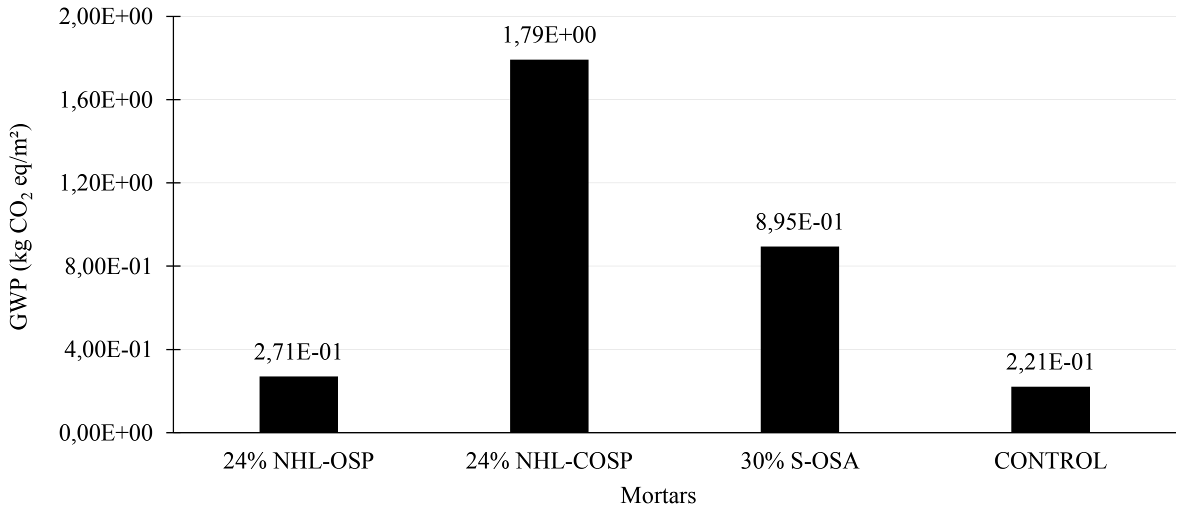

Fig. 3. Total GWP (kgCO_2 eq/m^2) of mortars. CONTROL: control mortar; 24% NHL-OSP: 24% of the hydraulic lime is replaced with oyster shell powder; 24% NHL-COSP: 24% of the hydraulic lime is substituted with calcined oyster shell powder; and 30% S-OSA: 30% of the sand is replacing by an oyster shell aggregate.

Differences in the material acquisition processes can be observed in Fig. 2. The grinding process of oyster shells to achieve sand-sized distribution has a lower environmental impact compared to the environmental impact caused by powder grinding. Calcination of the oyster shell has been shown to be the process with the highest carbon emissions. Oyster shell powder, obtained by mechanical process, has a lower environmental impact, approximately 22% less when compared to calcined oyster shell powder (mechanical and thermal process) and closer to the control mortar.

As observed, calcination is the process with the highest GWP per kilograms. Consequently, in Fig. 3 the 24% NHL-COSP mortar solution exhibited the highest carbon footprint per square meter when compared to the 24% NHL-OSP and 30% S-OSA mortar. In this case, it would make sense to assess the short-term and long-term cost/benefit of producing a mortar using calcined oyster shell, and whether it truly outperforms other solutions. This would determine if the calcination process is indeed necessary. Nevertheless, considering that all mortars have similar characteristics, the 24% NHL-COSP mortar, with 24% substitution of natural hydraulic lime with calcined oyster shell powder, stands out for its negative environmental impacts (Fig.3).

4. Conclusions

This work found to identify the environmental impacts of recovering traditional construction techniques in coastal regions by incorporating oyster shells into mortar to achieve the blue circular economy. The LCA of three different types of mortars was analyzed in terms of GWP and compared with each other and with a standard construction technique.

There are previous records of the use of oyster shell in coastal regions in ancient times. The shell was used to replace lime due to its scarcity. Nowadays these construction techniques are little used by the population. The accumulation of shells generated by oyster mortality in the aquaculture industry, and the disposal of shells in common waste after consumption by the food industry are problems that can be minimized through the recovery of traditional construction techniques.

Firstly, the mortar produced with 24% replacement of natural hydraulic lime by oyster shell powder (obtained by a mechanical process) was the solution with the lowest environmental impact generated. The solution replacing 30% natural aggregate by oyster shell aggregate was the second one with the lowest environmental impact. The solution (24% NHL-COSP) with shell calcination (thermal process) demonstrated the greatest environmental impacts. Thus, it is essential to assess the equilibrium between the performance enhancements and the potential negative environmental impacts.

Concrete and mortar are used worldwide in civil construction due to their ease of working, high strength, and wide availability of their components. On the other hand, high consumption raises concerns about the scarcity of raw natural aggregates, and it is of great importance to seek alternatives to mitigate these negative impacts, such as the replacement of natural materials by oyster shell-based products as a binder or aggregate. With this development, the cluster of activities associated with bivalves grows, extending in value to production activities, new distribution circuits and waste collection, generating employment and economic value, also with an impact on the social dimension. Finally, mention should be made of valuing the environmental dimension in which waste from consumption is reduced, which is thus sustainably incorporated into the territories where it is developed. The recovery of marine waste thus represents a good example of a blue circular economy.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Perspectives on integrated retrofitting of existing reinforced concrete buildings

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Abstract

Buildings account for 40% of energy consumption and 38% of CO_2 emissions in the European Union (EU). This substantial impact is primarily due to the delayed implementation of initial energy codes. Additionally, about 40% of the EU's buildings are situated in seismic-prone areas, many of which were constructed without meeting current safety standards. An estimated 65% of these structures require both energy and seismic upgrades. Given these challenges, there is an urgent socio-economic and environmental need to renovate the existing building stock. It is crucial to adopt an integrated retrofitting strategy, enhancing both efficiency and resilience against extreme events. This study provides a detailed examination of the integrated retrofitting of existing Reinforced Concrete (RC) buildings. Additionally, a review of current international policies (or incentive programs) related to independent (i.e., structural or energy) and integrated retrofitting (i.e., seismic plus structural) is presented and discussed. From the ten incentive programs evaluated, 77% focused on energy retrofitting interventions, while only 33% addressed structural improvement interventions. As anticipated, there is an increasing emphasis on programs that also consider the sustainable impact of these buildings' interventions but the combination of energy plus structural interventions still has a minor relevance.

Keywords: Incentive programs; Integrated retrofitting; Energy efficiency; Structural safety; CO2 emissions.

1. Introduction

The construction sector in the European Union (EU) accounts for 36% of carbon dioxide (CO_2) emissions, 40% of energy consumption, and 55% of electricity consumption (Comission 2020). A significant portion of this energy

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consumption and CO_2 emission stems from the heating and cooling of buildings. This trend can be attributed to the delayed introduction of the EU's initial energy codes for buildings, which were only formally established in the 1970s. By that time, approximately 66% of the EU's existing building stock had already been constructed (Bournas 2018). Addressing energy consumption in the building sector is pivotal to meeting the United Nations' goal of achieving net-zero greenhouse gas emissions by 2050 (Comission 2021). Presently, policies are growing that aim to sustainably renovate existing building structures, primarily focusing on reducing operational energy consumption and incorporating low-carbon materials during refurbishment (Council 2019, Comission 2020). However, these policies often overlook structural vulnerabilities, potentially leaving buildings at risk, especially in seismic-sensitive areas. Structural retrofitting and rehabilitation are typically performed independently from the energy retrofitting interventions (and vice-versa), which can be changed by the implementation of new policies that promote integrated interventions (Masi, Chiauzzi et al. 2019).

Furthermore, it is important to note that 40% of these structures are located in earthquake-prone areas and were originally built without sufficient safety measures. Approximately 65% of them are in need of both energy efficiency improvements and seismic retrofitting.

The present work aims to provide an overview of the integrated retrofitting of existing Reinforced Concrete (RC) buildings. Additionally, it will be presented and discussed a review of existing international policies (or incentive programs) related to independent and integrated retrofitting.

Nomenclature

RC	Reinforced Concrete
EU	European Union
EEF	European Energy Efficiency Fund
JTF	Just Transition Fund
CF	Cohesion Fund
RRF	Recovery and Resilient Facility
PPEC	*Plano de Promoção da Eficiência no Consumo da Energia Elétrica*
FNRE	*Fundo Nacional de Reabilitação do Edificado*
IFRRU	*Instrumento Financeiro para a Reabilitação e Revitalização Urbanas*
RpA	*Reabilitar para Arrendar- habitação acessível*
ARU	Urban Rehabilitation Area
IVA	*Imposto de Valor Acrescentado*
IMT	*Imposto Municipal sobre as Transmissões Onerosas de Imóveis*
IRS	*Imposto de Rendimento das Pessoas Singulares*
IRC	*Imposto sobre o Rendimento das Pessoas Coletivas*
IMI	*Imposto Municipal sobre Imóveis*
AIMI	*Adicional Imposto Municipal sobre Imóveis*
IRPEF	Personal Income Tax
IRES	Corporate Income Tax

2. Methodology of review

A critical analysis was conducted on 10 incentive programs, encompassing both European and Portuguese levels, as well as 8 tax benefits—5 in Portugal and 3 in Italy—financed by the European Union. The creation of the database was made feasible solely through the examination and research of incentive programmes and tax benefit in official documents and websites of the European Union, the Portuguese government, and the Italian government.

2.1. Review of existing incentive programs for buildings' retrofitting

Each incentive program was studied based on impact assessment of their aim (i.e., improvement of their energy efficiency and/or structural integrity, and/or CO_2 emissions); technical information (construction period, and type of construction of the target constructions); eligible investments (investment range, debt maturity, explanation of the investment, investment instruments, and co-investments); beneficiaries and investors.

To prepare this preliminary report, an exhaustive analysis was carried out of both the incentive programs available in the EU and in Portugal, assessing the following variables: energy efficiency; structural integrity, and CO_2 emissions. After reviewing it in detail, it is possible to observe that in some cases some programs were not yet applied or were unknown, i.e., the target stakeholders were not well specified, or the date for starting its implementation was not yet defined.

2.2. *Tax Benefits*

In addition to studying different incentive programs relating to buildings' retrofitting, 8 active tax benefits in Portugal and Italy were also analysed. Of these, 63% are from Portugal while 38% are Italian and the connections between the different tax benefits were explored and drawn. These benefits were analysed based on several criteria: impact assessment (including energy efficiency, structural integrity, and CO_2 emissions), technical details (such as construction period and type of construction), financial contribution within the program, the specific tax benefits, beneficiaries, and investors.

3. **Review of existing strategies for independent and integrated retrofitting of existing RC buildings**

Retrofitting existing building structures is one of the most important tasks nowadays, since there is a significant number of buildings that are exceeding the service life or have serious energy inefficiency or structural vulnerabilities or both. Several research works were undertaken during the last few years showing different strategies for carrying out independent seismic or energy retrofitting, but few ones focus on integrated retrofitting. The review herein presented is only focused on the existing buildings' external envelopes since it is a critical part of the buildings that affect their energy efficiency and that can have serious consequences when subjected to earthquakes (Masi, Chiauzzi et al. 2019).

The masonry infill walls constitute a significant portion of a building's envelope. On one hand, they contribute to ensuring thermal and acoustic comfort inside a building without sacrificing its aesthetic appeal. On the other hand, the thermal resistance of the infill walls plays a pivotal role in a building's energy consumption. This is particularly pronounced in high-rise structures where the ratio of infill walls to the total envelope area is considerable.

Numerous strategies have been developed to enhance a building's energy efficiency, with a specific focus on upgrading the buildings' envelopes. These techniques include green walls, naturally ventilated façades, interior insulation cladding systems, thermal insulation of external wall air chambers, kit systems, prefabricated units, party wall external insulation, external thermal insulation composite systems, and cement panels.

In response to the structural and non-structural damages observed in recent earthquakes, mainly concentrated in the infill masonry walls, several structural retrofitting methods have been proposed to reduce the seismic vulnerability of masonry infill walls. The primary concerns within the scientific community deal with validating these techniques' efficacy under both in-plane and out-of-plane seismic loading demands (Koutas and Bournas 2019).

Given the pressing need to bolster buildings' energy efficiency while enhancing sustainability and minimizing seismic vulnerability in earthquake-prone areas, there is a rising demand for integrated energy and seismic retrofitting. Addressing the seismic vulnerability of masonry infill walls can lead to the preservation of human lives and substantial economic savings. By ensuring these walls are robust, the need for future replacements or repairs can be drastically reduced, directly contributing to sustainable construction. The most pragmatic approach to achieve these goals involves merging techniques that are traditionally used. An integrated strategy promises to simultaneously boost a building's energy efficiency and improve seismic resilience through a singular intervention.

3.1. *Energy retrofitting*

Efforts in the construction industry have centred on bolstering energy retrofitting solutions for masonry infill walls. Among the most prominent methods is external thermal insulation. While this approach is generally more efficient than internal insulation, emphasizing thermal and energy efficiency improvement and thermal bridge effects reduction, it is especially adequate for walls.

The external thermal insulation (Barreira and de Freitas 2014) offers several benefits. It is less disruptive for occupants compared to internal retrofitting and excels in reducing thermal bridges. Moreover, it shields the building's facade from weather elements and retains indoor space, unlike the interior approach, which can be inconvenient for occupants and diminish the building's heat storage capacity. However, external retrofitting has its downsides, such as difficulties in maintaining heritage RC building facades' original aesthetic and the added cost of scaffolding.

A renowned energy retrofitting technique is the External Thermal Insulation Composite System (ETICS). Designed for walls, ETICS combines insulation and sheathing into one system suitable for both new and existing structures. The continuous insulation perimeter of ETICS effectively eliminates thermal bridges. Various insulation materials, such as EPS, XPS, and cork, can be used in ETICS. The system employs non-structural meshes and plastic connectors, which can mitigate temperature fluctuations in walls, reducing potential damage due to temperature-driven material stresses (Barreira and de Freitas 2014, Michalak 2021).

A party wall is a structural divider between two neighbouring buildings, often composed of two walls built at separate times. External insulation is appropriate for shared exterior walls, instances of adjacent building demolition, or when significant facade flaws, like unsealed openings or inconsistent insulation, emerge (Lowe, Wingfield et al. 2007). Polyurethane foam can renovate these walls, enhancing sealing and insulation consistency. However, to shield against UV rays, this foam requires protection, either through paint or a dense polyurethane elastomer layer.

Prefabricated "kit systems" offer another solution, delivering a ready-to-install product with an external layer, insulation (made of materials like XPS, EPS, PF, or PUR), and fixing devices. Another strategy uses cement panels for façade refurbishment. If external modifications are unfeasible, interior thermal insulation is an alternative. Its main drawback is the reduction in living space, coupled with potential inconveniences during the retrofit for occupants. Another efficient technique involves injecting insulating materials, such as mineral fibres, into wall cavities. For a more sustainable approach, consider naturally ventilated façades or Green Walls.

3.2. *Seismic retrofitting*

Seismic retrofitting of masonry infill walls aims to prevent the wall from collapsing during earthquakes. Two main seismic loadings can damage or even cause the collapse of the walls: in-plane (along the wall plane) and out-of-plane (perpendicular to the wall). In-plane loadings can result in the wall detachment from the surrounding frame, diagonal cracking, shear failure, and corner crushing, all dependent on wall type and geometry (De Risi, Gaudio et al. 2018). Out-of-plane seismic accelerations can cause partial or complete wall collapses (Anić, Penava et al. 2020). One factor intensifying collapse risk is the interaction of in-plane and out-of-plane demands. Damage from in-plane loadings compromises wall boundaries and it increases the wall vulnerability against out-of-plane loading ones. Other factors, like wall support width reduction, slenderness, openings, and masonry type, also affect performance and vulnerability.

Priorities for structural retrofitting are: i) Preventing collapse from out-of-plane loadings, and ii) Enhancing wall resistance to combined in-plane and out-of-plane loadings. Based on that, two retrofit strategies can be assumed. First, disconnecting the wall from the structural system to counter the wall's seismic influence on building. However, this strategy increases the out-of-plane collapse vulnerability (Calvi and Bolognini 2001, Stathas, Karakasis et al. 2019). Disconnection can be done through sliding devices or energy dissipation devices. Some countries adopt a gap-based disconnection method. The second strategy, focuses on strengthening the wall and connecting it to the building superstructure using methods such as: Fiber Reinforced Polymers (FRP) (Valluzzi, da Porto et al. 2014); Engineered Cementitious Composites (ECC), Textile Reinforced Mortars (TRM) (Kariou, Triantafyllou et al. 2018); and Ferrocement. Considering these strategies and techniques it is fundamental for optimizing seismic resilience of masonry infill walls to perform detailed performance assessment studies.

3.3. *Integrated retrofitting*

Recent research has centred on evaluating the effectiveness of merging structural and energy retrofitting methods. The primary approach adopted in these studies involves enhancing textile-reinforced mortar using thermal insulation materials. This method integrates the textile-reinforced mortar with a thermal insulation composite system (Gkournelos, Triantafillou et al. 2020). Also, there is a possibility to combine thermal plasters with reinforcing meshes well fixed to the RC structural elements, tackling at the same time both energy and structural improvements (Furtado, Rodrigues et al. 2023).

Artino, Evola et al. (2019) introduced an innovative approach that concurrently addresses structural and energy retrofitting. Their proposed method involves substituting hollow brick external infill walls with high-performance autoclaved aerated concrete blocks. Using a four-storey building as a case study, they evaluated the efficacy of this technique. The findings indicated a significant enhancement in structural resilience, particularly at the damage limitation state. However, smaller improvements were observed at the life safety and near-collapse states. In terms of energy efficiency, substituting the building envelope walls resulted in a 10% and 4% reduction in energy demand for heating and cooling, respectively.

4. Review of existing incentive programs for buildings' retrofitting

4.1. *General description*

A comprehensive review of the existing ten incentive programs in the scope of retrofitting/rehabilitation/renovation of existing buildings in Europe was performed. From these ten incentive programs, five of them are from Portugal and the remaining five are from other European countries. The preliminary observations are herein presented and discussed. The European programs presented below are the: i) European Energy Efficiency Fund (EEEF); ii) Just Transition Fund (JTF); iii) Cohesion Fund (CF); iv) InvestEU; and v) Recovery and Resilient Facility (RRF). Regarding the programs in force in Portugal that were considered in the database herein presented are: i) *Programa de Apoio ao Acesso à Habitação 1ºDireito; ii) Plano de Promoção da Eficiência no Consumo da Energia Elétrica* (PPEC); *iii) Fundo Nacional de Reabilitação do Edificado* (FNRE); iv) *Instrumento Financeiro para a Reabilitação e Revitalização Urbanas* (IFRRU); and v) *Reabilitar para Arrendar- habitação acessível* (RpA) promoted by Fundiestamo, Portal da Habitação and Entidade Reguladora dos Serviços Energéticos.

4.2. *Impact Assessment*

The introduction of incentive programs for building retrofitting carries significant consequences, including the delayed implementation of government measures and policies for renovating the building stock. Furthermore, it aims to promote comprehensive, integrated renovation efforts.

Regarding the programs under analysis in the present study that aim to promote energy efficiency improvement, Figure 1a shows that 50% are at the European level and 50% are at Portugal level. Currently, programs dedicated to improvement of the structural integrity/safety, particularly important in earthquake-prone regions, are applied differently in each European country, not having a common approach at the EU level. For example, in Portugal 40% of the programs under analysis were applied, with partial support from the European Union, but with a low rate of successful applications. Of the 10 programs under analysis, approximately 50% were provided exclusively by the European Union, 20% were applied in Portugal with partial funding from the European Union, 10% of the programs were not applied to this variable and 20% are unknown (Figure 1b).

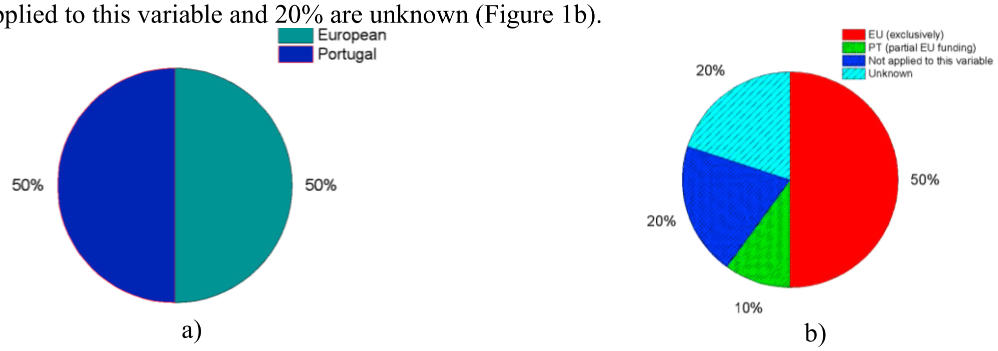

Figure 1. Percentage of incentive programs by scope (a) energy efficiency; (b) CO2 emissions/ green impact.

Regarding the aim of all the programs under analysis (i.e., improvement of the energy efficiency, structural integrity, and reduction of CO_2 emission), it was observed that only 1 program was fully dedicated to only improving the energy efficiency (10%), 2 addressed in simultaneous improving structural integrity, reduction of CO2 emissions and improvement of energy efficiency (20%), 1 addressed structural integrity combined with energy efficiency (10%)

and 6 programs addressed energy efficiency combined with the CO2 emissions (60%). This becomes evident that the environmental and climate impact of the buildings is the priority of international policies nowadays mainly justified by climate change. Nevertheless, it should be strengthened that the resilience of the building stock has serious environmental consequences if, in the case of a post-earthquake scenario, it is necessary to demolish part of the existing building stock.

4.3. *Technical information on target building typologies*

In all the European Union programs explained above, it was not found restrictions regarding the period and type of construction. This aspect is particularly relevant since the buildings built before 1980 were designed before the implementation of the energy codes for construction and also without seismic designing.

Nevertheless, in Portugal, some incentive programs have minor specifications such as being part of urban rehabilitation areas. These areas are defined by the Municipalities and aim to restore buildings in urban areas.

4.4. *Eligible investments*

Eligible investments can differ significantly depending on the program. They encompass a broad spectrum, from direct investments and diverse investment instruments to debt maturities and co-investments. Typically, the investment amounts span from millions to billions of euros, with debt maturities ranging between 10 and 30 years.

For smaller-scale investments, details are often more favourable than prevailing market conditions. This is particularly the case for comprehensive building rehabilitations intended for housing or other activities. Such projects prioritize the integration of optimal energy efficiency solutions as part of the rehabilitation process. This strategy embodies a firm commitment to revitalizing urban areas. By doing so, it supports the repopulation of city centres, enhances the quality of life, and emphasizes greater energy efficiency tailored to the specific area.

Investment instruments available include senior debt, mezzanine instruments, leasing structures, and forfeiting loans, which are usually backed by budget commitments. Co-investments may or may not be part of the program but normally in the energy sector, there is equity participation with direct cooperation with municipalities and private entities.

4.5. *Beneficiaries*

Typically, the beneficiaries of these incentive programs are municipalities, local, and regional authorities as well as public and private entities acting on behalf of those authorities such as utilities, public transportation providers, social housing associations, energy service companies, and taxpayers.

4.6. *Investors*

The primary investors in the 10 incentive programs that were examined include the European Commission, Deutsche Bundesstiftung Umwelt, a major European insurance player, the Corporate Pension Fund, the European Bank for Reconstruction and Development, the Council of Europe Development Bank, the Nordic Investment Bank, the Republic of Portugal, the Housing and Urban Rehabilitation Institute, Compete 2020, Portugal 2020, and the Financial Instrument for Urban Revitalization.

5. **Review of existing tax benefits**

The following 3 Italian tax incentives, namely, i) Superbonus, ii) Sismabonus, and iii) Ecobonus, are jointly financed by the European Union and the Italian government, as of ISSAC (2023). Concerning the tax incentives in Portugal that will be discussed, they encompass i) Imposto de Valor Acrescentado (IVA), ii) Imposto Municipal sobre as Transmissões Onerosas de Imóveis (IMT), iii) Rendimento das Pessoas Singulares and Imposto sobre o

Rendimento das Pessoas Coletivas (IRS; IRC), iv) Imposto Municipal sobre Imóveis (IMI), and v) Adicional Imposto Municipal sobre Imóveis (AIMI).

5.1. *Impact assessment/ Tax benefits*

In examining the impact of tax benefits, the Italian government distinguishes between benefits targeting a single area of impact and those addressing a combination, notably energy efficiency and structural integrity. The Superbonus exemplifies this approach. The Superbonus offers tax deductions for expenses related to energy and seismic retrofitting of residential buildings starting from 1 July 2020 until 31 December 2022 and in some special cases in 2023. This initiative not only fosters economic growth and job creation but also reduces energy consumption, championing an environmentally friendly transition. Covered interventions include external insulation, efficient window installation, heating and air conditioning system replacements, and the addition of renewable energy systems.

Another tax incentive, "Sismabonus", encourages earthquake safety in Italy. Taxpayers can claim this deduction against either the IRPEF (Personal Income Tax) or IRES (Corporate Income Tax). For properties in seismic zones 1 and 2, described in the UNI EN 1998-1, the deduction, enhanced by the Relaunch Decree (Decree-Law 19/05/2020 n.34), reaches 110% for certain seismic safety improvements. This includes work transitioning buildings to a lower-risk seismic category and investments in earthquake-resistant structures built after demolition and reconstruction (known as Sismabonus purchases) in seismic zones 1, 2, and 3, with expenses made between July 1, 2020, and December 31, 2021. The "Ecobonus" serves as Italy's energy-saving tax incentive guide. Depending on the nature of the work, claimants may receive an IRPEF refund ranging from 50% to 65% of the cost. For projects in condominiums, especially those enhancing both energy efficiency and seismic resistance, the Ecobonus can reach up to 85%.

In Portugal, there are five distinct tax benefits: i) IVA: This offers a 6% rate reduction on urban rehabilitation projects; ii) IMT: It provides tax exemptions on property purchases intended for rehabilitation and on the first transfer post-rehabilitation; iii) IMI: Municipalities can apply up to a 25% reduction for five years on energy-efficient urban buildings, along with a three-year exemption following urban rehabilitation; iv) AIMI: This permits deductions on taxable income equivalent to a portion of the IVA paid on environmental costs. Additionally, there's a 5% tax on capital gains for residents on the first sale post-intervention and a 5% tax on rental income for rehabilitated properties.

4. Conclusion, limitations, and future research opportunities

Buildings account for 40% of the EU's energy consumption and 38% of its CO_2 emissions, largely due to delayed implementation of early energy codes. Moreover, 40% of these buildings are situated in seismic regions but were constructed with inadequate safety standards. Roughly 65% require both energy and seismic retrofitting. A notable fraction of the EU population also faces heating challenges in their homes, posing health and energy poverty risks. Existing RC building envelopes play a pivotal role in energy efficiency and seismic performance. Unfortunately, these two parameters are often studied separately. While the European Green Deal has spurred energy retrofitting, it has not adequately addressed structural deficits, leaving many buildings vulnerable, especially in seismic areas.

This research work undertook a comprehensive review of existing energy, structural and integrated retrofitting approaches for envelopes of existing buildings. From this review, it was found that the combination of TRM-based solutions with the ETIC system can be a promising and effective strategy for integrated interventions of envelopes. Most of these programs prioritize energy retrofitting: 10% focus on only energy retrofitting, 10% focus on energy retrofitting combined with improvement of the structural integrity, 20% focus on energy efficiency combined with structural integrity and reduction of CO2 emissions. Finally, 60% focus on the combination of energy retrofitting and reduction of CO2 emissions. Owners have the opportunity to combine different incentive programs, enhancing RC buildings both structurally and thermally, while also contributing to environmental conservation by reducing CO_2 emissions. Notably, while EU programs have broad eligibility, some Portuguese initiatives are specifically tailored for urban rehabilitation areas. These programs typically benefit municipalities, regional governments, public and private entities, including utilities, public transportation providers, social housing associations, energy service companies, and taxpayers. Key investors include the European Commission, Deutsche Bundesstiftung Umwelt, European Bank for Reconstruction and Development, Nordic Investment Bank, Portuguese Republic, and several others. In Italy, tax benefits, like the Superbonus, support energy and seismic upgrades in the wider class of residential buildings. The Sismabonus allows for tax deductions on seismic safety initiatives, incentivizing the move to lower-risk building categories. Meanwhile, the Ecobonus facilitates deductions of up to 85% on energy conservation measures that also improve earthquake resilience. Portugal offers five main tax benefits. These include a 6% reduction in the IVA rate for urban rehabilitation, IMT exemptions for properties undergoing or completed rehabilitation, and IMI reductions for energy-efficient urban buildings with a lower percentage of refunding.

Finally, another important limitation is that the programs and benefits discussed are subject to frequent updates. For this reason, future research will require continual database refreshing, including the integration of new countries, programs, and tax benefits, ensuring comprehensive and up-to-date comparative analysis.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Questionnaire survey on the use of thermal insulation solutions in building facades of Portugal, Italy and Norway

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Abstract

The use of adequate thermal insulation solutions in the opaque walls is one of the most efficient passive strategies towards the improvement of the buildings' thermal performance. Nevertheless, beyond the thermal performance, a set of different performance criteria (i.e., hygrothermal performance, fire behavior, environmental footprint, among others) must also be considered when selecting thermal insulation materials. This study aimed to enhance understanding of the use of thermal insulation solutions in new construction and for the thermal retrofitting of building facades in Portugal, Italy and Norway. To that end, a questionnaire survey was prepared considering the relationships among the different Political, Economic, Social, Technological and Environmental criteria involved in the selection of thermal insulation solutions. The questionnaire was available online between November 2022 and February 2023 and respondents, primarily living and/or working in Portugal, Italy and Norway, were asked to answer questions related to the use and performance of different thermal insulation solutions. Results showed that different perceptions and levels of knowledge regarding the performance of several insulation materials could be ascribed to the respondent's country of residence.

Keywords: Thermal insulation materials; Questionnaire survey; PESTE criteria; Rating system.

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1. Introduction

Buildings account for a significant percentage of the global energy use, generating more than one quarter of the world energy-related CO_2 emissions (Laaroussi et al. 2020). As a result, several European directives (e.g., EU Directive 2018/844) and guidelines have been published with the aim of decreasing indoor thermal discomfort and improving the energy performance of new construction, while reducing the energy demand of existing buildings.

The use of thermal insulation solutions in the opaque walls is one of the most efficient passive strategies towards the improvement of the buildings' thermal performance (Schiavoni et al. 2016). Therefore, the selection of the most suitable thermal insulation material to be applied is fundamental for an adequate thermal performance of the building. Nevertheless, beyond the thermal performance, a set of different performance criteria (i.e., hygrothermal performance, fire behavior, environmental footprint, among others) must also be considered when selecting the thermal insulation solution (Parracha et al. 2023a).

This paper aims at providing a new understanding about the use of thermal insulation solutions in new construction and for the thermal retrofitting of building facades in Portugal, Italy and Norway. To that end, a questionnaire survey was prepared considering the relationships among the different Political, Economic, Social, Technological and Environmental criteria (i.e., PESTE analysis) involved in the selection of thermal insulation solutions. The questionnaire was delivered online between November 2022 and February 2023 and asked respondents living and/or working mainly in Portugal, Italy and Norway to respond to questions related to the use and the performance of different thermal insulation solutions.

The work reported herein is part of the wider EEA Granted EFFICACY project, which mainly aims at creating a database that can be used to select thermal insulation solutions to be applied in new buildings and thermal retrofitting of facades.

2. Questionnaire survey

A questionnaire survey (Parracha et al. 2023b) was structured into five sections related to Political, Economic, Social, Technological, and Environmental criteria (i.e., PESTE analysis). In the section related to Environmental criteria, a questionnaire-based rating system was used (Table 1) for asking people to rate the most common thermal insulation materials used in Portugal, Italy and Norway (Table 2) in accordance with their performance. In order to characterize the sample, the questionnaire survey also included demographic and calibration information (e.g., age, gender, living country, nationality, etc.). The responses were deposited at Mendeley dataset website (Parracha et al. 2023b). Further information about the questionnaire survey, data accessibility and data description can be found in a previous study by the authors (Parracha et al. 2023a).

Table 1. Questionnaire-based rating system used in the survey (adapted from Parracha et al. (2023a)).

Performance criteria:	**Questionnaire-based rating system (from 1 to 5)**
Durability	1 – less durable; 5 – most durable
Market price	1 – less expensive; 5 – most expensive
Needs of maintenance	1 – lowest need; 5 – highest need
Fire behavior	1 – worst performance; 5 – best performance
Biological susceptibility	1 – lowest bio-susceptibility; 5 – highest bio-susceptibility
Water performance	1 – lowest water retention; 5 – highest water retention
Mechanical performance	1 – lowest mechanical resistance; 5 – highest mechanical resistance
Sustainability	1 – most sustainable; 5 – least sustainable

Table 2. List of thermal insulation solutions included in the questionnaire (adapted from Parracha et al. (2023a)).

Thermal insulation solution	Commonly used in:
Insulation cork board (ICB)	Italy and Portugal
Mineral wool (MW)	Italy, Portugal, and Norway
Expanded polystyrene (EPS)	Italy, Portugal, and Norway
Extruded polystyrene (XPS)	Italy, Portugal, and Norway
Polyurethane foam (PUR)	Italy, Portugal, and Norway
Natural fibers (NF)	Italy
Aerogel blankets (AB)	*
Thermal insulating mortars (TM)	Portugal
Vacuum-insulation panels (VIP)	*
Vegetation – green walls (VEG)	*

*Thermal insulation solution was included in the list due to its innovative nature

The questionnaire was prepared with Google Forms and delivered online on social media and via email in the period between November 2022 and February 2023. The questionnaire was edited in English, Portuguese and Italian and the respondents were randomly approached (Parracha et al. 2023a). After the end of February 2023, all responses were screened to identify and remove possible duplicates.

3. Results

221 respondents completed the entire questionnaire survey (Parracha et al. 2023b). Out of these, 127 responses were from Portugal, 52 from Italy, and 24 from Norway, corresponding to ~ 92% of the total sample (203 responses).

Table 3 presents the results of some general questions included in the questionnaire with the aim of characterizing the sample. Results showed that approximately 90% of the Portuguese and Italian respondents were aged between 25 and 65 years old, whereas this value is slightly lower (~ 83%) in the case of Norway. The gender distribution indicates that men represent approximately 75%, 63%, and 49% of the responses obtained in Portugal, Italy and Norway, respectively. When considering the living place, the majority (> 65%) of respondents live in a city (> 10 000 inhabitants). Moreover, approximately 78%, 87%, and 79% of the responses in Portugal, Italy and Norway were from people with at least a master’s degree. In the case of Portugal and Italy, most respondents have more than 10 years of job experience (69% and 48%, respectively). In the case of Norway, most respondents are junior, with less than 5 years of experience (~ 46%). As expected, a flat in a building was pointed out as the most common type of house in the three countries. Finally, it is worth noting that most respondents work in private companies in the field of architecture, construction engineering, real estate and facilities management, and in public research institutions and universities (e.g., faculty members or students).

Table 4 presents the responses to some of the most relevant questions included in the survey considering a PESTE analysis (i.e., Political, Economic, Social, Technological and Environmental criteria). As it can be observed, 37% of Italian respondents and 52% of Portuguese respondents have thermal insulation in their buildings, a percentage significantly higher for the Norwegian respondents (~ 79%). Moreover, most Portuguese (~ 57%) and Italian (~ 62%) respondents have the perception that their building needs an energy retrofitting intervention. In the case of Norway, a lower percentage of respondents (~ 45%) identified this need, which is in line with the differences in the percentages of thermal insulation found in the three countries (Table 4).

In the Political section, results showed that most Portuguese (~ 62%), Italians (~ 79%) and Norwegians (~ 63%) are aware of possible governmental financial incentives for energy retrofitting interventions. However, the results also revealed that Portuguese and Norwegian respondents (i.e., at least 63% when considering both countries) believe that such incentives are insufficient. In contrast, approximately 56% of the Italians agree with the appropriateness governmental financial incentives.

Table 3. Demographic information of the Portuguese, Italian and Norwegian respondents.

	Countries	Portugal	Italy	Norway	Total
Age	18 – 24	9	2	4	15
	25 – 34	23	21	9	53
	35 – 49	69	14	10	93
	50 – 65	23	12	1	36
	Over 65	3	3	0	6
Gender	Female	65	19	6	90
	Male	62	33	18	113
Living place	City (> 10 000 inhabitants)	102	36	24	162
	Town (2 500 – 10 000 inhabitants)	17	10	0	27
	Village (< 2 500 inhabitants)	8	6	0	14
Level of education	High school graduate	4	4	1	9
	Technical/vocational training	3	1	1	5
	Bachelor’s degree	21	2	3	26
	Master’s degree	58	27	10	95
	Doctoral (Ph.D.) degree	41	18	9	68
Job experience	Junior (< 5 years)	20	18	11	49
	Intermediate (5 – 10 years)	20	9	5	34
	Senior (> 10 years)	87	25	8	120
	Retired	0	0	0	0
Type of house	Flat in a building	95	37	18	150
	Detached (single) house	18	11	4	33
	Semi-detached house	14	4	2	20

In the Economic section, the results showed that a significant percentage of the respondents (i.e., more than 79% in all three countries), believe that an energy retrofitted building would reimburse the investment costs, regardless of the country.

When considering satisfaction with the level of comfort inside the building, approximately 80%, 75% and 96% of Portuguese, Italian, and Norwegian respondents, respectively, expressed satisfaction. Also in the Social section, ~ 58% and ~ 63% of the Italian and Norwegian respondents reported that they did not require any additional device or equipment (e.g., air conditioning) to improve indoor comfort. On the opposite, ~ 76% of Portuguese respondents use such tool or equipment to ensure indoor comfort.

Furthermore, in the Technological section, a significant portion of the respondents in all three countries either did not know or did not answer to questions regarding criteria or guidelines for selecting thermal insulation materials useful for the energy retrofitting of buildings.

In conclusion, approximately 58% of respondents from Portugal and Italy either expressed disbelief in climate change or chose not to respond to the question. This percentage increases to ~ 83% when considering the responses from Norway.

As previously stated, a questionnaire-based rating system was used in the Technological section to evaluate the perception and knowledge of the respondents considering a set of different performance criteria (i.e., hygrothermal performance, fire behavior, environmental footprint, among others) of the most common thermal insulation solutions in the countries. 73%, 71% and 59% of the Portuguese, Italian and Norwegian respondents, respectively, considered they have technical knowledge about the use and performance of thermal insulation solutions. Fig. 1 displays the results of the questionnaire-based rating system concerning durability, market price, fire behavior, water performance, mechanical performance, and sustainability criteria.

Table 4. Responses to some of the most relevant questions included in the survey considering a PESTE analysis.

Criteria	**Question**		**Countries**			
			Portugal	**Italy**	**Norway**	**Total**
General question	Do you know if your building has thermal insulation?	Yes	67	19	19	105
		No	43	26	2	71
		Don't know	17	7	3	27
General question	Do you think your building needs an energy retrofit?	Yes	73	32	11	116
		No	34	12	10	56
		Don't know	20	8	3	31
Political	Are you aware of possible governmental financial incentives for energy retrofitting interventions?	Yes	79	41	15	135
		No	48	11	9	68
	If yes, do you think they are adequate?	Yes	36	29	9	74
		No	91	23	15	129
Economic	Is an energy retrofitting intervention worthy the investment costs?	Yes	119	48	19	186
		No	8	4	5	17
Social	Are you satisfied with the level of comfort in your house/flat?	Yes	101	39	23	163
		No	26	13	1	40
	Do you need any additional tool/equipment for improving the indoor thermal comfort?	Yes	96	22	9	127
		No	31	30	15	76
Technological	Do you know criteria or guidelines for selecting thermal insulation materials useful for energy retrofitting interventions?	Yes	43	18	9	70
		No	50	19	4	73
		No answer	34	15	11	60
Environmental	Do you believe in climate change? Did you see sign of its impact in your country and/or on your building?	Yes	54	22	4	80
		No	54	22	14	90
		No answer	19	8	6	33

Portuguese respondents identified ICB (agglomerated insulation cork board), MW (mineral wool) and XPS (extruded polystyrene) as the most durable solutions, while VEG (vegetation – green walls) was classified as the least durable. On the other hand, Italian respondents considered MW and PUR (polyurethane foam) as the most durable thermal insulation solutions, and ICB and NF (natural fibers) as the least durable. For Norwegian respondents, MW, EPS (expanded polystyrene board) and XPS were seen as the most durable solutions, while ICB, AB (aerogel blankets) and VIP (vacuum-insulation panels) were rated as the least durable. Interestingly, MW was the only thermal insulation solution considered as one of the most durable in the three countries

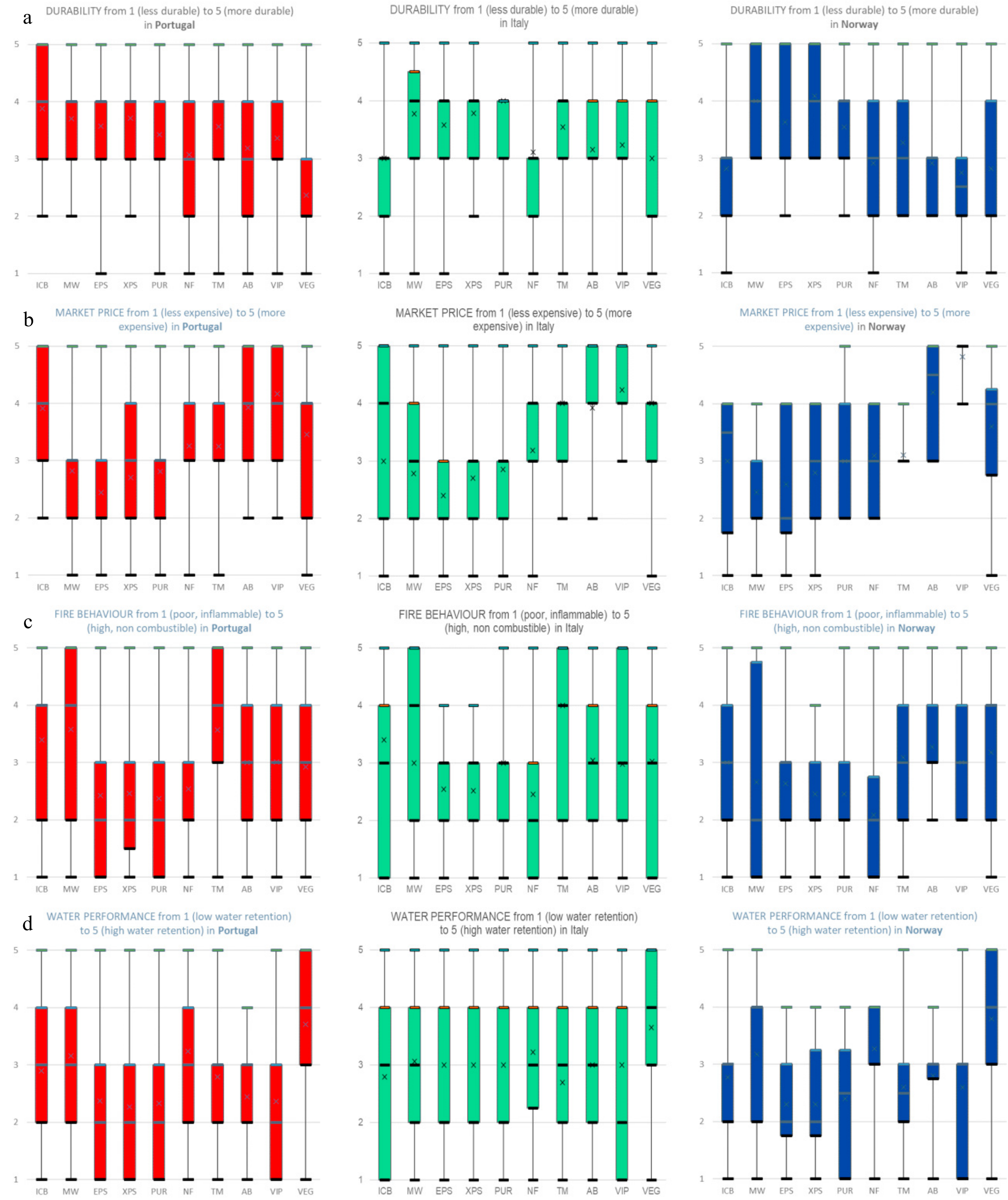

Fig. 1. Results of the questionnaire-based rating system in the three countries (Portugal – left; Italy – center; Norway – right) considering durability (a), market price (b), fire behavior (c), water performance (d), mechanical performance (e), and sustainability (f).

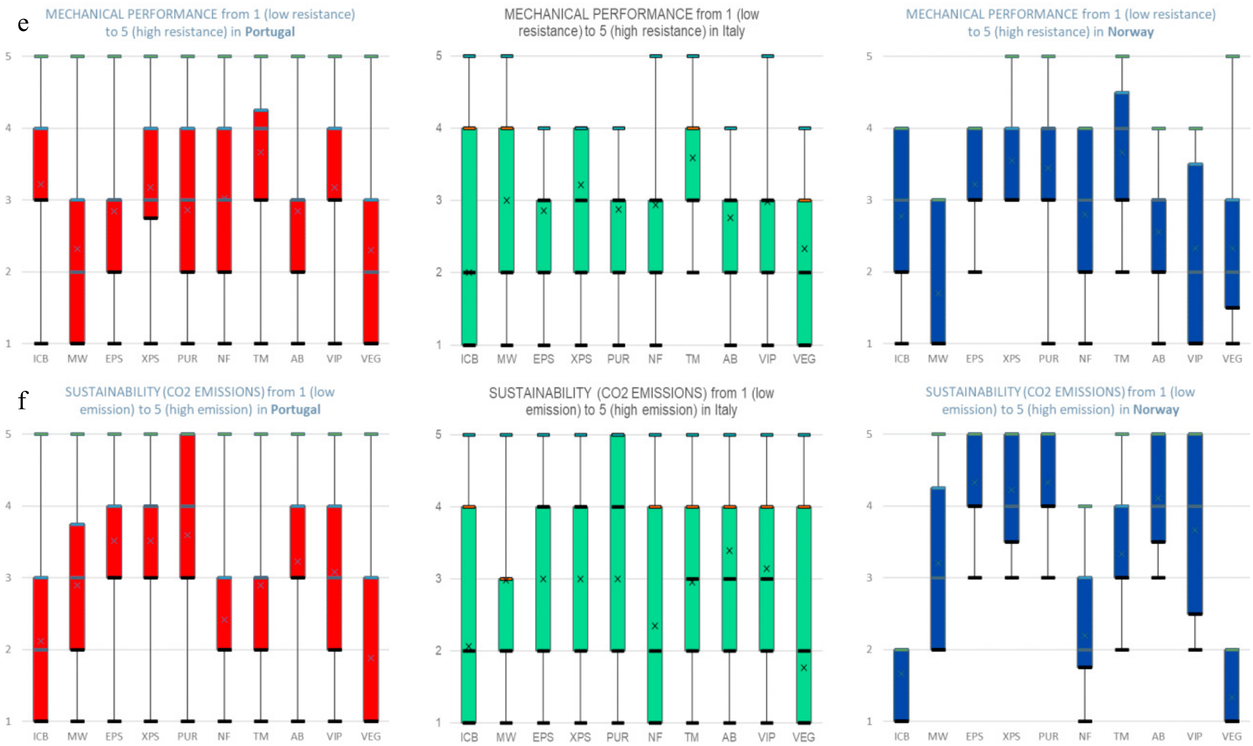

Fig. 1. (continued)

The most expensive solutions in the opinion of the Italian and Norwegian respondents are VIP and AB. These latter solutions were also considered the most expensive by the Portuguese respondents, along with ICB. In contrast, the least expensive solutions, as perceived by the respondents, are MW, EPS and PUR in Portugal, EPS, XPS and PUR in Italy, and MW and EPS in Norway. The high price of the VIP and the AB can be partially explained to the innovative nature of these solutions. Manufactures are currently optimizing these products to enhanced performance, while reducing costs. As expected, EPS was the only solution considered as the least expensive in all three countries.

The solutions with the best fire behavior in the opinion of the Portuguese and Italian respondents are MW and TM. For the Norwegians, AB presents the best fire behavior. On the other hand, the worst fire behavior for the Italian and Norwegian respondents was attributed to NF, whereas the Portuguese respondents considered EPS and PUR in this category of thermal insulation solutions.

All of the three countries considered VEG as the solution with the highest water retention. For the Italian and Norwegian respondents VIP was identified as the solution with the lowest water retention. Moreover, the Portuguese respondents rated EPS, XPS, PUR and VIP as the solutions with the lowest water retention.

When considering the mechanical performance, TM was pointed out as the solution with the highest mechanical resistance in all three countries. This result may be explained due to the innovative nature of this solution. In fact, TM are formulated with lightweight aggregates replacing sand and therefore have lower mechanical resistance when compared to traditional mortars. The lowest mechanical resistance was attributed with MW and VEG in Portugal, ICB and VEG in Italy, and MW and VIP in Norway.

ICB and VEG were classified as the most sustainable solutions in all three countries, whereas PUR was considered the least sustainable. Additionally, EPS was considered as one of the least sustainable solutions for the Norwegians respondents.

4. Discussion

Most respondents work in the fields of architecture, construction engineering, real estate and facilities management, public research institutions and universities, which makes this survey especially interesting to assess the expert knowledge and practice when concerning insulation materials. Moreover, most of the Portuguese (~ 57%) and Italian (~ 62%) respondents believe their building needs an energy retrofitting intervention. In the case of Norway, a lower percentage of respondents (~ 45%) identified this need. In Portugal, this fact can be partially attributed to the average age of the building stock, which can be older than the first thermal regulation dating back to 1990 (Ogut et al., 2023).

Results showed that most Portuguese (~ 62%), Italians (~ 79%) and Norwegians (~ 63%) respondents are aware of possible governmental financial incentives for energy retrofitting interventions. While there is an awareness of incentives for energy retrofitting, the prevailing idea among respondents is that these incentives do not meet expectations or requirements. This suggests that governments should reassess their policy and potentially increase the financial support for energy retrofitting interventions. Furthermore, a significant percentage of the respondents (i.e., more than 79% in the three countries) think that an energy-retrofitted building would compensate the investment costs. Approximately 80% of the Portuguese respondents, 75% of the Italians, and 96% of the Norwegians expressed satisfaction with the level of comfort inside their buildings. However, the majority of these respondents have completed their studies and do not belong to vulnerable populations facing energy poverty. In all three countries, most of the respondents did not know or did not answer the question related to criteria or guidelines for selecting thermal insulation materials that can be useful for the energy retrofitting of buildings. Finally, about 58% of Italian and Portuguese respondents either do not believe in climate change or did not answer the question. This percentage increases to ~ 83% when considering the responses from Norway. This lack of response or disbelief can be alarming, especially when considering that the majority are practitioners in the buildings and construction sector.

Some common results identified in all three countries regarding insulation materials include the following: i) mineral wool (MW) is perceived as the most durable solution, while vacuum-insulation panels (VIP) and aerogel blankets (AB) are considered the most expensive, and expanded polystyrene (EPS) is viewed as the least expensive; ii) vegetation – green walls (VEG) are noted for having the highest water retention, while VIP is associated with the lowest; iii) thermal insulating mortars (TM) are recognized for their high mechanical resistance; and iv) insulation cork board (ICB) and VEG are rated as the most sustainable solutions, while polyurethane foam (PUR) is considered the least sustainable.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Reuse of wood biomass ash to improve thermal behavior of gypsum plasters

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Abstract

Huge amounts of waste are generated each year in the world. In addition, the construction sector is one of the larger producers of residues and a huge energy consumer. Thus, architects, engineers and other actors of the building sector should give solutions in order to reduce that problem. In that sense, the idea of finding solutions for the end of the service life of materials, in order to promote circularity, has been studied by several researchers. In this study, biomass wood ash has been used as aggregate for the generation of new eco-efficient gypsum plasters, for its application in new buildings and rehabilitation works. In order to conduct an exhaustive characterization of the new composites, an experimental campaign of the plasters has been conducted: dry bulk density and thermal conductivity of the plasters have been measured. The results showed that it was possible to add up to 25% of wood ash without modifying the water/gypsum ratios. Moreover, thermal conductivity of the plasters has improved up to18% when the ash was added to the mixture. Finally, the effects of using the new gypsum composites in the thermal envelope of buildings was analyzed by its usage in a rehabilitation case study simulation.

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Keywords: Anti-graffiti; Climate change; Efficiency; Durability

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1. Introduction

The use of gypsum plasters and products is worldwide extended as interior coating in buildings (de Brito and Flores-Colen, 2015). Then, as it is part of the building envelope, its thermal behavior has been subject of study by multiple investigations (Gomes et al., 2017; Bicer and Kar, 2017; Pedroso et al., 2020). Most of them established that the thermal conductivity of a commercial gypsum paste is around 0.30 W/(m·K) (Pedreño-Rojas et al., 2019; Romero-Gómez et al., 2022) and it could be reduced by adding several types of additions. In that sense, many studies have analyzed the use of different aggregates in the mixtures to improve the thermal conductivity of the material. San Antonio-González et al. (2015) and del Río-Merino et al. (2019) evaluated the thermal enhancement of gypsum plasters that incorporate extruded polystyrene waste. Also, Dai and Fan (2015), Morales-Conde et al. (2016) and Pedreño-Rojas et al. (2017) achieved a substantial improvement on the thermal conductivity of gypsum composites when wood waste was added to the mixtures. Cherki et al. (2014) tested the thermal improvement of gypsum products by using cork as aggregate.

Also, some investigations analyzed the incorporation of ashes in the production of new gypsum plasters. Del Río-Merino et al. (2017) evaluated the use of ashes obtained from the production of different types of oils. Previously, Leiva et al. studied the incorporation of several types of ashes from the agro-industrial sector in the production of new gypsum plasters: olive oil production (2009) and rice husk (2014). They concluded that new materials with enhanced thermal and fire behavior can be obtained by adding up to 30 wt.% of aggregate to the mixtures to maintain the workability.

Finally, it must be noted that no previous experiences have been found in which wood biomass ash was used in the production of gypsum plasters. However, some studies analyzed its usage as cement partial replacement in the production of concrete (Fořt et al., 2020). Furthermore, wood biomass ash was also used in the production of clay composites (Fořt et al., 2018).

The primary aim of this study is to evaluate the thermal properties of gypsum plasters when wood biomass ash is incorporated as an aggregate. This research will focus on understanding the advantages of using this mixture as part of the thermal envelope in building rehabilitation projects.

2. Materials and Methods

2.1. Materials

The materials used to generate the new plasters are listed below:

- High purity commercial gypsum, classified as A1 (E-35) by the EN 13279-1 standard (AENOR, 2009).
- Wood biomass ash directly taken from a heat power district plant located in Móstoles (Madrid, Spain).

Those materials were mixed following different aggregate incorporation rates, up to 25 wt.%, maintaining the workability conditions of the pastes (AENOR, 2006). Furthermore, water content of the mixtures was determined by using the flow table and Vicat cone procedures defined in EN 13279-2 (AENOR, 2006). Table 1 collects the composition of each mixture under study related to the use of 1 kg of gypsum powder:

Table 1. Composition of all the mixtures under study.

Composition name	Gypsum [g]	Water [g]	W/G Ratio	Wood Biomass Ash [g]
Reference	1000	800	0.80	-
G+WBA 5%	1000	800	0.80	50
G+WBA 10%	1000	800	0.80	100
G+WBA 15%	1000	800	0.80	150
G+WBA 20%	1000	800	0.80	200
G+WBA 25%	1000	800	0.80	250

2.2. Test Methods

Gypsum mixtures were elaborated following the procedure defined by EN-13279-2 (AENOR, 2006), using the same requirements to obtain the dry state bulk density of the pastes. Prismatic specimens of 40x40x160 mm^3 were produced (Fig. 1).

Fig. 1. Samples preparation according EN 13279-2.

Also, to achieve the thermal conductivity of each plaster, ISOMET 2114 device was used, following the procedure described in ASTM 5334-08 (ASTM, 2009). To obtain it, circular specimens of 60 mm diameter and 15 mm height were made for each mixture.

To evaluate the benefits of their usage in the thermal envelope of rehabilitated buildings, a simulation of its usage in a traditional Spanish house rehabilitation was conducted. The thermal transmittance of the wall façade in three scenarios was analysed: original state and rehabilitated one using conventional coating and the other one with the application of the biomass-gypsum based coating. The thermal transmittance (U [$W/m^2{\cdot}K$]) of the wall façade was obtained using the expression presented in eq. 1:

$$U = \frac{1}{\sum R_i} \tag{1}$$

Where Ri [$m^2{\cdot}K/W$] was the thermal resistance of each layer of the façade wall according the Spanish CTE Building Elements Catalogue (Spanish Government, 2008).

3. Results and Discussion

3.1. Dry Bulk Density

As it is shown in Fig. 2, the addition of wood biomass ash was linked, for all the mixtures, to an increase on the dry bulk density of the composites, compared to the reference material. The highest increase in the density value was noticed for the G+WBA 20% mixture, achieving +21% higher density than the reference composite. In addition, it can be said that any of the plasters can be considered a lightweight material, as their dry bulk density always surpass 0.8 g/cm^2.

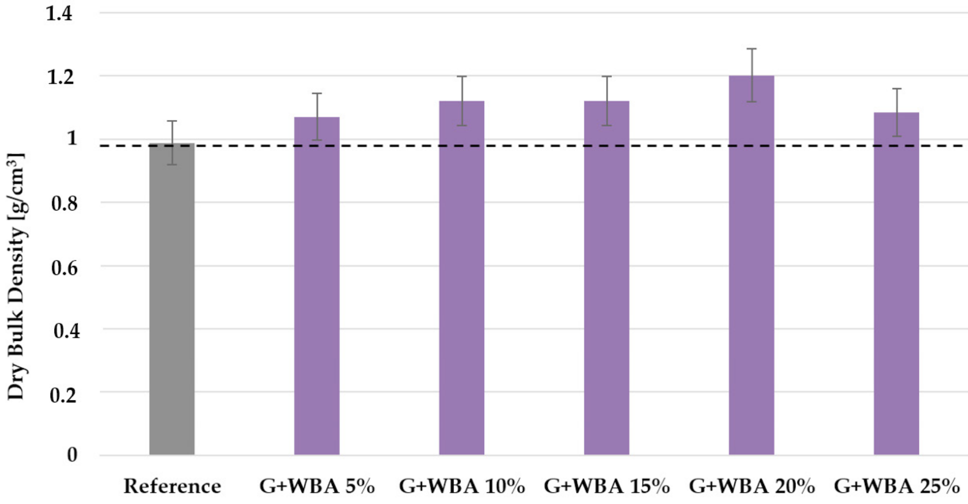

Fig. 2. Dry bulk density results with standard deviation.

3.2. Thermal Conductivity

Fig. 3 shows the registered values for the thermal conductivity of the new plasters. As it can be noticed, for all the composites, the increase on the percentage of waste added to the paste was always linked to a decrease on the thermal behavior of the material. Thus, the best performance in this case was achieved for the G+WBA 25% composite, achieving 0.247 W/(m·K) for its thermal conductivity (17.7% lower when compared to the reference material).

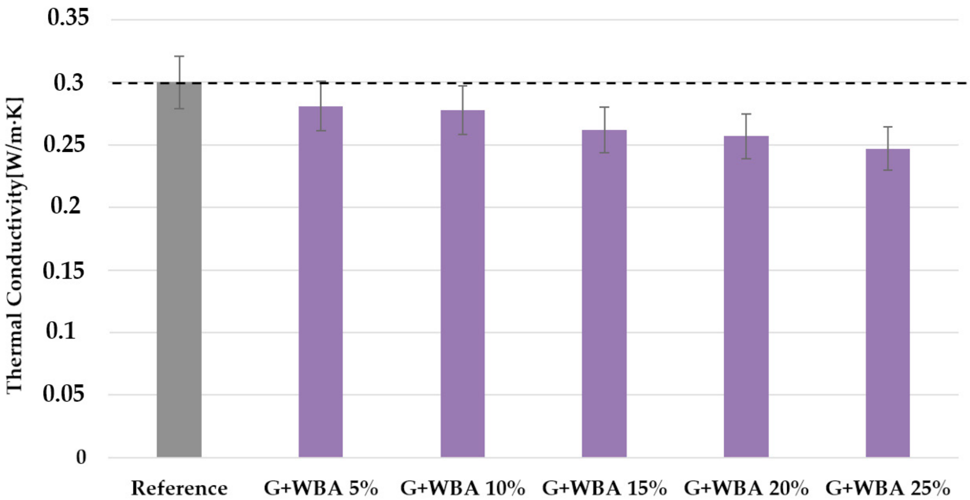

Fig. 3. Thermal conductivity results with standard deviation.

3.3. Discussion

In order to discuss all the obtained results, a comparison between the thermal conductivity values and the dry bulk density is presented in Fig. 4. As it can be appreciated, all the new composites did not follow the regular tendency of the literature in which a decrease on the density values was always linked on an enhancement on the thermal behavior of the material (Morales-Conde et al., 2016; San Antonio-González, 2015). In this case, heavier materials presented better thermal properties. This fact can be completed in a second phase with the mechanical values of the plasters. However, it must be noted that an improvement in the thermal conductivity was also found by previous research works incorporating ashes from the olive and rice production, which claimed lower thermal conductivity coefficients compared to the reference (Leiva Aguilera and Del Rio Merino, 2014; Leiva et al., 2009).

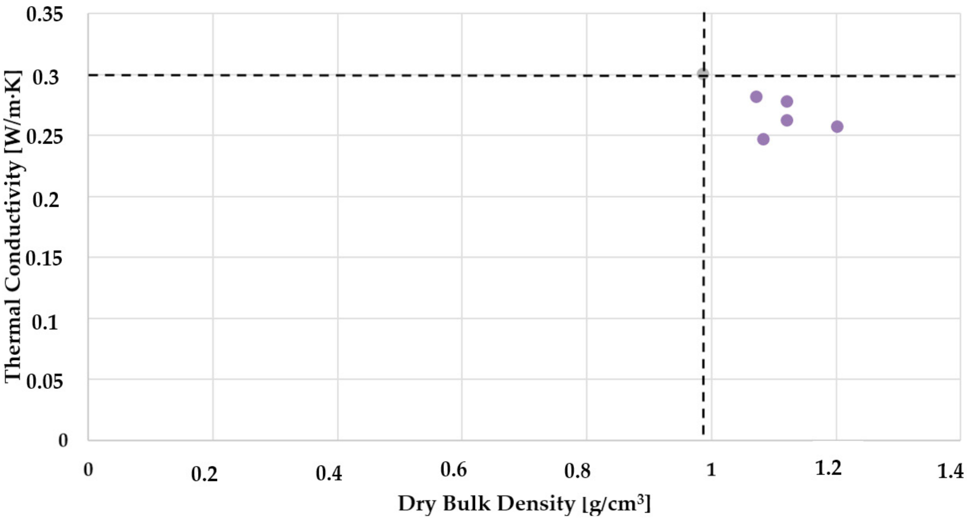

Fig. 4. Comparison between the thermal conductivity and dry bulk density values.

3.4. Case Study Building

Finally, trying to assess the real impact of the new products on a real case study building, a simulation based on a traditional Spanish building (XIX century) rehabilitation was carried out. On it, in order to evaluate the performance of the new gypsum composite in a theoretical rehabilitation work, the thermal transmittance (U-value) of the façade wall, using the thermal resistance of each layer/material, was evaluated under three different scenarios:

- *Scenario A:* Original state of the building, previous of its rehabilitation.
- *Scenario B:* Rehabilitated state using conventional gypsum panels for interior covering (2 cm air chamber + 1.5 cm plasterboard).
- *Scenario C:* Rehabilitated state using G+WBA 25% composite (the one with the best thermal performance) for the interior covering (2 cm air chamber + 1.5 cm G+WBA 25% plasterboard).

Fig. 5 presents the results for the thermal transmittance (U [W/m^2·K]) of the façade wall on the three scenarios under study.

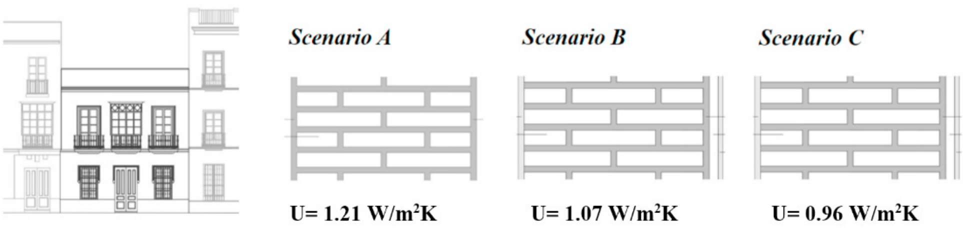

Fig. 5. Thermal transmittance of the façade wall of a traditional Spanish case study building.

As it can be noticed, an improvement of 20.7% (lower value) was obtained comparing the Scenarios A and C and 10.3% comparing B and C ones. This fact shows that biomass-gypsum based coatings are optimal for their use in cases where thermal improvement of a façade is required to achieve the minimum transmittance values required by the regulations (Spanish Government, 2022).

4. Conclusions

In this paper, the thermal behavior of new eco-efficient gypsum plasters with wood biomass aggregate was evaluated. The main conclusions of this research are listed below:

- It was possible to add wood biomass fly ash as aggregate in the development of new gypsum plasters up to 25 wt.% maintaining the workability requirements for the pastes.
- A slight increase on the dry bulk density (up to +21% compared to the reference material) was observed in the new composites.
- An improvement of the thermal behavior of the composites, up to 17.7% for the G+WBA 25% mixture, was noticed.
- The use of the new materials in the theoretical study of the thermal behavior of a rehabilitated façade example shows a significant improvement over the original state solution.
- The new materials are optimal for their use in cases where thermal improvement of a façade is required to achieve the minimum transmittance values required by the regulations.

As it can be appreciated, the developed plasters presented an important enhancement on their thermal properties, evaluating their mechanical properties in a second phase of the research.

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Statistical analysis of principal components (PCA) in the study of the vulnerability of Heritage Churches

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Abstract

Built heritage is constantly at risk due to anthropogenic or natural threats. Its vulnerability involves factors related to construction form, state of conservation and urban pressure, for this reason the assessment of vulnerability depends largely on its conservation and restoration. Therefore, the identification of these factors and the analysis of the correlation between them can be an effective tool in the fulfilment of integrated plans focused on the preventive conservation of these buildings. This study focuses on churches built in America (Colombia and Guatemala) between the 16th and 18th centuries, which have been analysed by calculating a global vulnerability index. Principal Component Analysis (PCA) was employed to obtain a better observation of the set of data and vulnerability indices to evaluate the behaviour of the factors that affect the model. This first approach by PCA allows to identify similarities and differences in the factors that affect the global vulnerability of each church and facilitate the prediction of typical future behaviours to establish prevention measures applicable to various buildings, moreover this study allowed to analysing the common characteristics and threats to help cultural heritage managers to propose preventive conservation measures applied to the maintenance of heritage buildings and the generation of urban policies focused on articulated plans in risk management, that included criteria based on sustainability and resilience.

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Keywords: conservation, heritage, principal components analysis, risk, vulnerability.

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1. Introduction

Churches of Popayan (2° 27' 15" N - 76° 36' 33" W) and Cartagena de Indias (10° 23' 59" N - 75° 30' 52" W) (Colombia) and La Antigua (14° 33' 27" N - 90° 44' 00" W) (Guatemala) built between the 16th and 18th centuries and located within the perimeter of their historic centres were studied by the evaluation of an index of global vulnerability (Ortiz et al., 2014; Ortiz et al., 2016, 2018; Ortiz and Ortiz, 2016; Rodríguez et al., 2021).

This assessment depends on the conditions of conservation and the environment and allow to classify the building as more or less vulnerable.

A statistical study using PCA was employed to locate representative data of the set of variables that influence or affect these churches conservation. The PCA was employed to define the relationship between variables, predict behaviours and set diagnosis evolutions in similar buildings (Moropoulou and Polikreti, 2009).

PCA is often applied in cultural heritage with a chemometric approach (Cardinali et al. 2021), in archaeological studies (Busto,2018) to evaluate chronologies. In diagnosis and conservation, Ozga et al. in 2014 identified polluting sources, Moropoulou and Polikreti studied climatic conditions in historical buildings (2009), Mu et al., (2020) implemented PCA in environmental monitoring for the prediction of pathologies, in these cases the dimension of the data is reduced to then build a model. Also, with an important utility in the microclimatic study of Rosenborg Castle, in Denmark with the use of the combination of statistical methods for the subsequent deployment of microclimatic sensors (Frasca et al., 2022).

2. Material and methods

Vulnerability was assessed using the method proposed by Ortiz and Ortiz, 2016; Ortiz et al, (2018), initially using an identification matrix that allows recording and confronting the factors causing impact on a building such as climate (winds, temperature, humidity, dew point, rainfall), soil characteristics (geotechnics, phreatic level), natural phenomena (volcanoes, earthquakes or floods), pollutants or biological agents (gases, particles or xylophagous) and anthropic action (urban dynamics) with the altered variables such as the characteristics of the materials, foundation or structure, the data obtained are then used to create a characterization matrix that synthesizes the action of the alteration agents on the building materials according to the possible alteration indicators that can be generated for the area studied (city, region or country), and then the effects are evaluated for each one, taking into account the alterations observed in the in situ visits and calculating the intensity of the damage; with the data previously obtained, the vulnerability index (VI) is calculated by dividing the total intensity of the disturbance indicators for each building by the sum of the total intensity of the disturbance indicators with the highest frequency, which corresponds to the most unfavourable case.

For this study specifically, the method proposed by Ortiz and Ortiz, 2016.; Ortiz et al., (2018) was adapted to the cases studies in Colombia and Guatemala with new variables as seismic vulnerability, traffic, land use, inadequate occupation of public space, cataloguing or level of use. Table 1 shows the four indexes that were studied: vulnerability index (VI), weighted vulnerability index (VIp), intrinsic expanded vulnerability index (VIe2) and global expanded vulnerability index (VIe1).

The vulnerability index (VI) in this case has been applied following the model of the RIVUPH and Art-Risk Projects, in Spain, Cuba and Colombia (Ortiz et al., 2014; Ortiz et al., 2016, 2018; Ortiz and Ortiz, 2016; Rodríguez et al., 2021; Turbay et al., 2019).

The VIp has been calculated with the weighting obtained from the opinion of experts using the Delphi method with the physical-chemical characteristics, texture, foundation, structure, construction system and alteration of the landscape (Ortiz et al., 2013).

The VIe2 has been calculated with the weighted vulnerability index and the opinion of the experts with those variables that are specific to the building, considering the factors that would enhance the vulnerability of the building from the point of view of its intrinsic properties, and that depend on the construction model, as well as its management and maintenance.

The VIe1 includes those factors previously developed by Ortiz and Ortiz (2016) and Macías (2012) such as cataloguing, level of use, fire resistance, roof design, state of facilities and constructive simplicity, and new variables due to the conditions of the heritage of Colombia and Guatemala, related to characteristics and dynamics of the historic centres such as: the periodicity of the maintenance of the building, the use of the land, the inadequate occupation of the public space, the vehicular traffic in the immediate environment, the seismic vulnerability and the inadequate interventions carried out in the building.

Table 1. Vulnerability indexes and the factors involved (VI, VIp, VIe1, VIe2).

Alteration factors	Soils, climate, natural phenomena, anthropogenic action	VIe1	VI - VIp	Building variables and its environment	VIe2
				Physical-chemical characteristics	
				Texture	
				Foundation	
				Structure	
				Construction system (finishes)	
				Urban Landscape	
				Fire resistance	
				Roofs	
				Installations	
				Seismic vulnerability	
				Simplicity of the construction solution	
				Traffic	
				Land use	
				Inadequate occupation of public space	
				Maintenance	
				Inappropriate interventions	
				Cataloguing	
				Level of use	

21 churches located in three cities (Popayán and Cartagena de Indias in Colombia and La Antigua in Guatemala) were studied in situ and 18 variables were identified as their vulnerability factors.

There are several multivariate statistical techniques that help to perceive what is not visible in the data sets, the PCA, reduces the number of observations (variables) that also allows to discover the hidden relationships between them, preserving the most relevant information of the set with its interdependent relationships, i.e., it does not distinguish between dependent and independent variables, but examines the interdependent relationships between the complete set of variables. In addition, the analysis of results is simple and can be the first step for other complementary studies such as the statistical analysis by clusters in charge of the search for relationships in a large symmetric matrix and whose variables or groups of variables specified can then be used to group the samples by distance function, which can be a good option having a clearer grouping criterion. The Excel program Xlstat was used to carry out the PCA. The procedure for data analysis is explained below.

- The PCA in the vulnerability study in Colombia and Guatemala is carried out to reduce the dimensions of the original data matrix and calculate the statistical weight of the sets of variables.
- The correlation between the variables was analyzed in the factorial space represented with the F1 and F2 axes. And it is explained by the circle of correlations that shows a projection of the initial variables in the factor space represented in two dimensions with the axes F1 and F2.
- The data was also analyzed to understand global vulnerability with a Biplot graph, observing the relationship between vulnerability, the variables that affect it and the churches studied.
- Finally, PCA was employed to propose preventive conservation, determining groups of churches in the factorial space and their location with respect to the variable incident on the vulnerability and the axes of the Cartesian plane.

3. Results

3.1. Simplification of the set of variables through PCA.

Table 2 shows the input data matrix that contains 18 variables and was explained by the combination of 13 variables located between the axes F1 and F2.

Table 2. Principal components analysis.

Initial variables / Input		Final variables / Output, main components		Final variables / Output, in other components	
Variables	Number of variables	F1 and F2 axis variables	Number of variables	Variables on other axes	Number of variables
Cataloguing, Level of use, Fire resistance, Roofs, Installations, Land use, Inadequate occupation of public space, Traffic, Simplicity of the construction solution, Seismic vulnerability, Inappropriate interventions, Physical-chemical characteristics, Texture, Foundation, Structure, Construction system, Maintenance and Urban Landscape	18	Axis F1 (33.1%): Fire resistance, Roofs, Physical-chemical characteristics, Texture, Foundation, Structure, Construction system and Urban landscape Axis F2 (20.8%): Level of use, Land use, Inadequate occupation of public space, Traffic and Seismic vulnerability	13	Other axes (46.1%) Cataloguing, Installations, Simplicity of the construction solution, Inappropriate interventions and Maintenance	5

3.2. Evaluation of the correlation between factors that affect vulnerability indices.

Fig. 1 shows the vectors in red of the 18 variables (factors that have been defined in the vulnerability indices) and the vectors in blue represent the supplementary variables or vulnerability indices (VI, VIp, VIe1, VIe2).

- Factors with positive correlation. The variables that define the state of conservation of the building, the materials and conservation are observed with positive correlation. That is, the vectors of foundation, structure, coatings, physical-chemical characteristics, texture and maintenance are close, they have the same direction and closed angles, which means that they influence each other positively. The alteration of materials affects the conservation state of the building as well as problems in the structure deteriorate the materials. In these cases, the way to stop deterioration in materials and structure depends on maintenance.

  The variables land use and inadequate occupation of public space also have a positive correlation. In the case studies, churches located in commercial sectors (high land use rating) also have a high level of inadequate occupation of public space.

  The correlation between seismic vulnerability, the simplicity of the construction solution and the roofs is also notable; churches that have a high seismic vulnerability tend to also be those with a complex construction solution, especially in their roofs.

  A final correlation to evaluate is between inappropriate interventions and the urban landscape, which could be related to interventions at the urban level that affect the shape, heights or colour of buildings.
- Factors with negative correlation. The cover factor is located opposite the fire resistance. The churches that are less vulnerable to fire resistance generally correspond to the churches with the highest roof ratings, that is, roofs with the worst performance characteristics for water evacuation. This is explained since churches with coffered ceilings are particularly simpler (gabled), but they would be the least resistant to fire due to the wood of their roof structures. Moreover, the variables fire resistance and simplicity of the constructive solution has vectors in an opposite way. In general, the churches with the lowest fire resistance rating (less vulnerable) are the highest rated in constructive simplicity. Constructive simplicity is qualified according to the criteria of Macías (2012). Fig. 1

also shows two other groups of variables that are close or close to the second axis F2 and have coordinate values close to 1 (traffic, land use and inadequate occupation of public space) and -1 (level of use) also, they have a value with respect to the first axis F1 close to zero. This indicates that there is a high correlation close to -1 (negative) between both groups of variables. This case could be important since churches located on streets with a high level of vehicular traffic are also located in areas with commercial and service-type land use, which generates negative urban dynamics.

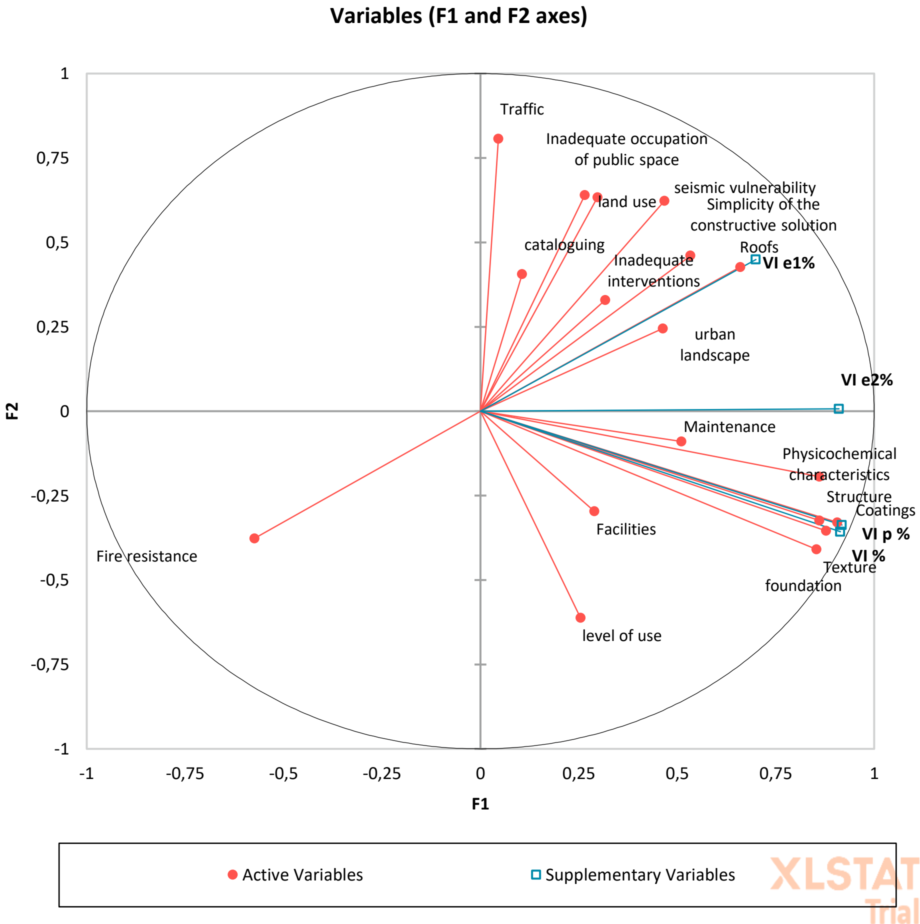

Fig. 1. Circle of correlations of the main axes.

3.3. Application of the statistical study using PCA to understand the global vulnerability of the churches studied.

The Biplot graph of F1 and F2 axes (Fig. 2) shows a summary of PCA, where some trends can be identified relating the churches and their main threats.

Fig. 2 shows the case of San Agustín (AGU) and San Francisco (SFP) in Popayan, their vulnerability is mainly affected by land use and inadequate occupation of public space, while San José (JOS) in Popayan is significantly affected by inadequate interventions since the earthquake occurred in 1983.

Fig. 2 also shows interesting diagnosis assessment in La Antigua, El Calvario (CAL) is affected by the lack of maintenance, Escuela de Cristo (ESC) is affected by the physical-chemical characteristics, structure, foundation, construction system and texture, all related to the state of conservation of the building, Belen (BEL) and Guadalupe (LUP) are affected by the state of the facilities and the level of use, in accordance with the little activity of the church and unsafe conditions of the facilities.

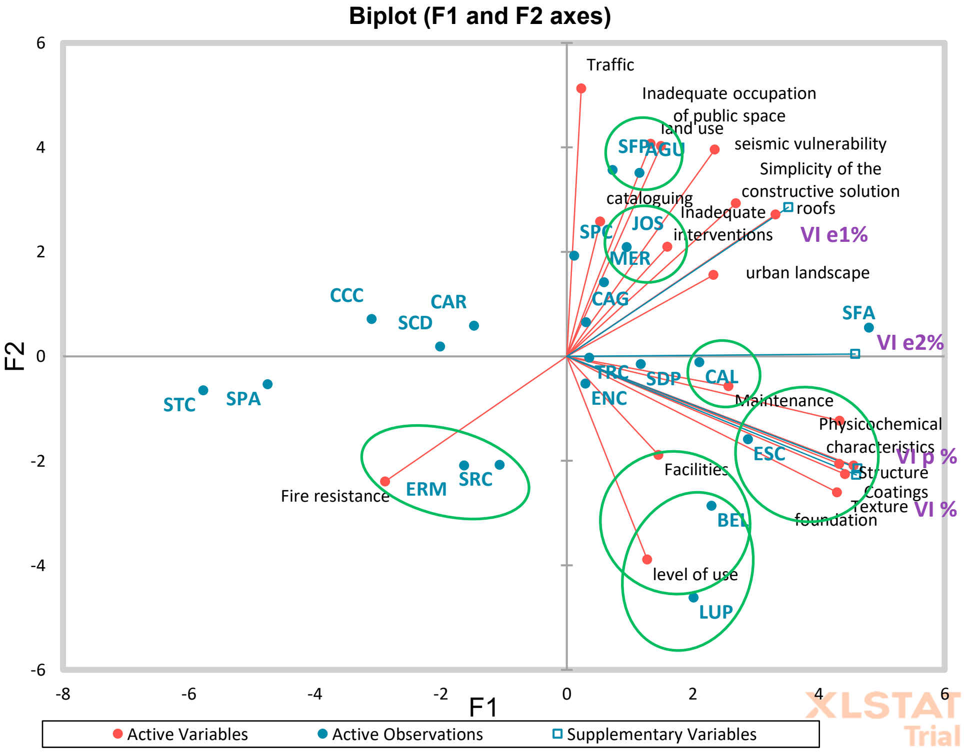

Fig. 2. Biplot graph observations on the F1 and F2 axes. The green circles include the churches (blue dots) and the determining factors in them (red dots).

The resistance to fire whose observation is drawn in a quadrant opposite shows that San Roque in Cartagena (SRC) and La Ermita de Popayan (ERM) are affected by a high vulnerability to fire (Fig. 2).

3.4. Vulnerability indexes

In the case of the supplementary variables (VI, VIp, VIe1, VIe2), it can be observed that their trend is well represented by the first F1 axis since their values are close to 1, which corroborates the statistical effect (Fig. 2). The vulnerability index (VI) and the expanded vulnerability index (VIp) are highly correlated since they share their internal variables and in turn are correlated with the structure of the monument which are the defining variables. While the global expanded vulnerability index (VIe1) and the intrinsic expanded vulnerability index (VIe2) are in another quadrant affected by the greater number of defining variables. It should also be noted that the intrinsic expanded vulnerability index (VIe2) is close to the variables that define materiality and structure, and therefore to the vulnerability index (VI) and the expanded vulnerability index (VIP).

3.5. Application of PCA to the study of preventive conservation.

Table 3 shows the number of monuments studied and their vulnerability degree classified in 5 levels from very low to very high (Ortiz and Ortiz, 2016), according to the least favourable condition of each building to the vulnerability index (VI, VIp, VIe1, VIe2).

The buildings according to their vulnerability degree have been represented in the Biplot graph F1-F2 (Fig. 3), identifying characteristics that are somewhat unified in their vulnerability to carry out decision-making regarding preventive conservation. These decisions have considered the stages previously described in the PCA.

Table 3. Summary table of monuments according to the vulnerability index (VI, VIp, VIe1, VIe2).

Degree of vulnerability	Very low	Low	On alert	High	Very High
Number of monuments according to the least favourable condition of each among the 4 indexes	0	2 SPA, STC	13 CAR, MER, CCC, SPC, SRC, TRC SDC, ERM, ENC, CAR, AGU, SFP, JOS	5 CAL, ESC, LUP, BEL, SDP	1 SFA

In very low vulnerability, no buildings were found (dark green) (Table 3), therefore the same recommendations are taken for buildings with low vulnerability.

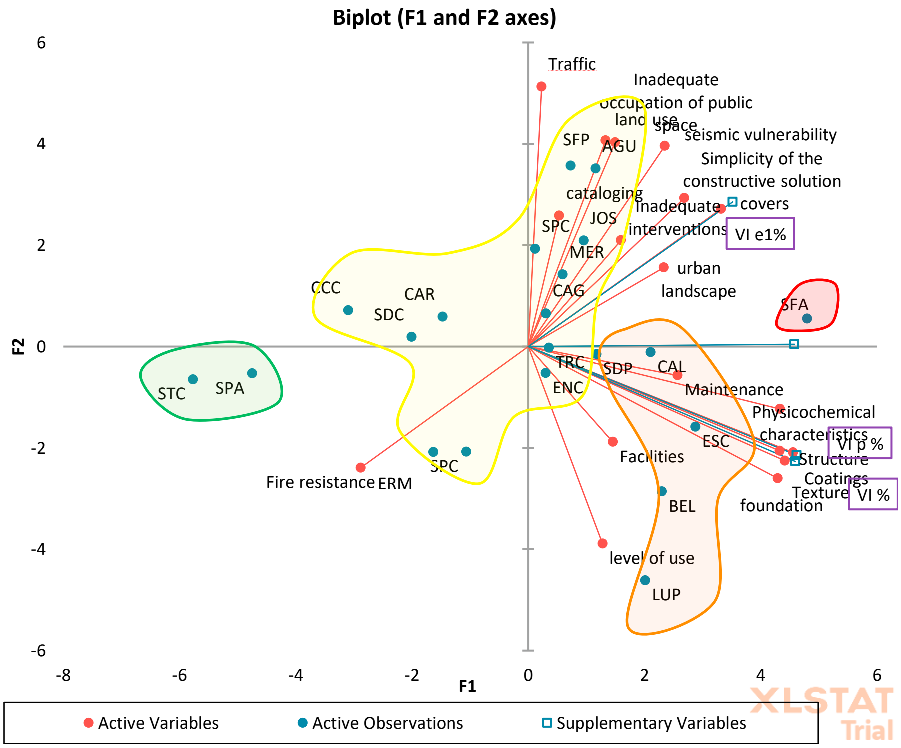

Fig. 3. Biplot graph observations on the F1 and F2 axes. The colours represent the level of mild vulnerability (green), alert (yellow), serious (orange) and very serious (red).

In the case of the churches with low vulnerability grouped in green (Fig. 3), they are simple in their construction with gable roofs, but with little fire resistance due mainly to their wooden ceilings, roofs and ornaments. Low vulnerability corresponds to churches with little complexity in their roofs with respect to rainwater evacuation, therefore, their seismic vulnerability is relatively low. Because of that, the preventive conservation for this category is summarized in structural and functional monitoring and preventive maintenance, with special attention to the maintenance of facilities that protect against fire, and the conservation of wooden structures.

The churches in alert (yellow) in Fig. 3 have been the most complex to group, since they are distributed in the four quadrants, so they do not share all the incidence factors. Some churches are affected by conditions related to urban pressure (traffic, occupation of public space and land use) in addition to being relatively seismically vulnerable and having suffered unfortunate interventions. In this group are: La Catedral (CAG) and La Merced (MER) of La Antigua Guatemala; San Agustín (AGU), San Francisco (SFP) and San José (JOS) in Popayan, and San Pedro (SPC) in Cartagena.

Other churches in alert such as San Roque in Cartagena (SRC) and La Ermita in Popayan (ERM) are mainly affected by fire resistance, physical and chemical characteristics, texture, foundation, structure, construction system and urban landscape. Meanwhile, La Catedral de Santa Catalina (CCC) and Santo Domingo (SDC) in Cartagena, and El Carmen in Popayan (CAR), are located with a relevant vulnerability in terms of urban pressure, due to the use of the surrounding land, inadequate occupation of public space, inadequate traffic and interventions, in addition to seismic vulnerability and a relative condition of vulnerability with respect to fire resistance.

Buildings with high vulnerability degree grouped in orange (Fig. 3), are mainly related to intrinsic factors such as physical-chemical characteristics, texture, foundation, construction system, and those related to the level of use of the building or maintenance.

Buildings with very high vulnerability degree (red) are mainly related to the physical and chemical characteristics of the materials, the foundation, the urban landscape, maintenance, roofs and structure.

These graphic classifications help cultural heritage managers to make decisions on preventive conservation to understand the complexity of the vulnerability.

4. Conclusions

The study using PCA allows us to identify the factors with the greatest statistical weight in the vulnerability assessment for each vulnerability model analysed and in the 21 churches studied. However, in this case these weights do not imply a significance for the simplification of the method, they allow us to understand the complexity of the vulnerability indices. The PCA has served as a clustering tool to identify similarities and differences in the factors that affect the overall vulnerability of each church, making it possible to predict typical future behaviours that allow cultural heritage managers establish preventive conservation measures applicable to several churches of the same type.

Specifically, it has been shown that churches that have a high seismic vulnerability tend to also be those with a complex construction solution and difficult roofs in terms of rainwater evacuation, therefore, the monitoring and operation of this group of buildings could focus on mitigating risks by specifying alternatives that cover vulnerability in a unified way. For fire mitigation, this study has revealed a negative correlation between fire resistance and roof design. The churches that are less vulnerable to fire resistance tend to be those with a more complex roof design and more problems due to rain percolation, while churches with wooden ceilings on roofs are more vulnerable to fires.

Urban plans and policies are essential to minimize global vulnerability in historic buildings and would have to be implemented at all degree of vulnerability (very low – very high) for preventive conservation purposes.

This study highlights the need to carry out studies in a greater number of churches so that the data set contains more information on affected monuments with different locations, since in this case the loads of variables F1 and F2 explain around 53% of the total variability, related to 13 of 18 variables, and with more observations the set could be better understood. In addition, together with other statistical methods, the results could be complemented as in the case of cluster analysis or discriminant analysis.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Structural Integrity – Historical developments through millennia

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Abstract

In this contribution, historical aspects through millennia of structural integrity development are presented, starting from the Great Pyramids in antient Egypt. Special attention is paid to the history of bridges, made of wood and stone in antient and medieval time, then from different kinds of iron and steel following the first Industrial revolution and finally by concrete, be it reinforced or pre-stresses, in modern times. The focus of this contribution is on bridges restoration, reconstruction and preservation as part of the world heritage. Two case studies are described, the old stone bridge in Mostar (Bosnia and Herzegovina) and a historical iron bridge in Transylvania (Romania). In the second case structural integrity analysis was performed in the form of Engineering Critical Assessment, to provide a solution for retrofitting the historical riveted steel bridge. This paper is dedicated to the memory of Prof. Stojan Sedmak (1929-2014), one of the fathers of the fracture mechanics in Southeast Europe. Motivation for our research is the paper published 12 years ago on the significance and applicability of structural integrity assessment, Sedmak et al (2012), which was based on the presentation at the Tenth Meeting "New Trends in Fatigue and Fracture" (NT2F10) in Metz, France, 2010.

Keywords: structural integrity; bridges; Engineering Critical Assessment; Failure Assessment Diagram

1. Introduction

Great pyramids in Egypt are certainly the best starting point to illustrate men's ingenuity in sense of structural integrity, Sedmak et al (2012), Sedmak et al (2020). They were built earlier than 4.5 thousand years. With its 146.6 m the Great Pyramid was the tallest man-made structure in the world until the 1880-ies, when the Washington monument (USA), Cologne Cathedral (Germany) and Eiffel Tower (France) were built. According to official estimates, 2.300.000

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stone blocks with an average weight of 2.5 ton were used, total weigh being about 5.75 Mtons. Great pyramid of Giza (Egypt) is still an integral object, constructed for unlimited life, exposed only to its own weight load and environment. Anyhow, one should also notice that more than 2 centuries of development were needed for such a remarkable achievement, since the first attempts were not successful ones, e.g., Sakkara pyramids (Egypt) (2750 BC) made of soil, which could not sustain its own weight.

Many centuries have passed in the meantime, with other remarkable achievements (Roman pantheon, Hagia Sophia (Turkey), Eiffel tower, Empire state building (USA), Sedmak et al (2020)) leading to another great achievement in the sense of structural integrity – the world tallest building, Burj Khalifa (United Arab Emirates), being the closest ever to fulfil old dream of reaching the stars.

Here, special attention is paid to the history of bridges, made of wood and stone in antient and medieval time, from different kinds of iron and steel following the first Industrial revolution and finally by concrete, be it reinforced or pre-stresses, in modern times, with a focus on their restoration, reconstruction and preservation as being part of the world heritage. Two case studies are described, the old stone bridge in Mostar (Bosnia Herzegovina) and a historical iron bridge in Transylvania (Romania). In the second case a structural integrity analysis was performed in the form of Engineering Critical Assessment, Radu et al (2022), Jeremić et al (2021), Kačmarčić et al (2021), Kirin et al (2020), Mijatović et al (2019), Arsić et al (2021), Radu et al (2020), Radu et al (2018), Neggaz et al (2020), Sedmak et al (2020), Golubović et al (2018), Sedmak et al (2010), Zaidi et al (2022), to provide a solution for retrofitting the historical riveted steel bridge by using the fracture mechanics' approach.

2. Methods: overview of Bridges construction history and selection of case studies

Bridges often show ingenuity of their builders since they are rarely simple structures from design and structural integrity point of view. The first bridges were made of stone and wood, the simplest ones being wooden boulders placed over a stream. The oldest stone bridge still in use, (https://www.oldest.org/structures/bridges/), often called Caravan Bridge, dated from 850 BC, was built in Izmir (Turkey), to cross River Meles, Fig. 1. One can see that so-called Roman arch was actually used even before the Roman Empire.

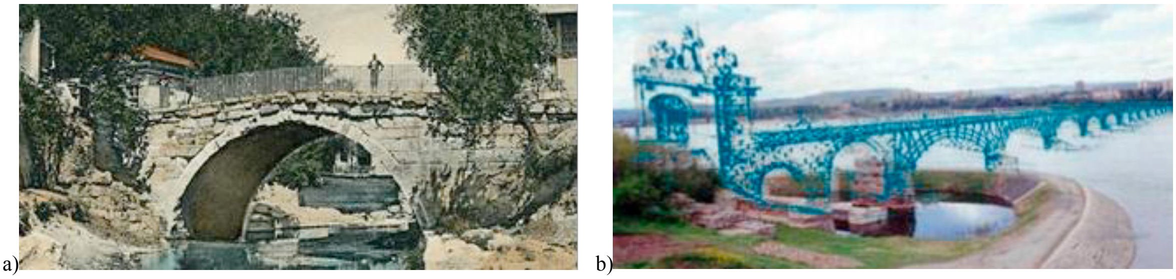


Fig. 1. (a) The oldest stone bridge – Caravan bridge in Izmir; (b) holographic presentation of Trajan's bridge over Danube.

The first bridge with a significant span was antient Roman bridge over the Danube, being a remarkable achievement in the early II century A.D, during Trajan reign. It was a segmental arch bridge, as shown in holographic projects in Fig. 1b, with total length 1135 m, representing one of the greatest achievements of antient Roman engineering, Fernandez et al (2023). Wooden arches with span 38 m, set on twenty brick masonry pillars, mortar, and pozzolana cement, were used, Fernandez et al (2023), O'Connor et al (1993), Ulrich et al (2007), Griggs et al (2007). In IV century it was surpassed in length by the legendary Constantine's Bridge (actually its existence is not proved yet), with total length 2,437 m, built in the same way at the lower Danube, using stone piers and wooden arches. Since wooden construction could not survive for a long time, both bridges were destroyed before the end of the IV century.

Another important achievement was from the XVI century, when the old bridge in Mostar, Fig. 2a, was built by Mimar Hayruddin to replace wooden bridge (https://en.wikipedia.org/wiki/Stari_Most), Andrejević et al (1990), Goodwin et al (1971). Other than the inscription on the bridge (1557-1566), nothing is preserved in writing. It was the widest man-made arch in the world at the time, with the span 30 m, made from mortar with egg whites. From the structural integrity point of view, it was a bit of a mystery how the bridge could sustain its own estimated weight, before young scientists, Aleksandar Vesic, from the University of Belgrade, proved in his D.Sc. thesis that the bridge was hollow and thus much lighter than previously thought Vesić et al (1956). Anyhow, longer spans and larger bridges required use of metal, starting with the first Industrial revolution Sedmak et al (2012), Sedmak et al (2020) , and different type of concrete later on, with total length over 100 Km. The old stone bridge is presented here as an excellent example how historical constructions should be preserved and even rebuilt after their destruction, as explained in the following text. The other case study is the road steel bridge in Romania, almost 100 years old, with a solution for consolidation and retrofitting, taking into account structural integrity assessment, which might be considered as the basis for other similar bridges.

3. Results

3.1 Case study 1 – old stone bridge in Mostar

The old stone bridge replaced even older wooden suspension bridge of dubious stability. Little is known about the construction of the bridge, since all that has been preserved is the name of the builder, Mimar Hayruddin. Upon its completion it was the widest man-made arch in the world. The 17th Century Ottoman explorer Evliya Çelebi wrote that the bridge "*is like a rainbow arch soaring up to the skies, extending from one cliff to the other... I, a poor and miserable slave of Allah, have passed through 16 countries, but I have never seen such a high bridge. It is thrown from rock to rock as high as the sky*." Muravljov et al (2011). Significant works was done in 1953-1955 to preserve the bridge from further damage, Muravljov et al (2011), as shown schematically in Fig. 2b and 2c.

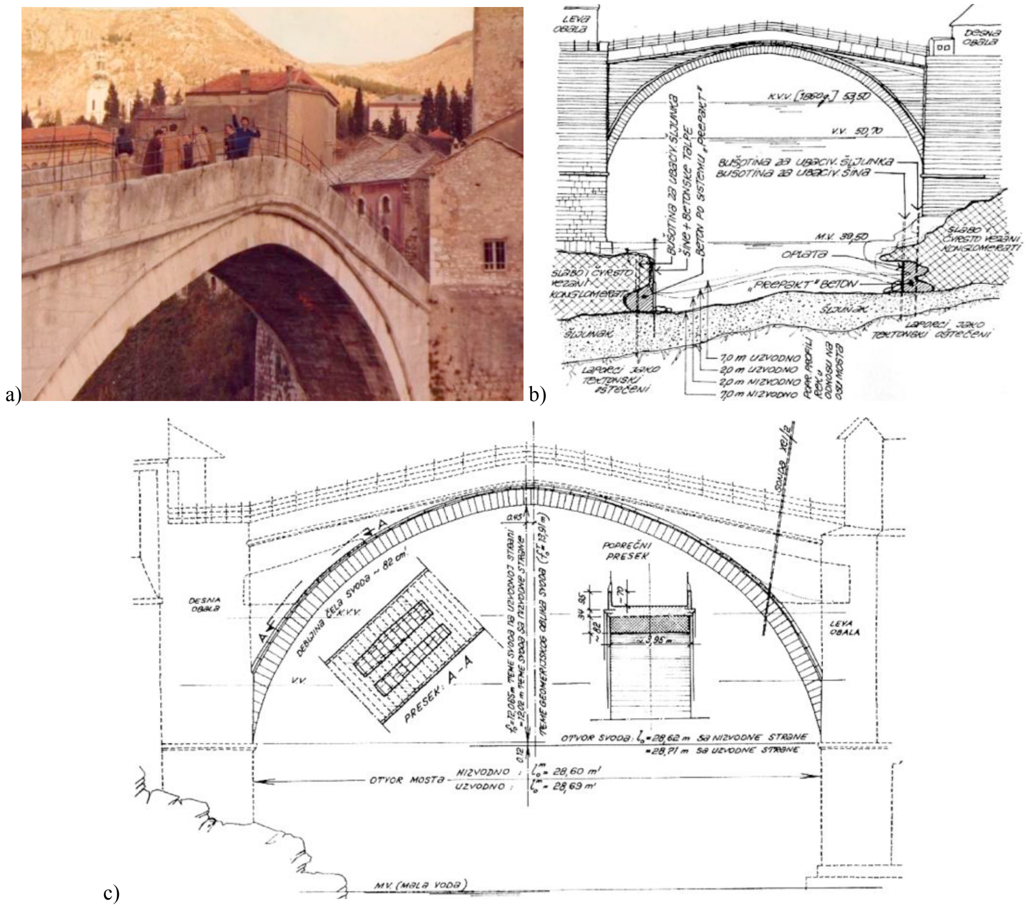


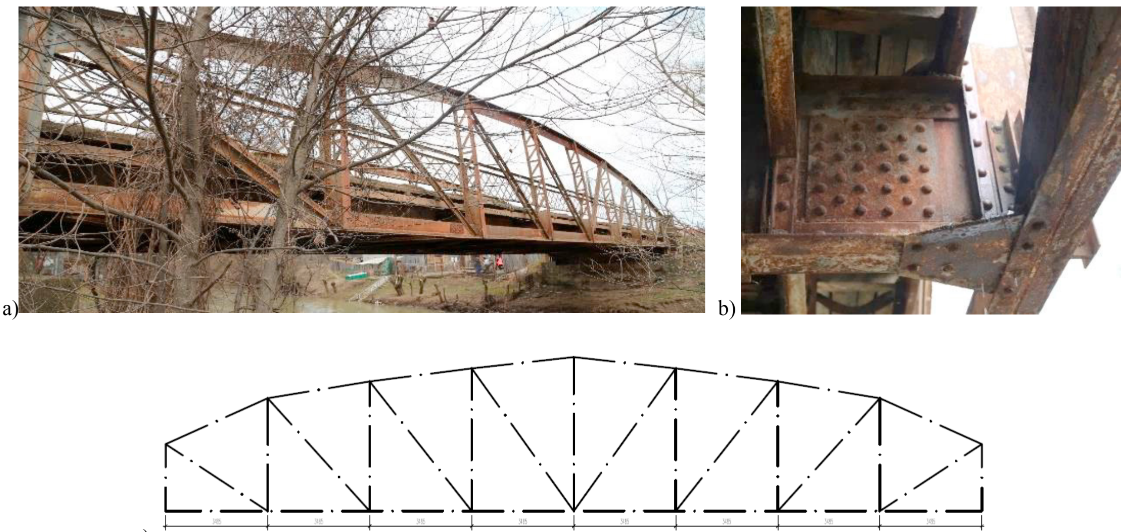
Fig. 2. (a) Old stone bridge; (b) Cross-section - rehabilitation of fundaments (original drawing), (c) Cross-section with hollow stones (original)

The most important work performed during 1953-1955 was on the rehabilitation of the foundations in order "to really secure the building for many years", Muravljov et al (2011). To this end, the project provided for the closing of the cavities on the side of the river with combined steel-wooden formwork (later replaced with reinforced concrete slabs), and then for the concreting to be carried out underwater in those underlain areas. This was made according to a special procedure, whereby the first was inserted gravel of a certain granulation was placed in the areas for concreting, and then it was bound by means of injection. Together with other procedures, this is an excellent example of successful restoration and preservation works.

The old stone bridge was destroyed 1993 during the war in Bosnia and Hercegovina, (https://en.wikipedia.org/wiki/Stari_Most#:~:text=Stari%20Most%20(Serbo%2DCroatian%3A,two%20parts%20of%20the%20city). In October 1998, UNESCO established an international committee of experts to oversee the design and reconst-ruction work, Amaly et al (2004). It was decided to build a bridge as similar as possible to the original, using the same technology and materials, Amaly et al (2004), providing one option how to rehabilitate important heritage structures.

3.2 Case study 2 – historical bridge in Transylvania

Road steel bridge in Transylvania was built almost 100 years ago (around 1925), Fig. 3a. Solution for consolidation and retrofitting of the bridge is presented here, taking into account structural integrity assessment. Critical values of crack-like flaws were determined for each case type using the Failure Assessment Diagram (FAD). These values are used as limit values for fatigue assessment based on fracture mechanics principles, to determine the number of cycles for a crack to extend from initial to critical dimension, i.e., failure, being nowadays standard procedure for remaining life evaluation, Golubović et al (2018). Here, we present Structural analysis of the existing bridge, Structural analysis of the proposed solution - retrofitted bridge, Engineering Critical Assessment considering most common possible discovered flaws (crack like type) and Fatigue assessment. The bridge is a riveted type, Fig. b, and has a parabolic truss main beam structure, with descending diagonals and an opening of L = 27.86 m, Fig. 3c. Figure 3d presents a few cross-sectional cuts. In order to strengthen the supporting structure, the new one is proposed, with a transversal beam, with main beam box girder 600x1800 mm, S355, as shown in Fig. 4.



a) b) c)

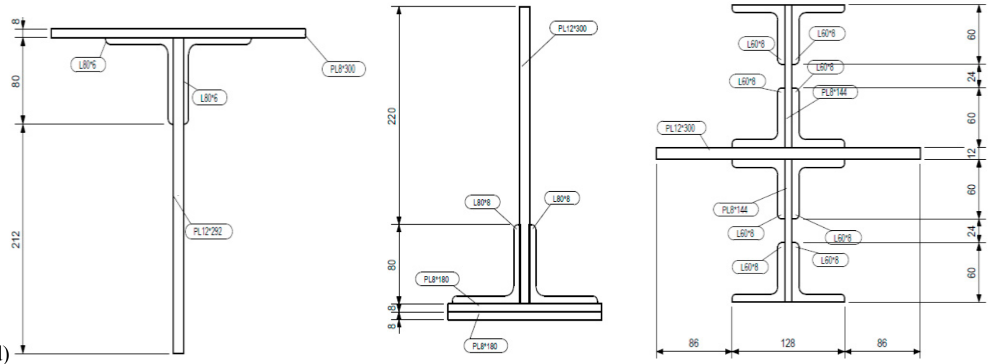
d)


Fig. 3. (a) Historical bridge in Transylvania; (b) riveted joints (c) scheme of supporting structure, (d) cross-sections

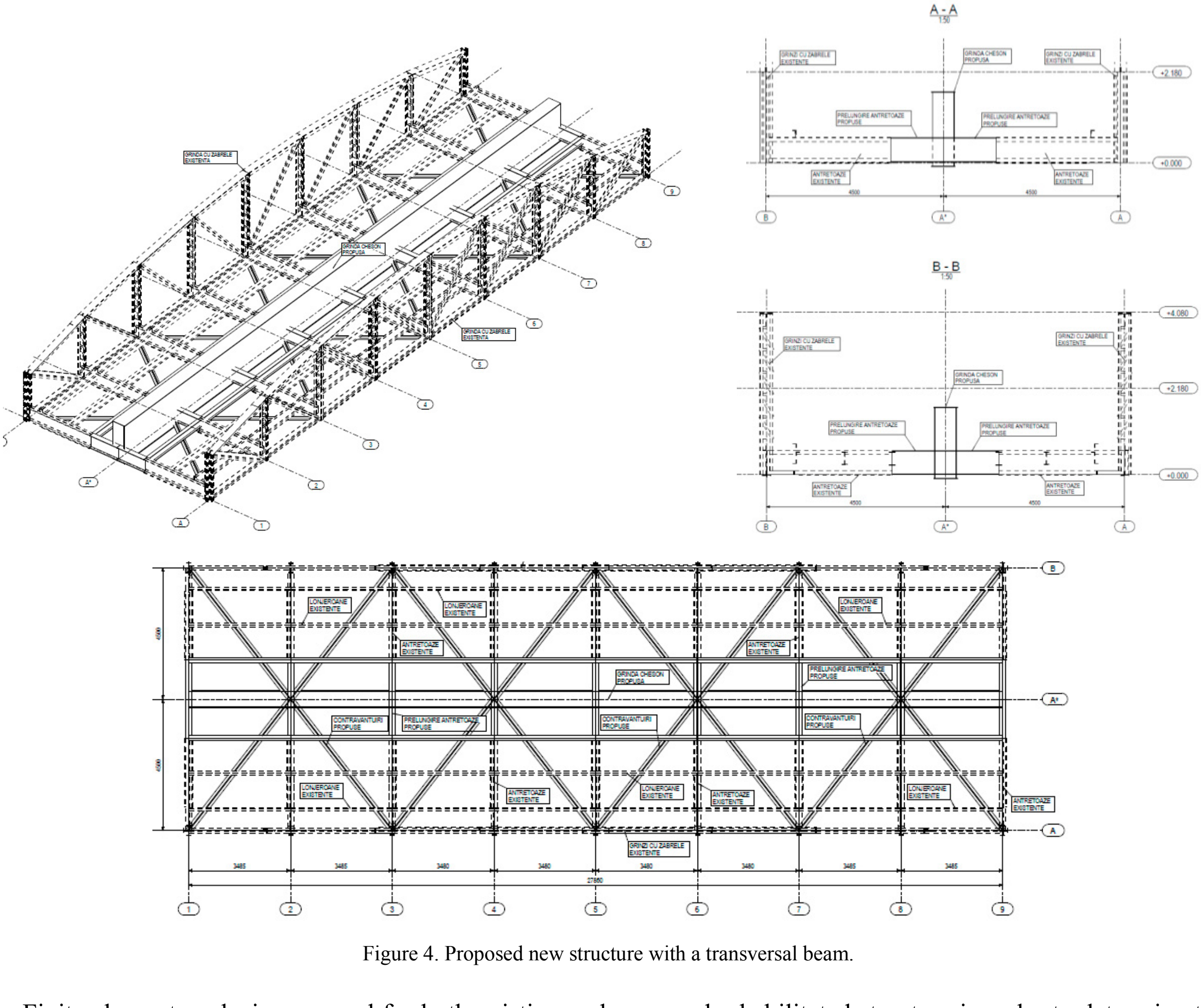


Figure 4. Proposed new structure with a transversal beam.

Finite element analysis was used for both existing and proposed rehabilitated structure in order to determine the stresses in the elements, as shown in Fig. 5a for the existing structure, and in Fig. 5b for the proposed one.

Comparison between stresses in the existing structure ("old") and proposed one ("new") is shown in Table 1. One can see that the highest stress value the existing structure (183.2 MPa) is reduced to 162.2 MPa in the new one, whereas the maximum stress is shifted to the deck main beam (291.8 MPa), which should be made of much stronger material than the original one (e.g., S355 steel type).

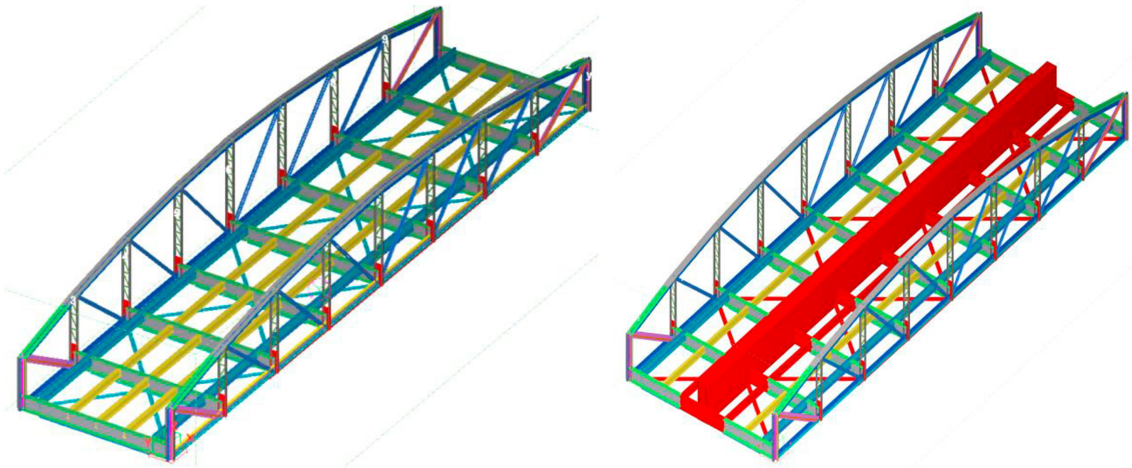


Figure 5. Stresses in a) Existing structure, b) Proposed new structure with a transversal beam.

Table 1. Stresses in "new" and "old" structure

Stresses - FEM analysis	**New structure**	**Existing structure**
Element	σ [MPa]	σ [MPa]
Main truss beam - lower chord	162.2	183.2
Main truss beam - upper chord	102.3	115.5
Main truss beam - diagonal 1	112.1	135.5
Main truss beam - diagonal 2	95.2	115.2
Main truss beam - diagonal 3	55.5	85.5
Main truss beam - diagonal 4	35.2	60.2
Deck transversal beam	285.3	115.1
Deck secondary beam	115.2	85.2
Deck main beam	291.8	N/A

3.2.1 Assessment of defects using ECA

An Engineering Critical Assessment (ECA) can be used during design, to assist in the choice of used details, during fabrication, to assess the significance of known defects which are unacceptable according to standards/fabrication codes and during operation/service, to assess flaws found in service and to make decisions as to whether they can safely remain, or whether down-rating/repair are necessary. In the first phase ECA determines the acceptability of the detected cracks in the structural element, while in the second one fatigue life is assessed for the elements containing cracks based on loading events history.

Starting point in static analysis is the Failure Assessment Diagram (FAD), levels 1-3, Radu et al (2022). Here, the level 2 is used to determine the stress distribution in the proximity of the flaws, represented by membrane – P_m, P_b, and bending stress components, Q_m and Q_b, Radu et al (2022) Then, the fracture ratio K_r is determined by equation (1):

$$K_r=K_I/K_{mat} \qquad (1)$$

where K_I is the stress intensity factor, and K_{mat} material property, typically the fracture toughness, K_{Ic}. Using the following formula for stress intensity factor

$$K_I=(Y\sigma)\cdot(\pi a)^{1/2} \qquad (2).$$

K_r can be calculated, if K_{mat} is known. Thereby, Y is geometry factor, σ is remote stress, *a* is crack length. Finally, the stress ratio L_r is determined according to equation (3):

$$L_r=\sigma_{ref}/\sigma_Y \qquad (3),$$

where σ_{ref} is the net stress in the crack cross-section, and σ_Y is the yield stress. The points of assessment are then represented graphically in (K_r, L_r) coordinates in the FAD level 2. In the case of existing structure, an edge crack-like flaw is considered as the most dangerous, Fig. 6a, with dimensions B=25 mm, W=120 mm, $2a_0$=30 mm.

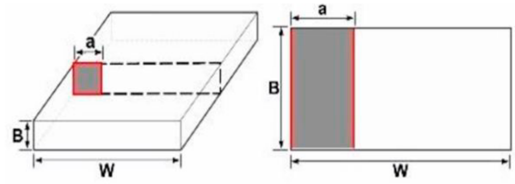


Figure 6. Geometry of an edge crack

Other data needed for the ECA is: σ_Y = 215 MPa; σ_m (ultimate tensile strength) = 375 MPa, K_{mat}=71.8 MPa·√m (SINTAP procedure), P_m = Primary stress – according to the structural analysis, P_b = 0, Q_m=0, Q_b=0. The point with coordinates (L_r, K_r) is shown in Fig. 7, together with 4 other points, considered elsewhere, Radu et al (2022). From this analysis one can find out the critical length of a through thickness flaw in area nearby the rivet (FP-TTF-5) to be less than assumed 30 mm, i.e., 28.408 mm.

3.2.2 Fatigue life assessment

The needed data are: Stress ranges, Limits of the crack growth (FAD), Fatigue crack grow law (one slope or two stages) and types and dimensions of the flaw, Radu et al (2022). Load spectrum for a given time is obtained from the distribution of the loads rearranged following a probability density function (PDF) using Weibull Distribution. Using Rainflow algorithm, the results were processed and was determined the block of stresses with stress ranges ($\Delta\sigma_i$) and the appearance frequency (n_i), Fig. 8.

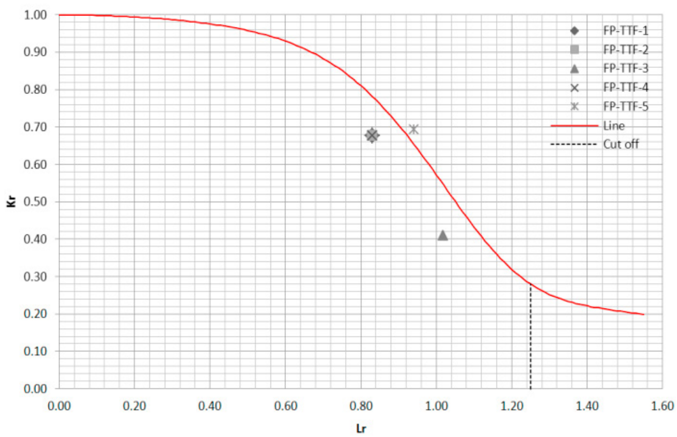


Figure 7. FAD, level 2, for the existing structure

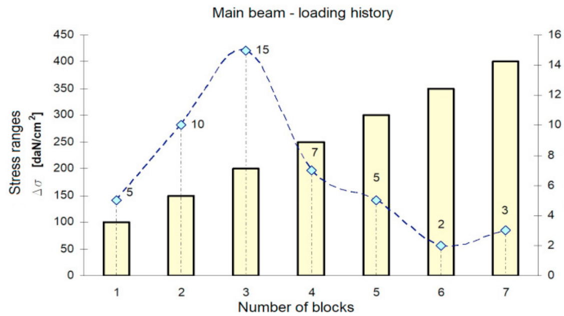


Figure 8. Stress range vs. number of blocks of different stress ranges

As in the case of static loading, 4 types of flaws were analysed and presented in Radu et al (2022), while here we present briefly the crack of initial length 5 mm to grow up to 7.5 mm, resulting in cca. 16 years of remaining life.

4. Discussion and conclusions

Solution for retrofitting an existing historical riveted steel bridge was considered using the fracture mechanics approach – Engineering Critical Assessment for the proposed structure.

The proposed solution maintains the bridge in operation and allows the unrestricted traffic of current convoys. Thus, the current deck is maintained in combination with a new deck in the central area consisting of a main beam (box girder type that takes up approximately ½ of the traffic loads), the beam of which are rigidly fixed the spacers that join part of the existing spacers on the current truss beams, so as to result in two distinct traffic lanes (approximately 4.0-4.25 m per each way), separated from each other by the newly added box girder beam.

It was shown that the critical crack length is 28.408 mm for static loading, whereas the remaining life for the crack of initial length of 5 mm, to grow up to 7.5 mm under typical amplitude loading, was estimated to 16 years.

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

Tailored Training for Building Resilience in Changing Climate: BeWare Project's Approach

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Abstract

The objective of the ERASMUS+ funded BeWare project is to provide education and training for professionals in the construction sector, aligning with the requirements of the European Green Deal. This initiative aims to enhance the resilience of buildings to climate change and extreme weather events, while fostering knowledge, innovation, and value addition in the construction industry. The project's core is the Vocational Education and Training (VET) program, tailored for evolving job market demands.
Benchmarking was conducted to evaluate emerging trends and professional requirements within the BeWare VET program. The main conclusions from the results are as follows: 1) The majority of the 63 analyzed syllabi focus on "sustainable buildings" and "energy," with less attention given to climate resilience and climate change mitigation; 2) the scarcity of training programs addressing these issues underscores the critical need to prioritize building resilience in the face of climate change and extreme weather events; 3) In the context of Construction Industry 4.0, BIM takes a central role, expanding the use of digitized data beyond traditional 2D modeling and; 4) Sustainable building gains momentum, with an emphasis on materials, life cycle assessment, circularity, sustainable development, environmental sustainability, and certification integrated into VET course curricula.

Keywords: Vocational Education and Training; Climate resilience; Climate change; Sustainability.

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1. Introduction

As the climate crisis continues to intensify, there has been a resurgence of interest in the role of Vocational Education and Training (VET) in fostering a greener economy and attaining decarbonization objectives (McGrath and Yamada, 2023). The importance of VET in addressing the climate crisis is emphasized by the European Commission, which notes that the construction sector, a vital component of the European economy, contributes approximately 9% to the Gross Domestic Product (GDP) of the European Union and provides employment for approximately 18 million individuals (European Union, 2016). Realizing innovation within the construction industry is intrinsically linked to the adoption of green and sustainable technologies, as well as embracing digitalization. These advancements are vital in creating a more sustainable, resilient, and inclusive Europe (European Commission, 2020). Despite the growing interest and recognition of the significance of green innovations, the current body of literature underscores a distinct gap in our comprehension of the requisite skills necessary for the effective integration of such innovations (Shamzzuzoha et al., 2022). Addressing this knowledge gap is important to ensure that the construction sector is adequately prepared to contribute to a more sustainable future.

The 2021-2024 BeWare project (http://bewareproject.com/), funded by ERASMUS+, is a two-year and two months initiative aimed at enhancing the skills of professionals in the field of Resilience and Sustainability of Buildings in relation to climate change and extreme weather events. This project recognizes the urgent need to equip professionals in the construction industry with the necessary knowledge and expertise to address the challenges posed by climate change and extreme climate. One of the main components of the BeWare project is the Vocational Education and Training (VET) program, designed to prepare professionals to meet the demands of the evolving job market (Mendes et al., 2022). The program encompasses six comprehensive modules, namely: Ecodesign and Social Needs, Insulation Materials, Nature-based and Waste-based Solutions, Energy Efficiency and Economic Assessment, Digitalization in Construction, and Risk Assessment. The methodology presented is guided by a comprehensive analysis of emerging trends and professional needs, with the following key objectives:

i) Make sure that the content of the syllabi aligns with the current and future job market demands.
ii) Contribute to the development of the BeWare VET syllabi.
iii) Identify the major issues addressed by the VET courses within the scope of BeWare VET program.
iv) Define gaps in subject matter content.
v) Integrate sustainability and resilience concepts throughout the syllabi.

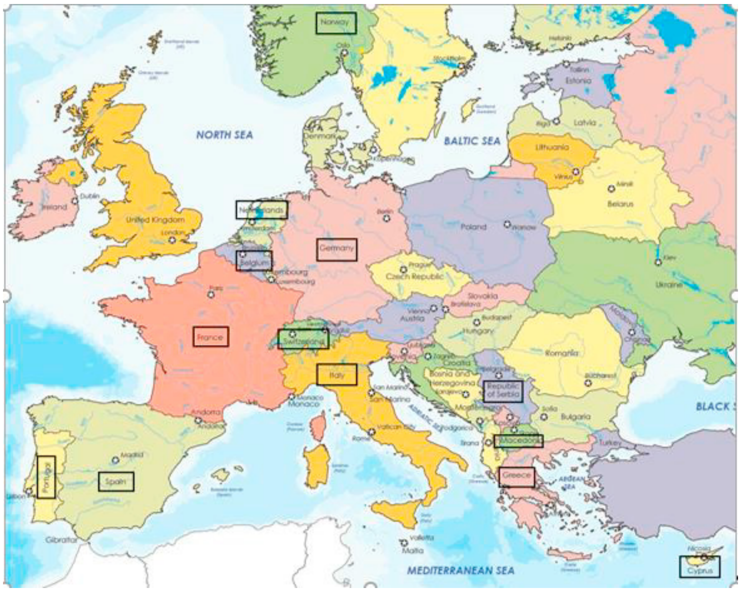
The results and analysis obtained mirror the content of 63 courses across 14 European countries, enabling the identification of the primary issues related to VET course trends, with "sustainable buildings" and "energy" emerging as the most prominent topics.

2. Methodology

To gather a broader sample of Vocational Education and Training (VET) offerings across Europe, we initially collected information on seventy-three courses from 14 European countries in 2022. This initial selection aimed to encompass countries with varying socioeconomic conditions and climate types, as illustrated in Figure 1. The criteria employed during the web search for VET courses and their respective syllabi included:

i) VET training programs tailored for a wide range of professionals, including specialized planners, project and civil engineers, architects, auditors for quality standards, company and facility managers, directors of production departments involved in maintenance, owners and managers of micro, small, and medium enterprises, mechanical engineers, as well as public or private contracting authorities.
ii) Courses that provide certification, with durations spanning from 1 hour to one year.
iii) Keyword searches that encompassed terms such as efficiency, sustainability, climate, green, and renovation.
iv) The compilation of data from a diverse array of European courses.

Additional information was gathered to provide characterization of the analyzed courses, including details on their types, delivery methods, providers, cost, and certification options. To facilitate the organization of the course program construction database, all topics were classified into four major categories: "Energy", "Building Information Model (BIM)", "Sustainable Buildings", and "Climate Resilience of Buildings”. This classification took into account the frequency of topics discussed within the courses and their alignment with BeWare aim. After this initial classification, subjects from different courses were grouped into themes based on their similarities in content. This meticulous analysis helped identify trends and shed light on the course content in specific subject areas.



a)

Country	Nº of courses
Belgium	4
Croatia	5
Cyprus	3
France	12
Germany	4
Greece	3
Italy	3
Netherlands	7
North Macedonia	10
Norway	2
Portugal	6
Serbia	7
Spain	7

Figure 1 – a) Geographic location of the countries consulted for the analysis of the courses and b) number of the courses analyzed by country.

3. Results

The majority of the analyzed courses fall into the category of VET, accounting for 92.0% of the total. These courses are typically offered either online (46.5%) or in person (36.6%), and they often employ a hands-on approach (44.4%). The institutions responsible for providing these courses are predominantly private organizations (36.0%) or universities (34.7%). Around 29% of the courses are offered free of charge, and for those courses with durations of 20 hours or less, the average fee is approximately 25 euros per hour. The vast majority of these compiled courses (93.4%) provide certification, which can take the form of either a certificate attesting to the successful completion of the course for trainees who have met the prescribed evaluation criteria, or a certificate confirming attendance for trainees who have not met the evaluation criteria. A noteworthy online course, "Energy Performance of Buildings and NZEB" (Portugal), has undergone 11 re-editions, indicating its popularity. This is followed by "BIM for manufacturers and companies" (North of Macedonia) and "BIM for builders and contractors" (North of Macedonia), both online courses, each having undergone five editions.

Out of the initial consultation of 73 courses, 63 online courses had accessible syllabi information or were VET. As a result, 63 course syllabi were further analyzed. In the analysis of modules from the 29 energy-related courses, the term “design” emerged as the most frequently mentioned concept. Additionally, words like “heat”, “neutral”, “renovation” and “bioclimatic” held significance (see Figure 2a).

In the context of the fourteen online VET courses focused on Building Information Modeling (BIM), common terms within the course content included “introduction”, “information”, “model”, “project”, “interoperability”, “application”, and “management” (see Figure 2b).

A total of sixteen courses were dedicated to the topic of “Sustainable buildings”, featuring frequently used terms such as “energy”, “construction”, “architecture”, “life cycle” and “materials” (see Figure 2c).

Regarding the four courses centered on climate resilience, the most frequently used words in the course content included “building/buildings”, “sustainable”, “considerations”, “action”, “climatic”, and “comfort”, as depicted in Figure 2d.

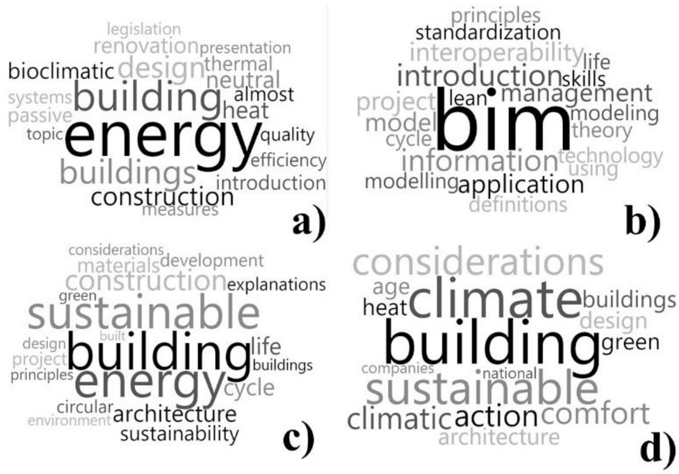


Figure 2 – World cloud of the modules a) of the 29 courses related to Energy; b) of the 14 courses related to BIM; c) of the 16 courses related to Sustainable building; d) of the four courses related to climate resilience.

After this initial screening, a more in-depth evaluation was conducted to classify the 63 VET courses into common categories. This classification was determined based on expert knowledge.

In the context of energy-related issues, the primary topics covered in these consulted courses were categorized into four overarching families. The first category, "Legal Requirements and Current Legislation," covers crucial topics such as energy efficiency standards, performance requirements for new and renovated buildings, nearly zero energy buildings (NZEB), and the foundational principles of energy-neutral and passive building design, with an emphasis on ecological and comfort considerations. The second category, "Evaluation of Energy Performance," explores various aspects, including international protocols for measuring and verifying energy savings, parameters related to heat losses and gains, energy and bioclimatic assessments, calculation methods for energy demands, and the utilization of software tools for energy efficiency. The third category, "Design and Planning" delves into the integration of bioclimatic energy principles into spatial, urban, and environmental planning, offering insights into ecological building and design. Additionally, it covers the design of outdoor spaces and the incorporation of renewable energy sources while considering the behavior of building occupants. Lastly, the "Elements" category examines ventilation methods (natural, hybrid, and mechanical) and the significance of insulation materials in energy-efficient building practices. This structured categorization enhances the understanding and application of energy-related concepts, with a focus on sustainability, efficiency, and environmental considerations.

The courses related to Building Information Model (BIM) have been structured into six distinct themes. The first theme, "Introduction to BIM" provides a comprehensive foundation, covering sustainability in construction, basic principles of BIM, technology and interoperability, and key principles of BIM Level 2, among other topics. The second theme, "BIM Standardization" focuses on the standardization of object libraries and open standards. The third theme, "Design" examines architectural and structural elements, dimensioning of facilities, BIM in design and pre-construction phases, and execution and post-construction workflows. The fourth theme, "Software" explores various BIM production tools and their applications in construction. The fifth theme, "BIM Dimensions" addresses temporal and economic planning, cost control, sustainability analysis, and facility management. Finally, the sixth theme, "The Role of BIM in Construction 4.0" discusses the digitalization of assets, augmented and virtual realities, prefabrication, and various applications of BIM in the modern construction industry. This systematic organization equips learners with a comprehensive understanding of BIM's principles and applications across the construction lifecycle, from design to construction and beyond.

Notably, courses related to "BIM" and "Green Buildings" addressed topics related to climate dimensions, given the increasing use of BIM for energy design and energy management of buildings. Green buildings, in particular, are oriented toward achieving a circular and carbon-neutral economy.

The courses pertaining to "sustainable building" have been organized into six key themes. In the first theme, "Introduction to Sustainable Buildings" trainees are introduced to the basics of sustainable construction and development, emphasizing the economic, social, and environmental aspects of sustainability. The second theme, "Materials" examines the selection criteria for materials, with a focus on special insulation in bioconstruction and the use of biobased and low-carbon materials. The third theme, "Life Cycle Assessment and Circularity," explores the importance of assessing the life cycle of building materials and achieving circularity in construction practices. The fourth theme, "Climate" covers green building concepts, energy efficiency, and the reduction of CO_2 emissions in buildings, along with considerations for thermal comfort and climatic design goals. The fifth theme, "Sustainability" addresses the financial and collaborative aspects of sustainable renovation and emphasizes the engagement of tenants and homeowners in sustainable practices. The sixth theme, "Environmental Sustainability" centers on broader environmental considerations. Finally, the seventh theme, "Certification and Sustainability" discusses various certification programs, including green seals, energy certification, and Passive house certification.

The topics covered in the climate resilience courses were systematically grouped into four main families. The first category, "Climate Action" addresses the significance of national and international efforts, climate initiatives at the city and sub-national levels, corporate involvement, and the acceleration of climate action. The second category, "Climate Comfort" explores the determination of comfort indices, the fundamentals of thermal comfort, climatic considerations, and their impact on comfort, as well as the effects of overheated living spaces on health and well-being. "Adaptation Measures", the third category, explores strategies for adapting existing building stock, addressing thermal vulnerabilities in various building types, and implementing cost-effective, climate-friendly adaptation measures. Lastly, "Green Buildings" highlights the components of environmentally friendly construction, physiological design objectives, the fundamentals of climate-responsive architecture, climatic analysis, and the intersection of sustainable architecture with climate considerations. This comprehensive categorization facilitates a nuanced understanding of climate resilience and its applications, particularly in the context of building design and construction.

The above classification provides a structured and comprehensive representation of the course topics within the 63 VET courses, enabling a clear and organized understanding of the primary themes and areas of focus. This systematic categorization has been instrumental in shaping the syllabus for the BeWare VET program, which comprises six distinct modules. These modules include Ecodesign and Social Needs, Insulation Materials, Nature-based and Waste-based Solutions, Energy Efficiency and Economic Assessment, Digitalization in Construction, and Risk Assessment. By structuring the courses and content in this manner, trainers are well-equipped to explore, understand, and apply essential knowledge and skills related to energy, climate resilience, BIM, green buildings, and sustainable construction, all while preparing for the challenges posed by a changing climate.

4. Conclusions

This analysis is based on the content of 63 European courses, offering valuable insights into the predominant trends in VET programs. Notably, it highlights "sustainable buildings" and "energy" as the central areas of focus. While these courses do address climate resilience and climate change mitigation, they do not receive the same level of attention. Prioritizing the enhancement of building resilience in the face of extreme weather events and climate change is crucial.

This emphasis is driven by the limited availability of training programs designed to tackle these issues, despite the global commitment of many countries to fulfill the Paris Climate Agreement (United Nations, 2015) and the increasing challenges posed by extreme weather events. It is essential to note that the primary areas covered in this context are thermal comfort and energy efficiency, with relatively less attention given to climate risk assessment.

Within the framework of Construction Industry 4.0, BIM takes center stage. The expansion and utilization of digitized data in the construction sector have paved the way for the broader application of BIM beyond traditional 2D modeling.

Lastly, the concept of sustainable building is gaining momentum, with a growing emphasis on materials, life cycle assessment, circularity, sustainable development, environmental sustainability, and certification as integral components integrated into the curriculum of VET courses. This underscores the industry's commitment to addressing sustainability and environmental considerations in construction practices. The authors believe that the gathered information can assist those who are interested in creating courses related to these topics.

Acknowledgements

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ESICC 2023 – Energy efficiency, Structural Integrity in historical and modern buildings facing Climate change and Circularity

The TEnSE approach to assess the nudge of stakeholders in the choice of thermal insulation materials

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Abstract

The buildings' energy efficiency and the energy poverty can be improved through the implementation of active and/or passive retrofit solutions. The thermal insulation of building envelope is one of the most employed retrofit solutions. Several thermal insulation materials are currently available in the building market. However, the choice of a specific material can depend on an ensemble of requirements ascribed to four domains – Technical (T), Environmental (En), Safety (S) and Economic (E). The TEnSE approach is here proposed to investigate the influence of specific stakeholders or nudgers in the selection of thermal insulation materials for building retrofit. It is a three-step approach, that starts from a) the identification of a set of alternatives and decision criteria, b) the assignation of parameters and their normalization, and c) the definition of a weights' matrix and calculation of the Stakeholders' Score. As an example, here, the TEnSE is used to study the influence of stakeholders in the choice of the most used thermal insulation materials in three countries of the European Economic Area. The TEnSE approach can be used beyond a

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products' score tool, as experts in social sciences and climate/energy policies could depict what are the decisional patterns of public, private, and people to enhance the green awareness and fill the legislative and political gap towards this topic.

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Keywords: TEnSE approach; building retrofit; stakeholder influence; sustainability; EFFICACY

1. Introduction

The European (EU) Directive 2018/844 brings about defining strategies aimed at decreasing the energy demand of existing buildings together with the improvement in the energy performance to reduce carbon dioxide emissions from the building sector by more than half by 2030 and close to zero by 2050. Indeed, about 75% of existing buildings in Europe are energy inefficient and more than 90% of these buildings will still exist in 2050 (Sandberg et al., 2016). Consequently, there is a pressing need to carry out the maintenance, refurbishment, and retrofit of these buildings. However, approximately 8% of Europeans, predominantly in southern and eastern EU countries (Recalde et al., 2019; Sánchez-Guevara Sánchez et al., 2017), have difficulties of accessing to essential energy products and services in their buildings due to Energy Poverty (EP) thus limiting the decarbonization process and the energy efficiency. Both short-term and long-term measures can be implemented to reduce the disparities among Europeans in EP. Short-term measures is mainly driven by political decisions, long-term measures by the improvement of the energy efficiency of buildings through active and passive solutions (Directive 2010/31/EU). The thermal insulation of building envelopes is one of the most applied passive solutions and it is witnessed by the increase (around 3.5% of Compounded Average Growth Rate - CAGR) of the demand for thermal insulation materials in building applications. The building market includes a large variety of thermal insulation products, and for this reason, several methods have been developed to help identifying the best possible alternative among items or systems or processes based on the decision-makers' preferences and priorities. These methods are commonly called Multi-Criteria Decision Making (MCDM) methods. Although the performance of MCDM methods was successfully tested in a wide range of applications (Balali et al., 2020; Mahmoudkelaye et al., 2018; Milani et al., 2013; Parece et al., 2022; Sharma et al., 2023; Zagorskas et al., 2014), one of their limitations is the coupling between a criterion and its relative importance which may vary case-by-case depending on the professional priorities of single experts (Laguna Salvadó et al., 2022). However, it was possible to categorise these criteria into four domains (economic, social, technological, and environmental) representing the pillar of sustainability and to identify the most popular criterion within each domain (Siksnelyte-Butkiene et al., 2021). Another limitation of MCDM methods is related to the validation of outputs that can be proven mainly through practice (Zakeri et al., 2023). Currently, to the best of authors' knowledge, no study has been conducted to understand whether the selection of thermal insulation materials for building retrofit has been influenced by specific stakeholders or nudgers.

In this paper, we describe a straightforward approach to better understand the influence of specific stakeholders or nudgers in the selection of thermal insulation materials for building retrofit under various contexts. The approach is called TEnSE as it considers four objective domains – Technical (T), Environmental (En), Safety (S) and Economic (E). The TEnSE makes it possible a comparison on preferences at different regional scale. Here, we provide an example in the application of TEnSE in three countries of the European Economic Area.

Nomenclature

A	alternative
DC	decision criteria
E	economic domain
En	environmental domain
EPD	environmental product declaration
p	parameter
p'	normalized parameter
S	security domain

StS	stakeholder score
T	technical domain

2. Methodology: TEnSE approach

Nowadays, the selection of the most suitable thermal insulation material for building retrofit should involve an ensemble of requirements rather than only the thermal performance of the material itself (Al-Homoud, 2005). These requirements can be ascribed to four domains – Technical (T), Environmental (En), Safety (S) and Economic (E) – as demonstrated in the literature (Antwi-Afari et al., 2023; Hatefi et al., 2021; Moussavi Nadoushani et al., 2017; Parracha et al., 2023; Siksnelyte-Butkiene et al., 2021).

The TEnSE approach was developed in the framework of the EEA grants EFFICACY (Energy eFFiciency building and CirculAr eConomY for thermal insulating solutions), whose overall objective is to provide a comprehensive database contributing to the New European Bauhaus. The TEnSE can be classified as an inverse decision-making approach (Jern et al., 2017), as it allows to objectively compare data and metadata of a set of alternatives of a given item or system or process (in this study thermal insulation materials) and to identify the underlying influences behind the selection of specific alternative in a country or in a region. The TEnSE is based on the schematic workflow in Fig. 1 and structured in three steps briefly described in the following subsections.

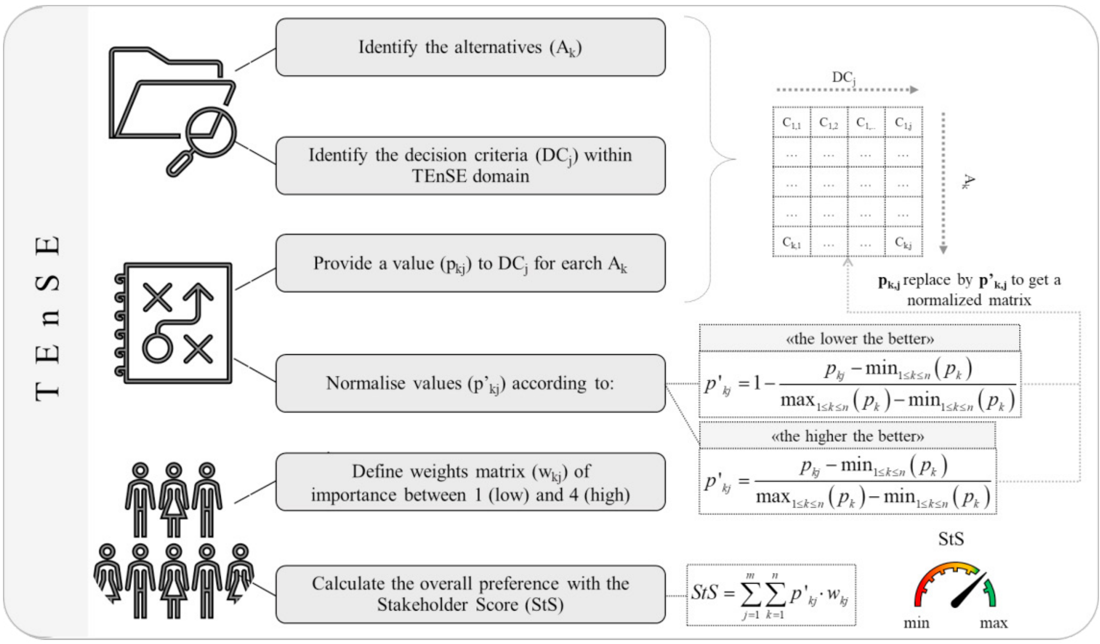

Fig. 1. Schematic workflow of the TEnSE approach.

2.1. Identification of alternatives and decision criteria

This step allows to define the input matrix, based on a set of alternatives (A), among items or systems or processes, that can be employed in a specific context, such as the thermal insulation materials for building retrofit. After that, one or more decision criteria (DC) are selected for each domain considering a set of quantitative and measurable parameters (p). In this way, it is possible to define the input matrix, where each row corresponds to an alternative (A_k) and each column to a decision criterion (DC_j). For thermal insulation materials, Siksnelyte-Butkiene et al. (2021) provided an overview of DC commonly considered in the scientific literature corresponding to TEnSE domains.

2.2. Assignation of parameters and parameters' normalization

In this step, p values for the selected DC_j in T, En and S domains can be gathered from the Environmental Product Declarations (EPD, in accordance with EN 15804:2012+A2:2019 and ISO 14025:2006) of each alternative (A_k) and, in the case of E domain, from the national/international price lists. Data (p_{kj}) feed the input matrix defined in the previous step.

For each DC_j along A_k, parameters (p_{kj}) are linearly normalized between 0 and 1 (p'_{kj}), where 0 corresponds to the worst case and 1 to the best case among the alternatives. The normalization considers the rules: *"the lower the better"* if the best case corresponds to low values of the parameter; and *"the higher the better"* if the best case corresponds to high values of the parameter. The main advantage to normalize p values relies on analyzing dimensionless criteria without the influence of different units and ranges of measure (Felinto De Farias Aires and Ferreira, 2022; Zakeri et al., 2023). The p_{kj} matrix is replaced by the new p'_{kj} matrix.

2.3. Definition of a weights' matrix and calculation of the Stakeholders' Score (StS)

The construction of weights associated with stakeholders are commonly defined via surveys or questionnaire filled in by specific experts (Siksnelyte-Butkiene et al., 2021). This can be responsible for a biased evaluation on the reason behind the choice of thermal insulation materials, as it would depend on the expertise of the stakeholders involved. To consider the relative importance of stakeholder within each domain, twenty-four scenarios, corresponding to a set of six permutations for each domain, are defined by associating a weight (w) – from 1 (low importance) to 4 (high importance). The w matrix is reported in Table 1.

The Stakeholders' Score (StS) is computed by multiplying p' and w matrices. According to this formulation, StS can only range between 0 (no influence by any stakeholder) and 10 (strong influence by specific stakeholders).

StS can be globally visualized via stoplight charts: green indicates the highest preferred solution (StS > 5) and red the less preferred solution (StS < 5) by one or more stakeholders.

Table 1. Permutations of weights (w) to compute Stakeholders' Score (StS) according to TEnSE approach from 1 (low importance) to 4 (high importance).

Domain (parameter)	Weights (w) for Stakeholders																							
	Technical expertise						Environmental expertise						Safety expertise						Economical expertise					
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*	*t*	*u*	*v*	*w*	*x*
Technical	4	4	4	4	4	4	1	1	2	2	3	3	1	1	2	2	3	3	1	1	2	2	3	3
Environmental	1	1	2	2	3	3	4	4	4	4	4	4	2	3	1	3	1	2	2	3	1	3	1	2
Safety (social issues)	2	3	1	3	1	2	2	3	1	3	1	2	4	4	4	4	4	4	3	2	3	1	2	1
Economic	3	2	3	1	2	1	3	2	3	1	2	1	3	2	3	1	2	1	4	4	4	4	4	4
Total	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**

3. Application to the most used thermal insulation materials

The TEnSE was here tested to objectively identify whether specific stakeholders have oriented the choice of the most used thermal insulation materials in Italy, Norway, and Portugal. These countries belong to the European Economic Area but significantly differ in terms of Energy Poverty (Ogut et al., 2023) as well as of environmental and legislative fields.

Following the three-step procedure of TEnSE, we identified the set of alternatives in the building market, i.e., the thermal insulation materials commonly used in the three countries, from the surveys conducted by market research for Norway and by the Erasmus Plus project OERCO2 (Open Educational Resource) for Italy and Portugal (Fig. 2). Then, we considered the following decision criteria for each TEnSE domain:

- T: thermal conductivity as the parameter to evaluate the thermal performance of the material because it is independent from the application thickness.

- En: amount of the equivalent carbon dioxide ($CO_{2,eq}$) emissions per 1 m^2 of the material in the cradle-to-gate approach to consider the Global Warming Potential (GWP) before its application in the retrofit.
- S: fire reaction according to EN 13501-1:2018 so to pay attention to the safeguard of the intervention and use (e.g., smoke release).
- E: price of the thermal insulation material per 1 m^2 (€ m^{-2}) per the whole thickness range to pay attention to the influence of the market on the selection of a thermal insulation material.

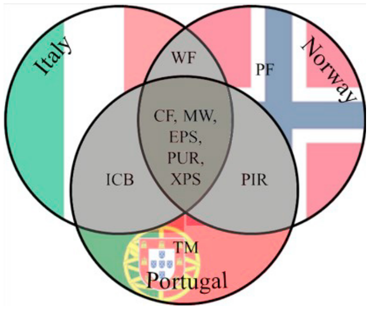

Fig. 2. Thermal insulation materials commonly used in Italy, Norway, and Portugal. CF = Cellulose fibre; ICB = Expanded cork agglomerate; WF = Wood fibre; MW = Mineral wool; TM = Thermal mortars; EPS = Expanded polystyrene; PF = Phenolic foam; PIR = Polyisocyanurate; PUR = Polyurethane foam; XPS = Extruded polystyrene.

After the extraction of data from the EPD and the national price lists reported in the footnotes of Table 2, it was applied the rule *"the lower the better"* for each parameter to compute the normalized matrix p' reported in Table 2.

Table 2. p' matrix on the most used thermal insulation materials in Italy, Norway, and Portugal, constructed on data retrieved from EPD (in footnotes) and national price lists.

Thermal insulation material based on EPDs	T	En	S	E		
				Italy	*Norway*	*Portugal*
Cellulose fibre (CF) (1)	0.24	0.05	0.8	0.85	n.a	0.62
Expanded cork agglomerate (ICB) (2)	0.08	1.00	0.2	0.71	0.00	0.35
Wood fibre (WF) (3)	0.32	0.11	0.2	0.89	0.90	0.61
Mineral wool (MW) (4)	0.52	0.03	1.0	0.44	0.90	0.37
Thermal mortars (TM) (5)*	0.00	0.00	1.0	0.65	1.00	0.00
Expanded polystyrene (EPS) (6)	0.28	0.00	0.2	0.41	0.96	1.00
Phenolic foam (PF) (7)	0.96	0.01	0.6	0.00	n.a	n.a
Polyisocyanurate (PIR) (8)**	0.88	0.03	0.8	0.24	0.77	0.77
Polyurethane foam (PUR) (9)	1.00	0.01	0.2	1.00	0.70	0.29
Extruded polystyrene (XPS) (10)	0.44	0.02	0.2	0.52	0.92	0.88

(1) CAPEM, (2) Amorim Cork Insulation, (3) IBU – Institut Bauen und Umwelt e.V., (4) KnaufInsulation, (5) DIASEN srl, (6) Finja, (7) Kingspan, (8) Europerfil, (9) Polyurethan dammt besser, (10) DANOSA
*Thermo-renderecological thermal and breathable, formulated with cork, natural hydraulic lime, clay and diatomaceous powders.
**Fire reaction of PIR varies according to additives (from B,s2-d0 to F). In this study, B,s2-d0 was considered as it was the most occurred. It is worth noticing that in this paper the criterion is related to safety of households, although it could be considered as a technical parameter.
Unit Cost Italy: https://prezziario.regione.veneto.it/, https://www.regione.lazio.it/cittadini/lavori-pubblici-infrastrutture/tariffa-prezzi-lavori-pubblici
Unit Cost Norway: https://www.xl-bygg.no/, https://www.obsbygg.no/, https://www.byggmakker.no/, https://www.kork24.no/shop/11-lyd-og-varme-kork-isolasjonsplater/, https://isotech.no/isokit/
Unit Cost Portugal: http://www.geradordeprecos.info/

Per each country, we computed the StS matrix by multiplying the w matrix (Table 1) with the p' matrix (Table 2). It is evident that there is not an evident underlying aspect behind the selection of thermal insulation materials in the three countries as the StS ranges between 2 and 7 (Fig. 3). In Norway and Portugal, the choice of PIR could be driven by the attention devoted to the low thermal conductivity and the high reaction to fire. The latter would play a key for

Norwegian experts in safety when it comes to retrofitting wooden dwellings that are very numerous in the country. In Italy, the selection of ICB could be driven by environmental experts and in less extent by economic experts, that could drive the preference towards a local raw material (Italy is the 5th cork producer in the world). Environment-oriented Portuguese stakeholders would influence the choice of ICB, as Portugal is the first producer of cork in the world. The main difference among countries is due to the E domain, although the global market is moderately competitive due to many suppliers in the building sector.

Thermal insulation materials		Technical expertise						Environmental expertise						Safety expertise						Economic expertise					
		a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**
Italy	CF	5	5	4	4	4	4	5	5	4	4	3	3	6	5	6	5	6	5	6	5	6	5	6	5
Italy	ICB	4	3	5	4	5	4	7	6	6	5	6	5	5	5	4	5	3	4	6	6	5	6	4	5
Italy	WF	4	4	4	3	4	3	4	3	4	3	3	3	4	3	4	3	4	3	5	5	5	5	5	5
Italy	MW	5	6	4	6	4	5	4	5	3	5	4	4	6	5	6	6	6	6	5	4	6	4	5	4
Italy	TM	4	4	3	4	2	3	4	4	3	4	2	3	6	5	6	5	5	5	6	5	6	4	5	4
Italy	EPS	3	3	3	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	3	2	3	2	3	3
Italy	PF	5	6	4	6	4	5	2	3	3	4	4	4	3	3	4	4	5	5	3	2	4	3	4	4
Italy	PIR	6	6	5	6	5	5	3	4	3	5	4	5	5	5	6	5	6	6	4	4	5	4	5	4
Italy	PUR	7	7	7	6	6	5	4	4	5	4	5	4	5	4	6	4	6	5	6	5	7	6	7	7
Italy	XPS	4	3	4	3	3	3	2	2	3	2	3	2	3	2	3	2	3	3	3	3	4	3	4	4
		a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**
Norway	CF																								
Norway	ICB	2	2	3	3	4	4	4	5	4	5	4	5	3	4	2	4	2	3	3	3	2	3	2	2
Norway	WF	5	4	4	3	4	3	4	3	4	3	3	3	4	3	4	3	4	3	5	5	5	5	5	5
Norway	MW	7	7	6	6	5	5	5	5	5	5	4	5	7	6	8	6	7	7	7	6	8	6	7	6
Norway	TM	5	5	4	4	3	3	5	5	4	4	3	3	7	6	7	5	6	5	7	6	7	5	6	5
Norway	EPS	4	4	4	3	3	2	4	3	4	2	3	2	4	3	4	2	4	3	5	5	5	5	5	5
Norway	PF																								
Norway	PIR	7	7	7	7	6	6	5	5	5	5	5	5	6	6	7	6	7	7	6	6	7	6	7	7
Norway	PUR	7	6	6	5	6	5	4	3	4	3	5	4	4	3	5	4	5	5	4	4	5	5	6	6
Norway	XPS	5	4	5	3	4	3	4	3	4	2	3	3	4	3	4	3	4	3	5	5	5	5	5	5
		a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**
Portugal	CF	4	5	4	4	3	3	4	4	3	4	3	3	5	5	6	4	5	5	5	4	5	4	5	4
Portugal	ICB	3	3	4	3	4	4	6	5	5	5	5	5	4	5	3	4	3	3	4	5	3	5	3	4
Portugal	WF	4	3	4	3	3	3	3	3	3	2	3	2	3	3	3	2	3	3	4	3	4	4	4	4
Portugal	MW	5	6	4	6	4	5	4	4	3	5	3	4	6	5	6	6	6	6	5	4	6	4	5	4
Portugal	TM	2	3	1	3	1	2	2	3	1	3	1	2	4	4	4	4	4	4	3	2	3	1	2	1
Portugal	EPS	5	4	4	3	3	3	4	3	4	2	3	2	4	3	4	2	4	3	5	5	5	5	5	5
Portugal	PF																								
Portugal	PIR	7	7	7	7	6	6	5	5	5	5	5	5	6	6	7	6	7	7	6	6	7	6	7	7
Portugal	PUR	5	5	5	5	5	5	2	2	3	3	4	4	3	2	4	3	4	4	3	3	4	3	5	4
Portugal	XPS	5	4	5	3	4	3	4	3	4	2	3	3	4	3	4	3	4	3	5	4	5	5	5	5

Fig. 3. Stoplight charts of Stakeholders' Score (StS) where the influence in the selection of each thermal insulation material is rated as low (red), neutral (white) or high (green). Grey areas indicate thermal insulation materials where E domain is missing (Table 2).

4. Conclusion

The TEnSE approach lays its foundation upon the fact that when we make a decision, our expertise and experience affect that decision. The TENSE first gives the idea that the optimal solution should cover higher expectations for a high number of stakeholders and should not be focus on only one perspective. One of the limitations of the TEnSE is the dependency on environmental product declarations and price lists that can be specific of an area. Notwithstanding the TEnSE approach has the potential to become more than a products' score tool. In fact, experts in social sciences and climate and energy policies, analyzing the TEnSE scores in specific countries could depict the decisional patterns of public, private, and people when dealing with the selection of thermal insulation materials. In addition, from the scores analysis they could gain targeted feedback to enhance 1) the social awareness and social acceptability of greener and more sustainable thermal insulation solution; and 2) to fill the existing gaps in the legislation or in the guidelines, in a way that the next directives will be closer to the real understanding and needs of citizens. These TEnSE hidden potentialities have the capability of influencing the two missing domains, i.e., the social and the legislative/political. Since the TEnSE approach has exhibited significant promise, could yield valuable insights in various contexts.

Further research will be developed to understand the relationship of the stakeholder's score with the climate and legislative contexts of specific geographical areas. Indeed, it would allow to understand how the role of stakeholders can affect the development and implementation of solutions in areas that will be differently impacted by the ongoing climate change.

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Waste-based materials in residential house construction

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Abstract

Waste from the construction sector has been increasing considerably in recent years, making it urgent to find alternatives to this waste that will enable us to preserve the environment and ecosystems. Many studies demonstrate the viability of using this and other waste in the construction sector, such as wood, ashes, and plastics. This article presents a review of research works where residual materials have been applied in the construction sector. To achieve this objective, a total of 35 articles were reviewed, published in English-speaking journals between 2015 and 2023. This review shows that, although in recent years efforts have been made for the application of waste materials in the construction sector has been significant, however, there is still work to be done in the study of the behavior of these residual materials, such as the emission of greenhouse gases, as well as the importance of residual materials pretreatment to ensure compatibility with the rest of the components. Another important aspect is that most studies consider environmental aspects without taking into account social and economic issues surrounding them in the construction sector.

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Keywords: Waste; construction materials; energy efficiency; environmental impact

1. Introduction

Construction and demolition waste (C&D) is the largest waste stream in the EU, according to European data (European Commission, 2018), with C&D waste accounting for around a third of all waste generated in the EU.

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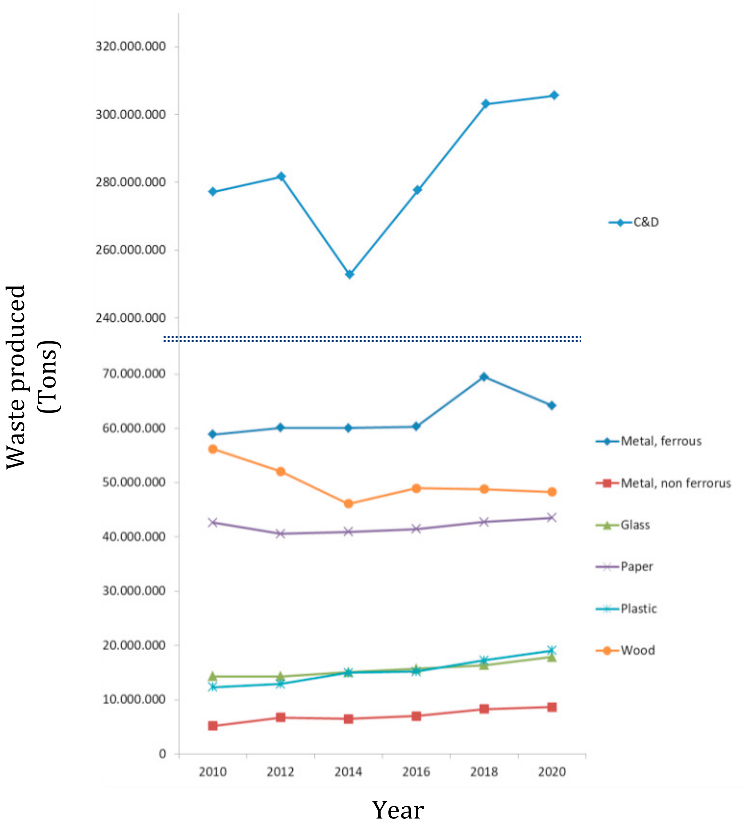
Throughout the life of one European citizen, around 160 tons of C&D waste can be generated. The Waste Framework Directive (EU) 2018/851 had the aim of recycling 70% of C&D waste by 2020. However, most member states only recycle around 50% of C&D waste. Figure 1 shows the waste tons produced in the EU from 2010 to 2020 and the increase in waste generation in recent years, with construction and demolition waste being by far the largest generator.

The lack of confidence in the quality of the waste materials and the lack of knowledge about the potential health risks are the main barriers to improving the rates of recycling and reuse of C&D waste. This lack of trust decreases demand for C&D wastes recycled, which slows down the development of C&D waste management and recycling infrastructure in the EU (European Commission, 2012). For that reason, in 2016, the European Commission presented the EU Construction and Demolition Waste Protocol (European Commission, 2016).



ɔstat, 2023).

Fig. 1. Evolution of waste production in the European Union from 2010 to 2020 (Eurostat, 2023).

The Construction and Demolition Waste Protocol is part of the EU Construction Waste Management Strategy 2020 (COM (2012) 433) (European Commission, 2012) in addition to the Communication on Resource Efficiency Opportunities in the Construction Sector (COM (2014) 445) (European Commission, 2014). This protocol is also part of the Circular Economy Package adopted by the European Commission in March 2020 (COM (2020) 98 final) (European Commission, 2020). The main goal of the Circular Economy Package is to encourage sustainable products in those sectors that need raw materials and have a high potential for waste recirculation, as in the case of the construction sector. The aim of the package is to decrease the use of energy and non-renewable resources, reuse construction components or products as much as possible, reinforce the restoration of old buildings and reuse components whenever possible (Wang, 2018). Those are the main reasons behind Green Building. Green Building refers to buildings whose structure and orientation use less energy or even reuse water. Green Building also entails the use of environmentally friendly materials and resource-efficient processes throughout the entire life cycle of a building:

from the design of the building, through the extraction and transportation of raw materials, the construction stage, the use and maintenance stage of the building, the renovation, and the final demolition to recycling waste.

Taking into account the initiatives proposed by the European Commission and considering the initiatives for a circular economy in the construction sector, some research efforts have focused on studying how the addition of different kinds of waste, such as construction waste, industrial waste, and agricultural waste, affects construction materials and the structural properties of buildings. This alternative can add value to waste by returning it to the production chain without causing human or environmental damage. Recent studies have shown that the addition of waste to construction materials can improve mechanical and thermal properties and reduce environmental impacts (Guo, 2018), as is the case with the addition of ashes resulting from a biomass combustion process in the manufacture of conventional bricks (Sutcu, 2019; Muñoz 2021), the addition of paper pulp waste (Muñoz, 2020) and the use of iron ore tailings in the construction of clay bricks (Mendes, 2019). These studies have demonstrated the technical and environmental feasibility of incorporating different waste into main components for the production of material construction. In addition, the material obtained is inert and non-hazardous. Another study used wheat straw waste, sunflower seed cake, and olive stone flour to produce bricks (Bories et al., 2015). During the last decade, some research demonstrated that incorporating waste in the construction materials increases porosity, water absorption and thermal insulation and is correlated with a decrease in bulk density and flexural strength. Moreover, these studies demonstrated the technological and environmental advantages of reusing this type of waste. The research also point out that this alternative leads to reduced costs due to the use of waste to replace clay and reduced transport costs due to the production of lighter products.

For the reason briefly introduced in this section, the main purpose of this research is to analyze the current state of the use of residual materials in the construction sector. Particularly, we aim to answer the following questions.

- What is the current trend in the use of waste materials in the construction sector?
- What are the recent issues that we must face in construction waste material?

In order to answer these questions, the information has been collected from the scientific literature and a description of the main residual materials used has been analysed. In addition, a description has been carried out of the current trends in waste materials in construction and the recent problems that we must face to promote the use of these waste materials and promote the circular economy in this sector. After this brief Introduction (1), we present our concept and methodological description of the analysis of the reference bibliography (2). The results of the bibliographic review are presented in Chapter 3, where the questions raised at the beginning are answered. Chapter 4 offers the final conclusions.

2. Materials and methods

The methodology used to carry out this study has focused on 4 steps (Fig 2), following the methodology proposed by Rowley et al (2004): (1) Formulate the questions that are the objective of the article. (2) Select the relevant articles in the study. (3) Analyze the information provided by the selected articles. (4) Evaluate the scientific articles analyzed and answer the questions initially posed.

Step 1: Questions formulation. This review article focuses on answering the questions previously asked.

Step 2: Find relevant references in this field of research. To analyse the most relevant paper, the ScienceDirect and Web of Science databases were used as an electronic database through a search structured by keywords. The keywords of the research were: sustainable construction, construction and demolition waste, sustainable raw materials, green buildings. A period of time from 2015 to 2023 has been considered. A total of 280 papers were found under these premises.

Step 3: Analyse the information provided by selected articles. Of all the selected articles, those articles that do not use residual materials or that do not consider sustainable construction materials were discarded. A total of 35 articles were reviewed to achieve the purpose of the paper.

Step 4: Evaluation and response the questions proposed. This step includes the analysis and synthesis of each study included in this review article. The results are discussed in the following section 4 of this article and answer the research question previously formulated in step 1.

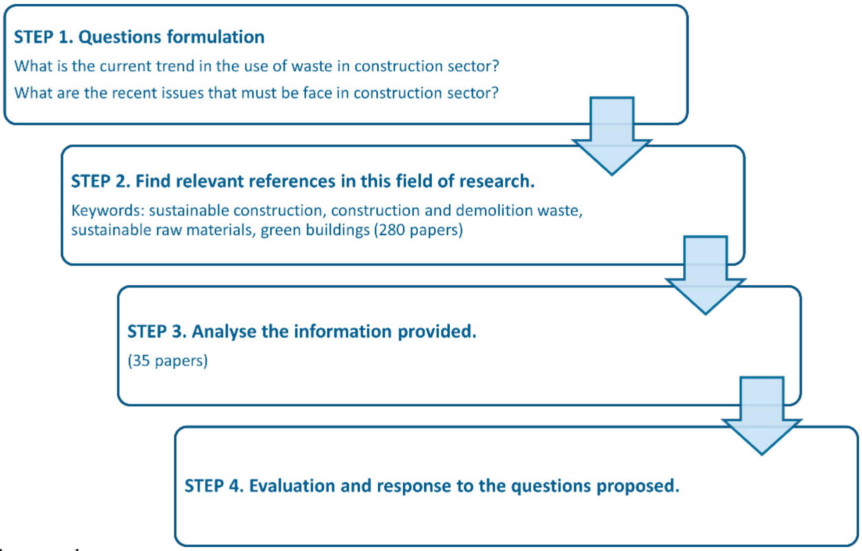


Fig. 2. Methodology used to accomplish the results.

3. Results

This section shows the main results obtained from the review carried out. This section has been divided into 3 sections as shown as follows:

3.1. Current status of construction waste classification

Rubble, concrete, steel, and wood are some examples of wastes generated in the construction sector. It is important to consider that waste is the worst problem in the construction sector and has significant implications for energy efficiency and a negative environmental impact. Construction and demolition waste are generated during the stages of building construction, maintenance, and final demolition. This waste is assorted and includes brick, concrete, cement, glass, wood, and plastics. Some construction wastes are dangerous because they generate leaching, which can impact the environment or even generate toxic substances during the degradation process and which might be dangerous to human beings. Therefore, it is crucial to properly manage this waste (heavy metals, paints, solvents, and asbestos) (Barbuta, 2015). The primary wastes from construction and demolition are listed below:

- Mineral waste: During the extraction process of raw materials and the production stage of construction materials, significant amounts of mineral waste are generated. Such waste includes granite, marble, and limestone. Using these residues could mitigate the negative impacts on the environment and offer significant energy savings (Barbuta, 2015).

- Inert waste: Harmless inorganic waste is a common waste of the construction sector. Harmless waste is not chemically or biologically reactive and does not break down over time. Among the inert waste, we can find sand, plaster, concrete, and cement, among other types (Barbuta, 2015). Reuse of this waste allows significant economic savings, energy savings and reduced environmental impacts.

- Wood waste: Wood is one of the construction materials that has the greatest potential for recycling since it is used in many construction elements as well as doors, windows, boards and so on (Cetiner, 2018; Berger, 2020).

- Plastic waste: Currently, plastic material is an essential waste category where most of it can be reused. Different types of plastics are used to produce concrete, such as polypropylene, polyethylene, polyvinyl alcohol, polyvinyl chloride, nylon, aramid and polyesters. One of the most frequently used plastics is polyethylene terephthalate (PET), since it is used for food packaging. The disposal of these types of waste creates serious problems for the environment (Ahmed, 2023). Some PET waste is recycled as short fibre reinforcement in structural concrete, synthetic coarse aggregate for lightweight concrete, or resin for polymer concrete (Kim, 2010). Plastic manufacturers also produce plastic waste as rejected raw material, which can be recycled to produce building materials (Zelinskaya, 2019).

- Steel: This material can be reused and transformed into other products or used as scrap. To reduce pollution from its production, researchers have replaced part of the cement and natural aggregate content with industrial by-products such as steel slag, ferronickel slag, copper tailings, and copper slag (Kurniati, 2023).

- Glass: Glass recovered as waste can be melted down as fibreglass for reuse. Recycled glass is a good option as a component based on construction materials. Numerous research works show the potential of recycled glass to be used as a substitute for aggregates and/or cement (Mohajerani, 2015; Lu, 2019; Sandanaya, 2020).

- Hazardous waste: The sources of hazardous waste include fuels, paints, silicone and sealing products, battery oils and lubricants, antifreeze, adhesives, strippers and solvents, and wood treated with toxic products. These residues require a specific management process to avoid environmental contamination and health risks.

3.2. Current trends in construction waste materials

In recent years, waste from different sectors has been used to reduce costs. Such waste can be classified as follows (Barbuta, 2015):

- By-product waste is that waste that is generated as a consequence of industrial processes. This classification includes grinding slag, fly ash, silica fume, metals, glass and recycled aggregates. These wastes are mixed with cement to reduce the extraction of minerals from the soil and, in turn, reduce atmospheric pollution (Wang, 2018). Fly ash is waste from power plants or from various solid material incineration processes. Fly ash from municipal solid waste incineration (MSWI) can be used as raw material in sintering and cement preparation (Guo, 2014). Other studies demonstrate that the use of ashes from biomass combustion in the manufacture of bricks shows similar mechanical behaviour to conventional brick. In addition, the use of these residues in construction materials yields a savings of 5% in the carbon footprint and 4% of energy consumption (Muñoz, 2021).

- Natural fibres: Natural fibres are forestry products that are usually classified as waste. They are environmentally friendly, low-cost materials. Among them, we can find curauá fibre (*Ananas erectifolius*) (Bilcati, 2018), piasava fibre (*Attalea funifera*) (Nunes, 2016) and hibiscus fibre (Moses, 2015), which have good properties as reinforcement in various cement mortars. The presence of these natural fibres in cement has been shown to improve tensile and flexural strength, reducing the development of microcracks and improving the internal effects of the cement (Wang, 2018).

- Waste water sewage sludge: The progressive increase of this type of waste poses a difficult waste management problem. One of the solutions to the ongoing increase of this waste is its employment in the construction sector. Using sewage sludge in construction materials eliminates some of the costly and energy-intensive utilization steps. In addition, the final product obtained is typically stable and safe (Swierczek, 2018). The sludge and ashes from the burning of the sludge can be used to produce ceramic products such as tiles, bricks, and pavement. Investigations have been undertaken in this field (Orlov, 2020; Wolff, 2015).

- Paper industry sludge: The paper industry has paper sludge as a by-product, which has a high calcium carbonate content, organic matter and other minerals. Due to its pozzolanic activity, paper sludge can be used with cement mortars, concrete, and ceramics in the construction industry (Cusido, 2015; Vashistha, 2019; Mymrin, 2020).

- Agricultural waste: Agricultural wastes such as cork, straw, cellulose, coconut fibre or cotton are often used as building insulating material. Using these materials in the construction sector decreases the environmental impact (Massoudinejad, 2019). In addition, they contain large amounts of CO_2 captured from the air, so their use in buildings contributes to reducing CO_2 emissions in the atmosphere (Bozsaky, 2019). Certain agricultural residues, such as rice husks, banana leaf ashes, bamboo leaves or bagasse ashes, present pozzolanic activity, which is why they are used in the manufacture of high-resistance concrete (Barbuta, 2015; Tiza, 2021; Dhiman, 2022).

3.3. Recent issues in construction waste material

Currently, the main waste materials recycled in the construction sector are ash and cement waste since they have demonstrated good structural properties and pozzolanic activity and are compatible with traditional materials (He, 2021). These materials have shown good structural properties that enable reduction in the use of raw materials, a reduction in residual materials, and a reduction in CO_2 emissions in the cement production process, thus mitigating environmental impacts throughout the life cycle of the building. However, some authors have shown that cement adsorbs CO_2 during its life cycle so that during the use stage of the building, the use of cement reduces the amount of CO2 in the atmosphere. For this reason, it is necessary to study CO_2 absorption during the use stage of the building and see if a balance is achieved between the CO_2 emission during the production process and the CO_2 absorption during the use stage of the building. Moreover, some researchers have shown that the incorporation of ashes increases CO_2 emissions due to the decomposition of carbonates and water consumption, which highly affects the ecosystems (Muñoz, 2023).

As explained above, plastic waste has been studied for its use in construction materials for a long time; for some years, this waste material has been a top priority due to the large amount of plastic waste that is generated, and it is increasing, as can be seen in Figure 1. For this reason, managing this waste is essential to safeguarding and restoring the environment. Recent studies have analysed the viability of using plastic waste in cement (Sandanaya, 2020; Tawab, 2020; Qi, 2023), and among polyethylene terephthalate (PET) is used the most because it is widespread used to produce water bottles and food. On the other hand, as recently indicated by Kazemi et al. (2021), most studies conducted on construction materials have not taken into account the importance of pre-treating waste polymeric materials to ensure their compatibility with construction materials. Consequently, there is a critical need to understand the science of polymer functionalization in order to adjust the surface properties of recycled granules for specific applications.

Wood scraps are another type of waste that is widely used today in the construction sector. Wood waste can be found in different shapes, including offcuts, shavings, sawdust, slabs and bars. However, these wastes also contain other types of materials such as nails, hinges, and anchors for structures. Wood chips, including fragments, can vary in size and may cause health risks. In addition, wood waste can be irregular in shape and is not always suitable for reuse. For these reasons, the collection, transport and storage of wood waste takes up a large volume due to the irregularity and lack of uniformity in the shape and structure of wood waste, which makes the management process of this type of waste more expensive and difficult. Another major issue related to wood waste management is preservative-treated wood in the waste stream, which is hazardous and requires a separate management process for recovery. This hazardous waste makes the classification and recycling more difficult (Jahan, 2022).

Most of the studies found in the literature perform a life cycle analysis that considers only the environmental aspect. Furthermore, most studies consider greenhouse gas emissions but do not consider the rest of the environmental impacts, such as the extraction of raw materials, water pollution, etc. The economic and social aspects should also be considered to provide a more complete and realistic perspective. Each dimension must be analysed when developing or improving a product or process to meet sustainability criteria. LCSA supports the identification of trade-offs between dimensions and enables better decision-making in policy and industry. Moreover, some researchers argue in their studies that the use of waste materials sometimes generates additional costs due to waste management, availability and transportation, as well as complex treatment processes. Therefore, studies must expand the optimisation of these processes to balance the environmental benefits and cost reduction of these materials (Sandanaya, 2020).

4. Conclusions

This paper presented a review of the published scientific literature related to the application of residual materials in the construction sector. Through the analysis of 280 research papers published during the period 2015 and 2023 the main trends in the construction sector and the main issues that must be addressed to promote the circular economy and increase the use of residual raw materials were identified. A total of 35 articles were analysed to achieve the purpose of the paper and answer the questions initially posed. On the other hand, researchers must continue analysing waste materials in the construction and evaluating with the aim of decreasing in a near future the use of raw materials, decreasing the generation of waste and promoting the circular economy in the construction sector. Furthermore, it is important to take into account the environmental impacts but also the economic and social impacts surrounding them in the construction sector.

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