Resilient and adaptive renovation of 20th century buildings towards net-zero carbon built heritage – The approach of the SINCERE research project

E. Tziviloglou[1][0000-0002-2935-9629], C. Stentoumis[2][0000-0001-9972-1761], J. I. Alvarez[3][0000-0001-9170-7404], E. Stathopoulos[4][0000-0003-3713-5833], S. Diplaris[4][0000-0002-9969-6436], A. Sfetsos[1][0000-0003-1906-8059], D. Vlachogiannis[1][0000-0001-8287-5123] and I. Karatasios[1][0000-0002-3482-0424]

[1] National Centre for Scientific Research " Demokritos", Institute of Nanoscience and Nanotechnology, 15341, Athens, Greece
[2] up2metric, 115 21, Athens, Greece
[3] University of Navarra, Pamplona 31008, Spain
[4] Centre for Research and Technology Hellas, 57001, Thessaloniki, Greece

Abstract. In contemporary European urban landscapes, the presence of 19th and 20th-century modern period architecture stands as a defining characteristic, contributing significantly to EU Built Heritage. These structures serve as substantial reflections of local and national identity. However, despite their historical significance, many of these buildings present considerable challenges in terms of energy efficiency, particularly in heating and cooling systems. Addressing this issue is crucial for preserving their cultural value while aligning with contemporary sustainability goals. The SINCERE project endeavors to explore the intrinsic worth of Built Heritage while offering practical solutions to improve energy performance and reduce the carbon footprint of historic buildings. Through the integration of innovative restoration materials, energy-efficient technologies, ICT tools, and socially innovative approaches, SINCERE aims to facilitate the transition of these structures towards net-zero carbon emissions. Adopting a holistic approach, the project encompasses various scales, from individual building components to entire cityscapes, considering factors such as structural integrity, architectural uniqueness, and local environmental conditions. Additionally, SINCERE aims to empower stakeholders with innovative solutions covering the entire lifecycle of buildings, from restoration to maintenance. By providing sustainable restoration options and raising awareness through outreach, the project fosters a culture of preservation within European communities, securing the legacy of Cultural Heritage for future generations.

Keywords: built heritage, structural and thermal retrofitting, extended reality, digital twins

1 Introduction

Built Heritage holds unique cultural, social, environmental, and economic value, playing a vital role in preserving history and culture while offering opportunities for climate action and resilience, as highlighted by initiatives like the EU's "Green Deal." Climate Change (CC) poses significant challenges globally, impacting environments, societies, and economies. To ensure the transmission of Cultural Heritage (CH) to future generations, it is crucial to develop tools and technologies to protect Built Heritage from CC risks and align its preservation with the Sustainable Development Goals (SDGs) outlined in the UN's "2030 Agenda for Sustainable Development." Renovating 19th and 20th-century buildings using resilient and adaptive technologies contributes to reducing greenhouse gas (GHG) emissions, conserving EU heritage, and promoting economic growth, social well-being, and environmental preservation in cities, in line with circular economy principles.

SINCERE is European collaborative research project which aims to explore the significance of built CH values while offering strategies to reduce the carbon footprint and enhance energy efficiency in historic structures, aligning with the goals of achieving net-zero carbon buildings. This is achieved through the adoption of innovative, sustainable, and economically viable restoration materials and methods, alongside energy harvesting technologies, ICT tools, and socially innovative approaches.

Employing a multi-scale approach (Fig. 1), SINCERE addresses various levels, from material to city-scale, focusing on the structural elements, external envelope, and transparent components of buildings. These interventions are staggered over different timeframes to furnish decision-making support to stakeholders involved in the process. Consideration is given to the entire lifecycle of buildings, encompassing restoration, operation, monitoring, and maintenance phases.

Energy performance enhancements, tailored to the unique characteristics of each building including its structural, architectural, functional, and material attributes, are optimized with respect to local environmental conditions and anticipated future climate changes. SINCERE offers a range of sustainable restoration options, evaluated using Building Information Modeling (BIM) and Digital Twin (DT) tools tailored for historical buildings, facilitating the selection of optimal solutions and the planning of necessary adaptation measures.

Lastly, SINCERE prioritizes public awareness and engagement, aiming to empower Europeans to advocate for the preservation of Cultural Heritage buildings. This is accomplished through the dissemination of scientific findings via cultural activities at both national and international levels.

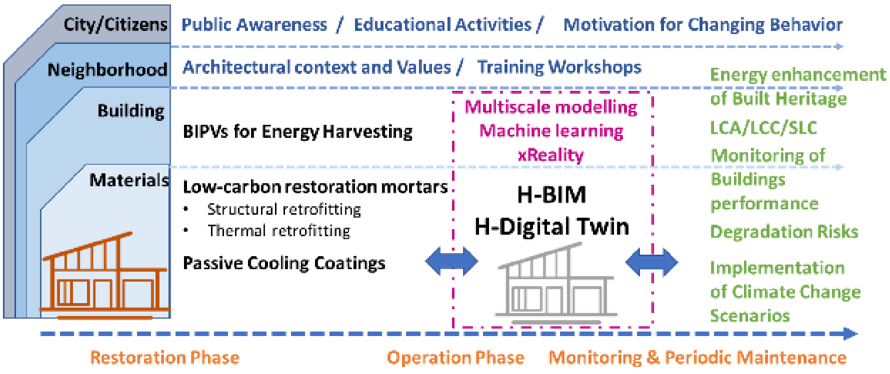


Fig. 1. Different scales and actions towards net-zero energy buildings.

2 Project objectives

The SINCERE project aims to achieve seven distinct research, technological, and societal objectives (OBJ) as presented below, each of which corresponds to key outcomes within the project framework. In line with these objectives, the project encapsulates its core strategies and methodologies that are applied in four pilot cases across Europe (Madrid-ES, Rhodes-GR, Ostrava-CZ, Holon-IL)

OBJ-01: Transform CH buildings to a key actor and main stage for raising stakeholders' and citizens' awareness on renovation/reuse concept, as a circular economy element to tackle climate change.

OBJ-02: Development of a smart interoperable platform integrating Historic BIM (H-BIM) / Historic DT (H-DT) and immersive XR technologies to provide the digital tools for sustainable renovation and retrofitting of CH buildings.

OBJ-03: Reduction of environmental impact during restoration and maintenance, by developing low-energy and low-carbon restoration mortars, with enhanced compatibility and service life.

OBJ-04: Reduction of energy demands during operation of the restored CH buildings due to enhancement of building thermal performance and enhancement of the service life of repair mortars and of heritage building.

OBJ-05: Enabling solar energy harvesting during building operation, with green, low-cost, large area fully sustainable building integrated photovoltaics (BIPVs).

OBJ-06: Understanding the multi-scale and multi-physics behaviour of high-performance repair mortars and developing fast-running numerical design tools to achieve whole-life carbon savings.

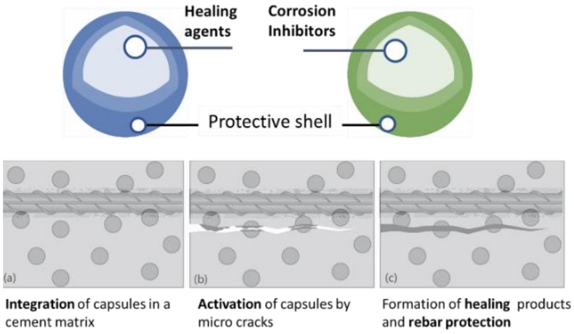
OBJ-07: Validation of SINCERE technologies at 4 demonstration sites - Pilots, in Spain, Greece, Israel and Czech Republic, and assessment of societal, economic, and scientific impact.

3 Methodology

In framing the methodology for the research and development of innovative technologies, inspiration is drawn from the Getty Conservation Principles for Concrete of Cultural Significance and the Cádiz Document InnovaConcrete Guidelines for the Conservation of Concrete Heritage. Emphasizing holistic approaches, this methodology aims at modernizing upgrades to CH concrete buildings while preserving their historical significance, enhancing performance, and ensuring sustained durability.

3.1 Incorporation of advanced functionalities in low-carbon structural retrofitting cementitious composites

Novel low-carbon and low-embodied energy binders that have been produced at lower temperature than OPC and incorporate high amounts of Supplementary Cementitious Materials (SCMs) are studied for use in structural retrofitting cementitious composites, ensuring compatibility with historic concrete. The feasibility and effectiveness of incorporating functionalities such as self-healing [1] and reinforcement protection into structural retrofitting materials (Fig. 2) are evaluated. Advanced cementitious composites for structural retrofitting, including Textile Reinforced Mortars (TRM) [2] and fiber-reinforced high-performance concrete (UHPFRC) [3], are be produced on different scales. The performance of these mixes is evaluated according to EN standards, with particular focus on tensile and bending behavior, crack development, and monitoring using digital imaging and non-destructive tests. Long-term durability is assessed through experimental and numerical modeling approaches, feeding into life cycle assessments and H-DT models.



Integration of capsules in a cement matrix

Activation of capsules by micro cracks

Formation of **healing** products and **rebar protection**

Fig. 2. Encapsulated healing agents and corrosion inhibitors for elongating the lifespan of repair interventions.

3.2 Development of low-carbon thermal retrofitting mortars

SINCERE focuses on the production, characterization, and assessment of low-carbon mortars with enhanced thermal properties. Two types of repair mortars are developed: one incorporating microencapsulated Phase Change Materials (PCMs) [4], and the other integrating sustainable insulating materials. PCMs with inorganic shells compatible with restoration mortars and those made from natural and sustainable materials are considered. The phase change temperatures are chosen according to different climates and regions in which to apply the mortars obtained. The phase change temperature, heat enthalpy, particle size distribution, and compatibility with mortar matrix is evaluated. Optimal shell composition for microcapsules will be determined, along with the incorporation rate of PCMs and their performance in terms of fresh state, compatibility, and durability. Additionally, the chemical and phase compositions of hemp-based mortars [5] is be characterized, along with mechanical properties, thermal conductivity, water resistance and durability performance. resistance. Thermal properties of hardened mortars are assessed through differential scanning calorimetry, thermal conductivity measurements, and infrared thermography under various conditions. Real application simulations with hot-box models that allow the dynamic study of heat transfer are also used in their characterization [6].

3.3 Development and upscaling radiative cooling paints and membranes

A rational design approach guides the integration of various physical mechanisms in SINCERE systems. Porosity and nano-/micro-particles, including phase change materials (PCMs), are utilized to enhance solar reflectance, adjust surface wettability, optimize heat emission, and reinforce mechanical robustness and UV resistance. Controlled porosity plays a crucial role, enabling efficient light scattering for solar reflectance and enhancing heat emission through multiple scattering of Mid-Infrared (MIR) radiation. Additionally, pores can facilitate the creation of super-hydrophobic or self-cleaning surfaces like slippery liquid-infused surfaces (SLIPS).

Nano-/micro-particles augment the properties of the polymer host, offering hardness modification, UV resistance, light scattering for reflectance, and enhancement of heat emission in the MIR window. PCMs, when incorporated, enable the creation of novel radiative cooling composites [6].

3.4 Development of solar energy harvesting BIPVs

In SINCERE, halide perovskite solar cells [7] are integrated into building surfaces (windows and facades) for efficient, low-cost energy harvesting with zero carbon emissions. The flexible and color-tunable properties of halide perovskites make them ideal for BIPVs, particularly on vertical facades. Perovskite cell color can be adjusted by varying thickness and composition, while transparency is controlled by the perovskite layer's thickness during fabrication. To ensure high efficiency and stability, focus will be on 3D formamidinium-rich absorbers and lead-free perovskites. Energy alignment between perovskites and charge transport layers are optimized for efficient charge extraction, with attention to device physics to minimize voltage and current losses.

3.5 Computational multiphysics-multiscale material modelling in CH and integration in LCA/LCC/SLCA

SINCERE's development of materials and technologies is complemented by the formulation, implementation, and validation of multiscale modeling and design techniques. Computational tools will accurately quantify the carbon footprint of these materials, facilitating comparison with conventional counterparts and informing a Durability Based Design approach. This approach integrates data on material composition, embodied energy, waste, and durability improvement over the entire life cycle. Economic impacts are evaluated, comparing total costs incurred across the life cycle of materials and components with those of conventional products [8]. Environmental and social impacts are also assessed through life cycle approaches, considering factors such as environmental life cycle costing and social life cycle assessment according to UNEP/SETAC guidelines. The ultimate goal is to implement strategies for sustainable improvement, using numerical simulations and laboratory tests to train AI algorithms and support materials design processes. These results will also inform evolutionary damage risk assessment through H-BIM and H-DT, validated against monitoring data from pilot demonstrators.

3.6 Immersive technologies and digital twinning in heritage buildings' lifecycle management

Immersive technologies, and in particular mixed reality (MR) and virtual reality, are gradually changing the way people interact with machines and digital information and SINCERE brings these technologies to the lifecycle management of built heritage. In

SINCERE, a location-based indoor MR application is developed for mobile phones (Fig. 3), as well as a virtual reality application. The MR application takes advantage of recent advances in computer vision AI to automatically understand the scene around a user in a building by means of automatic object detection, classification, segmentation, and 3D reconstruction to facilitate operation and maintenance field tasks. The mixed reality and virtual reality applications are the advanced interface of the historical digital twin platform that form the basis of all static and real-time information and content organization and the predictive models for material degradation, energy consumption, and climate changes bridging the physical and digital building. SINCERE proposes a DT framework to optimise energy performance of heritage buildings and assess and improve buildings' lifecycle management by providing predictive analytics and insights for energy consumption, structural durability patterns, and materials service life. The H-DT developed in SINCERE exploit a historical BIM (of suitable level of development – LOD) as a spatial reference and backbone of the visual DT. The BIM model is made and regularly updated by multi-sensor reality capturing. DT leverage advanced analytics and simulation techniques to evaluate the effectiveness of different restoration options; by simulating various scenarios one can identify the most cost-effective and durable solutions for energy optimization and structural longevity thus providing decision-making tools involved in the restoration process. Various key parameters are considered such as energy consumption patterns, building structural characteristics, environmental conditions, occupancy and usage patterns, technological solutions, cost considerations and predictive modeling [9-11].

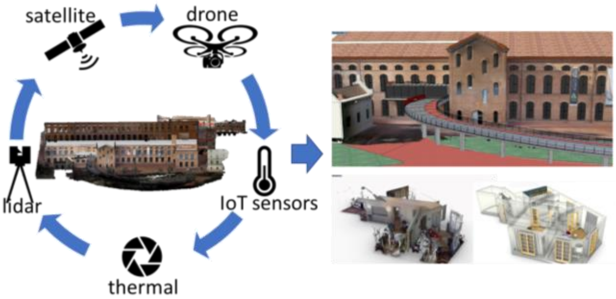


Fig. 3. Multimodal recording of built heritage.

3.7 Climatic models/scenarios, Risk assessment and future projections validated by historic data

In SINCERE, advanced climate modeling techniques generate high-resolution projections for CH sites using CMIP6 SSP scenarios [12]. Employing statistical downscaling and ML/AI, uncertainties are minimized, and extreme event scenarios are predicted accurately. A unique aspect is the focus on compound climate events, enhancing understanding of complex factors impacting site degradation. Stakeholders participate in selecting CH degradation modes. Impact models, validated with historical data and IoT sensors, inform customized risk assessments [13]. SINCERE integrates climate projections with impact models, providing early warnings via the project's H-DT.

4 Project outcomes and impact

SINCERE materials and technologies are tailored to address the specific needs outlined below, aligning closely with the project outcomes for Built Heritage as identified by relevant authorities and industry professionals in the CH sector.

Enhanced availability and performance of solutions for reliable and respectful historical renovation of heritage buildings, preserving architectural and cultural identity. SINCERE addresses this need by providing several innovative and sustainable materials and digital tools for respectful retrofitting of Built CH, from material to city levels.

Sustainable, energy and resource-efficient historical renovation of heritage buildings by:

- implementing novel types of low-carbon cements, including encapsulated admixtures for self-healing and protection of rebar reinforcement in historic concrete,
- developing low-carbon restoration mortars for latent heat storage and insulation,
- reducing the embodied carbon in the finished products and extending service life of green repair mortars, following LCA/SLCA-centered building approach, and
- developing an IoT platform for multiple data collection and interpretation and one H-BIM/ H-DT tool for automated analysis and simulation processes.

Protection of the value and long-term inclusiveness, accessibility, and usability of cultural heritage sites by:

- supporting the concept of adaptive reuse and rehabilitation of existing CH buildings,
- promoting the Preservation of Built Heritage via novel ICT and green materials, SINCERE contributes to the inclusive and sustainable ways of living described in the New European Bauhaus.
- proposing multi-functional materials that could provide new criteria for modifying the legal or regulatory constraints for conserving and managing 20th century listed buildings and thus maximizing the economic and societal benefits for EU citizens.

Cost-effective and **less disruptive modernisation** and **preservation of** the **Built Heritage** environment by:

- using low-carbon retrofitting materials compatible with the historic substrate,
- enabling energy savings during production of restoration materials,
- using transparent BIPVs, supporting at the same time the efficient energy production for adaptive modernization,
- by applying radiative cooling coatings that can save over 65% of buildings energy consumption, which is consumed by HVAC systems,
- by using XR and building performance simulation tools that offer the ability for visualizing the aesthetic impact at early design-stage, thus analysing and evaluating any conflicts or alterations in advance.

Enhanced prevention and monitoring of the Built Heritage environment by:

- enhancing the sustainability of repair mortars, implementing low carbon, yet durable cements,

- developing an interoperable platform integrating H-BIM/H-DT technologies for providing tools not only for real-time monitoring,
- providing several tools for visualising in several modes (XR) the results, thus facilitating communication, education, storytelling, and citizen engagement actions,
- providing DT and machine learning algorithms for optimizing both materials and Built Heritage performance, predicting also critical structural and degradation risks.

Acknowledgements

This work was funded by the European Union's Horizon Europe research and innovation programme, under Grant Agreement No 101123293 (SINCERE- The Second Life of Modern Period Architecture: Resilient and Adaptive Renovation towards Net-Zero Carbon Heritage Buildings)."

References

1. Papaioannou, S., M. Amenta, V. Kilikoglou, D. Gournis, and I. Karatasios: Synthesis and integration of cement-based capsules modified with sodium silicate for developing self-healing cements. Construction and Building Materials 316 (2022).
2. Peled, A., A. Bentur, and B. Mobasher: Textile Reinforced Concrete (1st ed.), CRC Press (2017).
3. Ferrara, L.: High performance fibre reinforced cementitious composites: Six memos for the XXI century societal and economical challenges of civil engineering. Case Studies in Construction Materials 10 (2019).
4. Rubio-Aguinaga, A., J.M. Fernández, Í. Navarro-Blasco, and J.I. Álvarez. Enhancement of Latent Heat Storage Capacity of Lime Rendering Mortars. in Conservation and Restoration of Historic Mortars and Masonry Structures.. Cham: Springer Nature Switzerland (2023).
5. Haik, R., I.A. Meir, and A. Peled: Lime Hemp Concrete with Unfired Binders vs. Conventional Building Materials: A Comparative Assessment of Energy Requirements and CO2 Emissions. 16(2), 708 (2023).
6. Kośny, J., J. Thakkar, T. Kamidollayev, M.J. Sobkowicz, J.P. Trelles, et al.: Dynamic Thermal Performance Analysis of PCM Products Used for Energy Efficiency and Internal Climate Control in Buildings. 13(6), 1516 (2023).
7. Vasilopoulou, M., A. Fakharuddin, A.G. Coutsolelos, P. Falaras, P. Argitis, et al.: Molecular materials as interfacial layers and additives in perovskite solar cells. Chemical Society Reviews 49 (13), 4496-4526 (2020).
8. di Summa, D., M. Parpanesi, L. Ferrara, and N. De Belie: A holistic life cycle design approach to enhance the sustainability of concrete structures. 24(6), 7684-7704 (2023).
9. Wu, Y., C.T. Maravelias, M.J. Wenzel, M.N. ElBsat, and R.T. Turney: Predictive maintenance scheduling optimization of building heating, ventilation, and air conditioning systems. Energy and Buildings 231 (2021).
10. Scaife, A.D.: Improve predictive maintenance through the application of artificial intelligence: A systematic review. Results in Engineering 21 (2024).
11. Bouabdallaoui, Y., Z. Lafhaj, P. Yim, L. Ducoulombier, and B. Bennadji: Predictive Maintenance in Building Facilities: A Machine Learning-Based Approach. 21(4), 1044 (2021).
12. "Summary for Policymakers", in Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, C. Intergovernmental Panel on Climate, Cambridge University Press, pp. 3-32 (2023).
13. Psaroudakis, C., G. Xanthopoulos, D. Stavrakoudis, A. Barnias, V. Varela, et al.: Development of an Early Warning and Incident Response System for the Protection of Visitors from Natural Hazards in Important Outdoor Sites in Greece. 13(9), 5143 (2021).