

Chapter 36

Leveraging AI-coupled Digital Twin Ecosystems for all Sustainable Development Goals in the Built Environment

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Abstract

This chapter presents the results and outcomes of FRESH-BIM/FRESH-DT, two internationally co-funded, awarded, and published joint projects, addressing urgent inefficiencies in global construction practices—producing 32% of global energy and carbon emissions, 40% waste, and >80% time/cost overruns—while also tackling often-overlooked social, biodiversity, and governance challenges. As such, this paper discusses utilising innovative technological advances to address these urgent problems in the built environment and heritage while aligning with the 17 UN Sustainable Development Goals (SDGs). Opportunities of utilising digital-twin (DT) and AI machine-learning functionalities in tandem are first demonstrated, to enhance different buildings’ sustainable performance aspects throughout different lifecycle phases, including energy/carbon reduction, improving users’ indoor microclimate, building materials’ circularity, reducing waste, optimising design/construction/operations time, cost, and quality processes. The approach considers broader impacts on social equity, biodiversity, and governance, aligning with the SDGs. This chapter then delves into implementation details of the FRESH-BIM/FRESH-DT projects performed in collaboration with government, academic, and industry bodies in the UK and Egypt, focusing on revitalisation of national heritage assets, to create a positive impact on increasing national tourism and contributing to GDP growth. The projects created an AI/DT analytics ecosystem with 5 deliverables, including a new classification system and an expert system for renovation of heritage assets, aligning with all UN SDGs, and on the route for national-scale adoption.

Keywords: *Digital Twin, Artificial Intelligence, Built Environment, Sustainable Development Goals, Heritage*

Introduction

The built environment is a major contributor to global sustainability challenges as a resource-intensive sector accounting for >32% of global energy consumption 34% of global CO₂ emissions¹, with only 16% of construction projects finishing on time/budget, and waste levels reaching 40%² due to

¹United Nations Environment Programme and Global Alliance for Buildings and Construction, *No Just Another Brick in the Wall: Global Status Report for Buildings and Construction 2024/2025*, 2025 <https://wedocs.unep.org/20.500.11822/47214>.

²Cuéllar-Reyes et al., “Causes of Cost and Time Overruns in Construction Projects and Methodologies for Their Mitigation.”

inefficiencies/rework. These inefficiencies are exacerbated by fragmented workflows, poor data integration, and delayed reactive decision making. As urbanisation accelerates and climate targets intensify, the need for intelligent/adaptive/sustainable construction practices becomes vital as a resolution. Innovative technologies, for example, Digital Twin (DT) and Artificial Intelligence (AI) offer transformative potential for these challenges. When used collectively, they enable real-time monitoring, predictive analytics, and lifecycle optimisation across design/construction/operational phases, supporting both technical performance and broader sustainability goals.

DT and AI Synergy Across Lifecycle Phases

A DT is a dynamic, virtual representation of a physical asset/system/process. It integrates data from sensors, building information modelling (BIM) data, and operational systems to simulate/analyse/optimise performance via diagnostics. Enhanced with AI, DTs become intelligent systems learning from historical and real-time data, enabling pattern recognition, anomaly detection, predicting outcomes, forecasting, decision-making, and recommending interventions. Together, they improve building performance, indoor microclimate, quality processes, and reduce waste/time/cost. This approach also considers broader impacts on social equity, biodiversity, and governance, aligning with all 17 UN Sustainable Development Goals (SDGs)³.

- **Design phase:** DT can simulate multiple design scenarios based on legacy or live Internet-of-Things (IoT) sensor telemetry data. AI algorithms can then generate multiple design alternatives to optimise energy/carbon performance, daylight penetration, thermal comfort, assess material usage/circularity, and cost constraints. AI-coupled DT enable scenario-testing, helping evaluate the impact of design choices on long-term sustainability⁴.
- **Construction phase:** AI can detect anomalies, forecast delays, and optimise resource allocation. DTs provide live dashboards of site activities, enabling proactive logistics, safety, and quality management. This reduces waste and improves stakeholders' coordination. Zahedi et al.⁵, found that DT applications in construction significantly reduce material waste and improve compliance with sustainability indicators to align with the SDGs.
- **Operational phase:** AI-enhanced DTs support predictive maintenance, energy optimisation, and occupant comfort. IoT sensors embedded in buildings feed data into DTs, which uses machine learning to identify inefficiencies and recommend adjustments. For example, in New York City, AI-paired DTs are used to comply with Local Law 97, which caps emissions from over 40,000 buildings. These systems track energy/water/waste/air quality data, enabling building owners to reduce emissions and improve ESG reporting⁶.

2 7th International Congress on Project Management and Engineering, Donostia-San Sebastián, July 10–13 (2023) http://dSPACE.aepro.com/xmlui/bitstream/handle/123456789/3362/AT01-055_23.pdf?sequence=1.

³Ehtsham et al., "AI_Powered_Advanced_Technologies_for_a_Sustainable_Built_Environment: A_Systematic_Review_on_Emerging_Challenges," *Sustainability* 17, no. 17 (2025): 8005 <https://doi.org/10.3390/su17178005>.

⁴Ehtsham et al., "AI_Powered_Advanced_Technologies," 8005.

⁵Zahedi et al., "Digital_twins_in_the_sustainable_construction_industry," *Buildings* 14, no. 11: 3613 <https://doi.org/10.3390/buildings14113613>.

⁶Ehtsham et al., "AI_Powered_Advanced_Technologies," 8005.

Circularity and Waste Reduction

With construction accounting for 40% of total global waste, DTs can track material flows, origin, composition, and reuse potential/opportunities, supporting circular economy practices and material passports. AI algorithms can then classify/select low-impact carbon-footprint materials, predict their end-of-life scenarios, waste/reuse types, and optimise deconstruction strategies for waste minimisation. Pierzchlewicz et al. (2025)⁷, found circular architecture strategies and lifecycle assessments (LCA) most effective when integrated with DT/AI systems. Linking with BIM and building management systems data, can assess embodied/operational carbon, enabling more accurate sustainability benchmarking.

Indoor Microclimate, Health, Social Equity, Biodiversity, and Governance

Indoor environmental quality is critical for occupant health, well-being, and productivity. AI-powered DTs can monitor temperature/humidity/air quality/lighting, adjusting systems in real-time to maintain optimal conditions. In smart buildings, these systems can reduce energy consumption by 30% while improving thermal comfort⁸. Löfstad Castle, Sweden DT was created for preventive conservation and operational sustainability to monitor/manage indoor climate conditions threatening preservation of its collections. AI-driven analytics identified high-humidity zones and guided installation of vapor barriers and energy-efficient ventilation strategies.⁹ Beyond technical performance, DT/AI can support social sustainability. Analysing/simulating user behaviour, accessibility, movement, occupancy, and demographic data can identify underserved communities, guide equitable resource distribution, and ensure inclusive environments. DT/AI also drives impact in governance, providing transparent, data-driven insights, supporting policymaking and stakeholder collaboration¹⁰.

FRESH-BIM and FRESH-DT: AI-Driven DT Ecosystems for Sustainable Heritage and Construction Transformation

The FRESH-BIM/FRESH-DT projects are two internationally co-funded initiatives, led by Dr. Noha Saleeb (Middlesex University, UK) to address the urgent renovation and sustainability challenges in the Egyptian heritage sector by leveraging AI-enhanced DT ecosystems to restore/optimize heritage assets, hence contributing to tourism and national GDP. These were published on the EAUC UN_SDG Accord website as impact case studies aligning with all UN SDGs and were awarded the Green Gown UK/Ireland Sustainability Champion Award 2024. The project was funded through institutional links grants from the British Council UK and the Science and Technology Development Fund (STDF) Egypt.

⁷Pierzchlewicz et al., “Recent Research on Circular Architecture: A Literature Review of 2021–2024 on Circular Strategies in the Built Environment,” *Sustainability* 17, no. 17 (2025): 7580 <https://doi.org/10.3390/su17177580>.

⁸Díaz Caselles et al., “Sustainability Performance in OnSite Construction Processes: A Systematic Literature Review,” *Sustainability* 16, no. 3 (2024): 1047 <https://doi.org/10.3390/su16031047>.

⁹Mazzetto Silvia, “Integrating Emerging Technologies with Digital Twins for Heritage Building Conservation An Interdisciplinary Approach with Expert Insights and Bibliometric Analysis,” *Heritage* 7, no. 11: 6432–6479 <https://doi.org/10.3390/heritage7110300>.

¹⁰Ehtsham et al., “AI Powered Advanced Technologies,” 8005.

This involved a consortium of academic/government/industry associated partners, including Cairo University, Ministry of Antiquities Egypt, Historic Environment Scotland, BuroHappold UK, Karnak Egypt. These collaborations enabled the projects to operate across both the UK and Egypt, focusing on heritage restoration, sustainable construction, and digital innovation.

Results and Discussion

Project Objectives: The overarching goal of FRESH-BIM/FRESH-DT was to create a scalable AI + DT + Analytics-Ecosystem to achieve the following objectives:

- Improve sustainability performance across the building lifecycle
- Enable intelligent renovation and operations of heritage assets
- Align with all 17 UN SDGs

Case Study: The flagship application of the ecosystem was restoration of the Toson Palace (Cairo), a nineteenth century heritage site with failing structural elements due to previous fires, deteriorating unmaintained spaces, corroding building services, and wildlife infestations (Figure 1). FRESH-BIM/FRESH-DT applied AI and DT to restore this heritage site, integrating structural analysis, social simulations, and predictive maintenance. The project further aligns with all 17 SDGs, as explained subsequently, and is currently being scaled nationally.

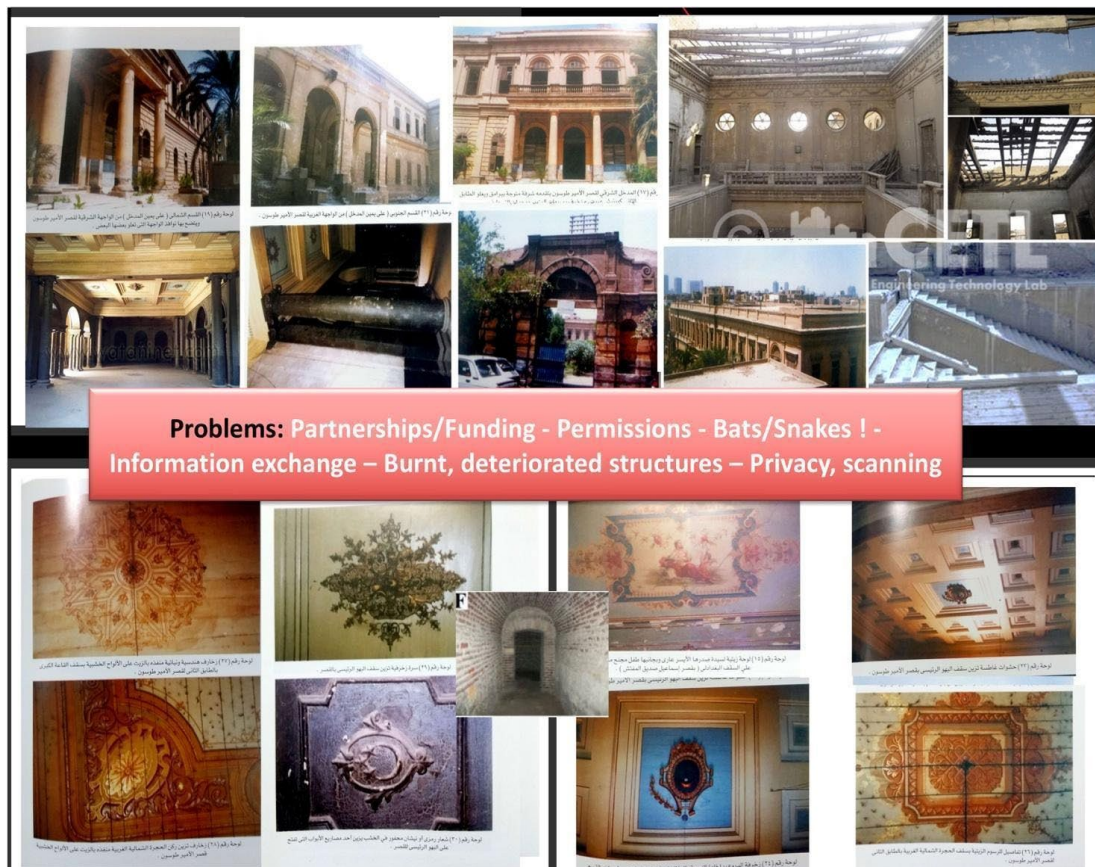


Figure 1: Toson Palace condition showing internal damaged status.

Outputs: The ecosystem produced **five key deliverables:**

1. *Heritage classification system:* A novel heritage asset-types' taxonomy, to guide renovation strategies and policy decisions. This was adopted by experts working on Westminster Palace and Big Ben Clock Tower renovations in London.
2. *Structural analysis framework:* Integrated 3D laser scanning, seismic analysis, and parametric modelling to assess building integrity and simulate environmental impacts.
3. *Expert renovation system:* AI-driven decision-support tool for optimising restoration workflows, material reuse, and cost/time efficiency.
4. *Social VR/AR simulations and analytics platform:* To simulate user behaviour, accessibility, occupancy patterns, and ensure inclusive design and cultural engagement.
5. *Real-time visual analytics platform for predictive maintenance:* Enabled proactive monitoring of building systems, reducing lifecycle costs and improving operational sustainability.

Project workflows started by conducting a comprehensive 3D laser scan of the whole building and surrounding estate with varying precision tolerances. Challenges included: permissions required from the Ministry of Antiquities and the surrounding school to scan adjacent walls, danger from bats/snakes' basement infestation, risk of collapse of stairs/roofs damaged by fires. Upon converting all point clouds to BIM models, the AI/DT system architecture was implemented:

- Sixteen sensor types (Figure 2) were installed in spaces with diverse functions/sizes/floors to capture indoor environmental conditions in both used/unused spaces, mobility, and occupancy in public user spaces, water/pollution/structure conditions.

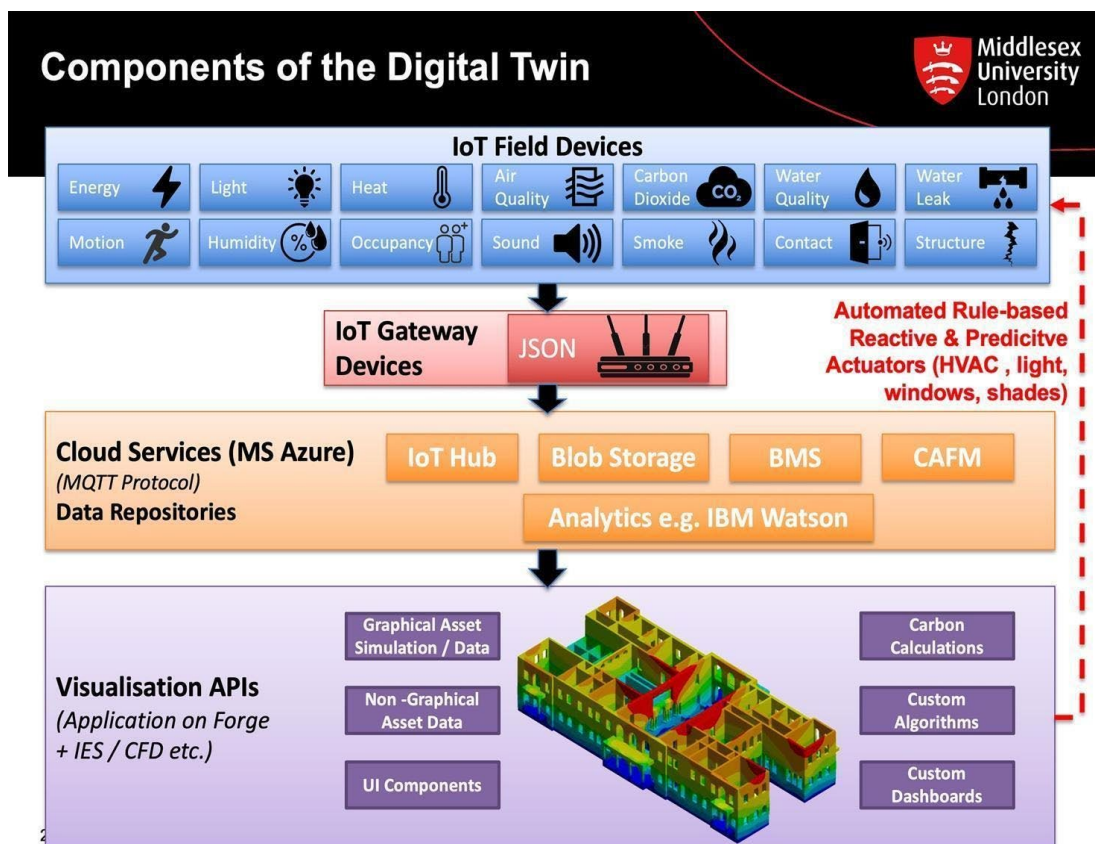


Figure 2: AI-coupled DT architecture.

- These were connected via JSON gateway devices to MS Azure cloud services and archival data repositories, connected to the BIM models to create the DT.
- AI machine-learning algorithms (Figure 3) and visualisation dashboards were created to analyse the data, predict future conditions, space usage, and recommend solutions for enhancing the spaces' performance.

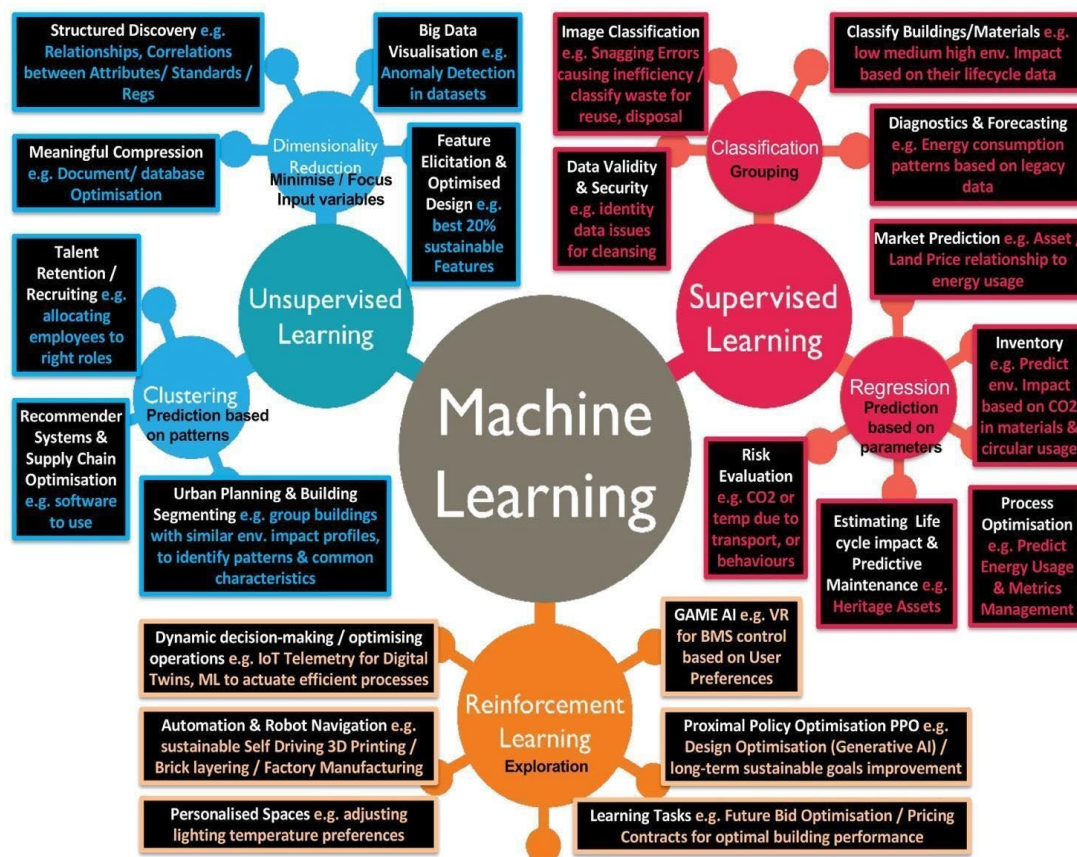


Figure 3: AI-Machine learning applications created within the project.

Alignment with all UN SDGs was as follows (Figure 4 and Figure 5):

- SDG_3: Health and well-being through improved indoor microclimates. Simulating natural ventilation, daylight distribution, thermal mass, and informing renovation strategies while preserving architectural integrity.
- SDG_7 and 13: Energy efficiency via predictive analytics for climate action, including HVAC system sizing, envelope performance (e.g., insulation/glazing/renewable energy integration). IES and OneClick LCA tools integrated with system assess embodied/operational carbon, with expected carbon savings of ~2.8 tonnes/year/building.
- SDG_9 and 11: Innovation and sustainable cities through smart heritage restoration. Simulated renovation workflows optimised time/cost for construction phasing, resource allocation, and budget forecasting.
- SDG_12: Circular economy via material reuse and lifecycle analysis
- SDG_4: Quality education via system integration in postgraduate curricula in the UK and Egypt. MSc BIM Management students (UK) participated in project data analysis, winning the Hong Kong Institute of BIM Award 2024.

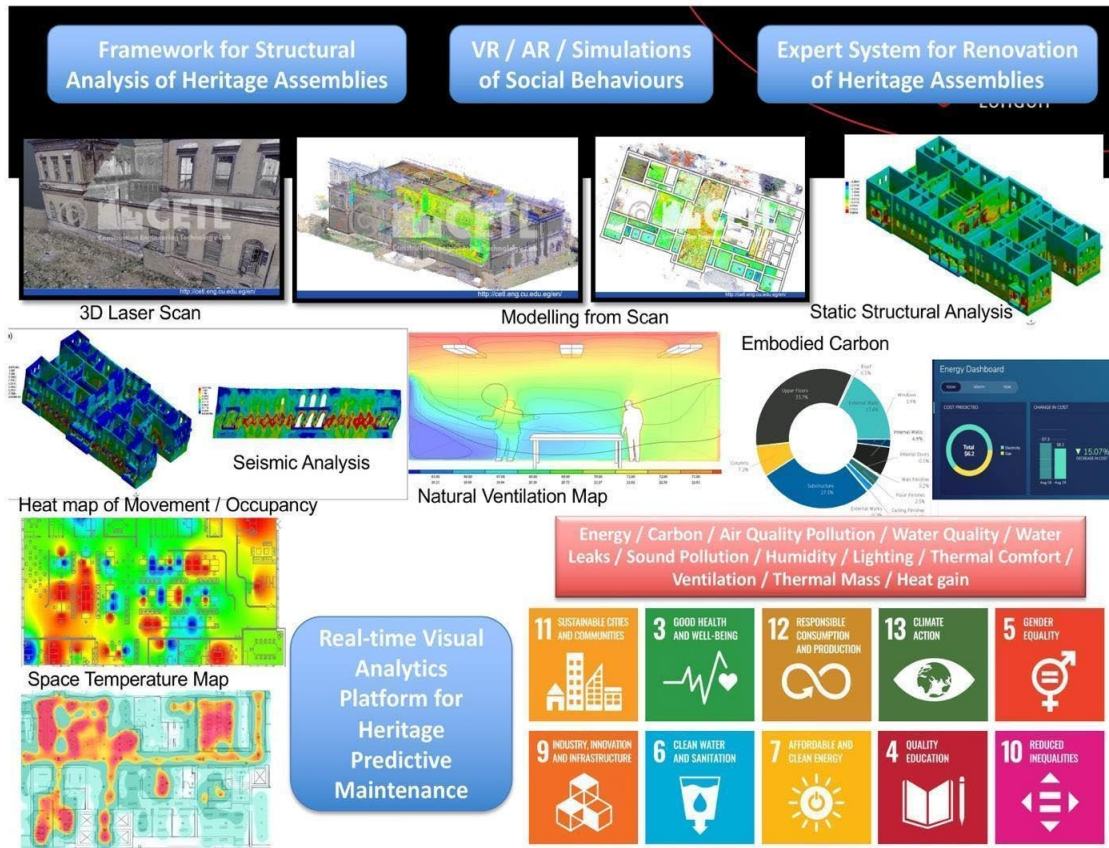


Figure 4: Project deliverables and their alignment to 10 SDGs (3,4,5,6,7,9,10,11,12,13).



Figure 5: Project workflows and their alignment to 7 SDGs (1,2,8,14,15,16,17).

- SDG_15: Safe relocation of bats and snakes to protect biodiversity
- SDG_6 and 14: Drainage system upgrades to reduce pollution in the nearby Nile River, improving water quality and aquatic ecosystem protection.
- SDG_2: DT of fruit/vegetable farms on the estate to support food production
- SDG_1 and 8: Job creation in maintenance/IT/tourism, contributing to GDP growth ~£12 billion/year in tourism revenue and 3 million jobs over 5 years, reducing poverty and promoting work/economic growth.
- SDG_5 and 10: AI analysed spatial usage patterns, social simulations modelled different user groups' behaviour/interaction with heritage spaces, to improve accessibility, equality/inclusion, wayfinding, mobility, inclusive space planning, and cultural/community engagement.
- SDG_16 and 17: Governance and partnerships through policy engagement and international collaboration, for example, UK Parliament, BIM4Heritage, BIMAfrica, CIOB, Egyptian Ministry of Antiquities, adopting a new system to guide national heritage renovations adoption.

Conclusion

The FRESH-BIM/FRESH-DT projects represent innovation in integrating AI/DT technologies for built-environment sustainable transformation. By developing a scalable ecosystem spanning design/construction/operations, the projects demonstrated how intelligent systems address environmental/social/economic/governance challenges. Their alignment with all 17 UN SDGs, real-world implementation in heritage sites, and adoption by national/international stakeholders underscore global relevance. These projects offer a replicable model for construction and heritage conservation, setting a benchmark for interdisciplinary, data-driven sustainability.

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