# University communities for the green/digital renovation of public buildings

RESEARCH AND EXPERIMENTATION

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Abstract. In the face of climate change and energy crises, the renovation of existing buildings is an adaptation imperative. Despite ambitious policies, effective progress is hindered by a limited focus on financial returns, neglecting the broader social and environmental dimensions of renovations. This paper presents a university-driven Living Lab methodology experimenting with Digital Twins to foster collaboration and engagement in the co-design of ambitious renovation projects for public buildings. Tested in a pilot project site in a historical context, the research demonstrates the potential to optimise renovation processes and outcomes. Results highlight the transformative impact of the methodology, while addressing challenges for scaling up and replication.

Keywords: Public buildings renovation; Living Lab; Digital Twin; Engagement; Co-design.

## Introduction

In the global context of correlated insecurities arising from climate change and energy crises, the critical objective of renovating existing buildings, given their well-documented and substantial adverse impacts, can be considered an adaptation strategy. Despite the broad perspective of the European Union policies, building renovation efforts remain limited when translated to national and local scales. Here, while rainfall incentives are provided to economically support the renovation effort, the prevailing approach remains focused on the quantitative return on investments, neglecting the broader social and environmental benefits (Fingleton and Jammet, 2021). This approach prevents the development of a comprehensive long-term vision, and the cultural transformation to achieve the necessary radical green transition. In the run toward adaptation, if predominant top-down and technocratic approaches are revealing shortcomings (Selje *et al.*, 2024), alternative community-driven, needs-based, place-based and participatory models are offering promising transformative and regenerative pathways. In the maturity context of the discourse on building renovations (Liao *et al.*, 2023), although "energy efficiency first" is the imperative of EU policies, the shift towards "beyond energy efficiency" concepts appears ready to support more qualitative, effective and future-oriented strategies.

The recently concluded EU co-financed Med-EcoSuRe project[1] (Mediterranean University as Catalyst for Eco-Sustainable Renovation) investigated innovative approaches for the renovation of public buildings by taking into account the social aspects related to the role, influence and impact of the wide range of renovation actors, and the opportunities of an improved collaboration. This paper focuses on the Italian contribution to the project, led by the University of Florence, with the mission to define a Living Lab (LL) methodology to innovate the renovation of public buildings (WP3), and to test it in a pilot action (WP5). In particular, the local LL experimented with Digital Twins (DT), as the best path to support more sustainable, reliable and collaborative processes.

Initially constrained due to the overlap of the project's launch with the Covid-19 period, this vision was in line with the EU initiatives emerging in those years in the context of the ambitious green transition of the Green Deal. Launched by the EU Commission in 2021, the New European Bauhaus initiative promotes sustainable solutions for transformation of the built environment by "engaging people at a grassroots level", "incorporating the views of various stakeholders into the process of design and implementation", and "prioritising people". These human-centric and social priorities are well represented in the LL approach. Key initiative to drive energy efficiency in the building sector, the Renovation Wave Strategy sets out measures to increase the rate and depth of renovations. In particular, it promotes "digital friendly renovations", suggesting simultaneously addressing "the twin challenges of the green and digital transitions". Considering the limited adoption of Building Information Modelling (BIM) (Daniotti *et al.*, 2022), the exploration of advanced digital technologies can find in LLs the ideal contexts for experimentation, enhancing the opportunities to improve renovation practices from the bottom.

Synchronising a virtual replica to the physical building, DTs represent a key enabling technology to foster, beyond enhanced prediction and analysis capacities, advanced interaction, comprehension and communication between building actors. In the case of building renovation, DTs can serve as catalysts to stimulate a collaborative and dynamic exploration and optimisation of renovation scenarios, enhancing energy performance and minimising the environmental impact of renovated buildings, as a strategic tool to support community-driven co-design processes for a shared and common vision of sustainable built environments.

## Methodology

Building on the LL approach, the methodology is grounded on the idea that universities are future-oriented micro-societies, where the development and testing of innovative solutions is ideal, given their guiding roles in education, research & development and third mission.

Initially designed to address the Med-EcoSuRe project's main objective – to reinvigorate the role of university managers in building renovations, the methodology unveiled the advantages of sharing knowledge and fostering collaboration among a diverse range of actors. The LL approach was designed to create a favourable environment where interdisciplinary and collaborative teams can work together to drive innovation and effectively address the challenges of renovation, ultimately advancing renovation processes of public building "beyond just energy efficiency".


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01 | Three phases of the LL methodology adapted to the five stages of the renovation process

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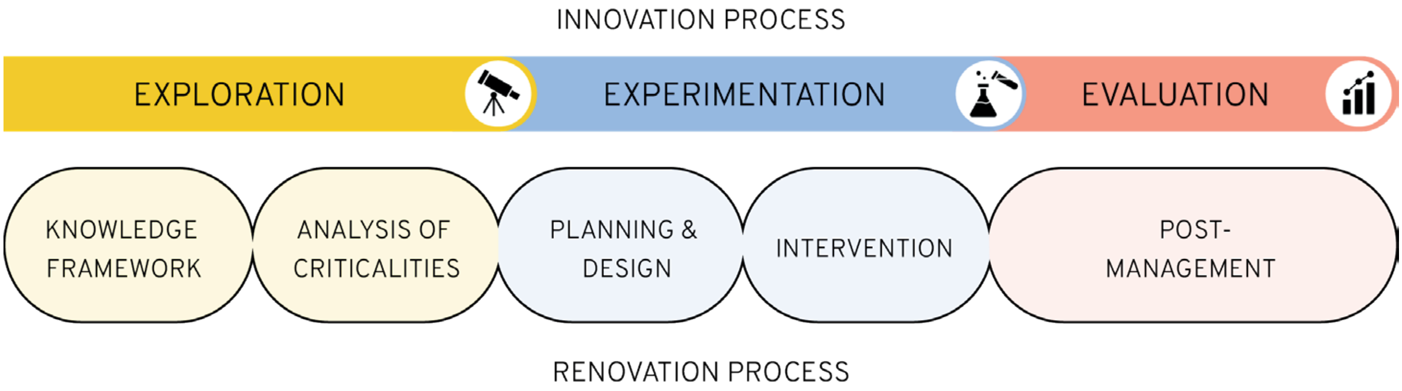



Considering the local mission, the specific objectives of the research project was to explore, experiment and evaluate the potential of DT in the real-world pilot action to advance renovation processes of public buildings.

*The Living Lab approach*

Although there is no single universally accepted definition of "Living Lab" from the review of previous literature, Hossain *et al.* (2019) identify two main paradigms in the LL approach, consisting of open innovation and user innovation. The European Network of Living Labs (ENoLL) describes LLs as "open innovation ecosystems in real-life environments based on a systematic user co-creation approach that integrates research and innovation activities in communities, placing citizens at the centre of the innovation process"[2].

The literature presents a variety of definitions, reflecting the multifaceted and evolving nature of this concept. However, it is possible to identify some common elements that characterise LLs.

They take place in real-world settings, such as neighbourhoods, cities, or university campuses, allowing solutions to be tested under realistic conditions, and their social impact to be assessed through iterative user feedback. LLs are a promising tool to stimulate co-creation of tangible (e.g. products, systems, etc.) and intangible (e.g. knowledge, value, services, etc.) innovation outcomes by including diverse users in all stages of design and commercialisation processes, recognising their ability to develop solutions that meet their target needs.

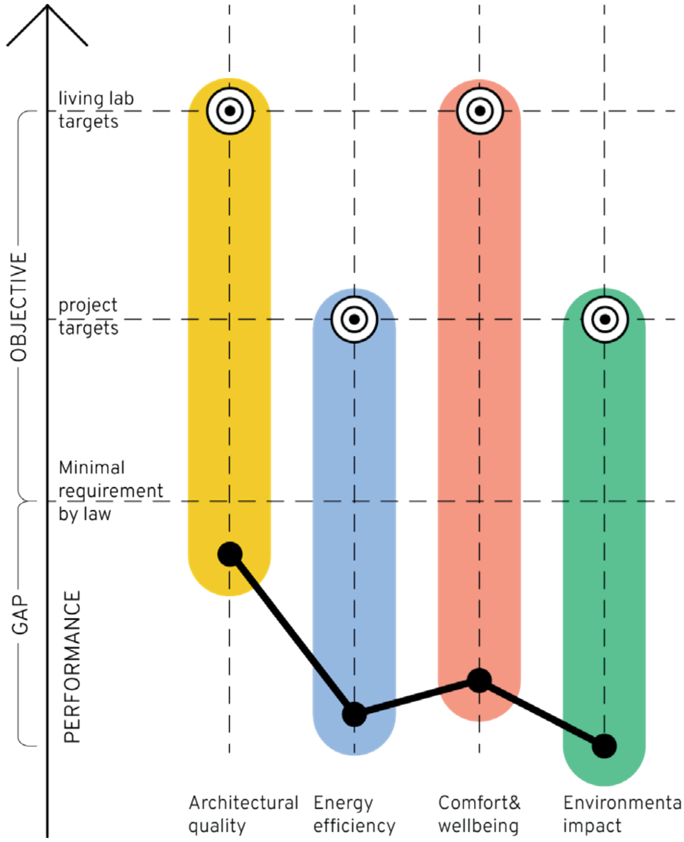
To foster the process and actively engage stakeholders, LLs can use a variety of methods (multi-method approach) such as workshops, focus groups, and online collaborative platforms. Finally, LLs are characterised by the presence of multiple stakeholders working together to achieve common innovation goals. The literature highlights the importance of public-private-people partnerships (4Ps), in which universities, companies, governments and citizens actively participate in innovation activities (van Geenhuizen, 2016). This collaboration takes the form of a "quadruple helix", which encompasses user-oriented innovation models, to take advantage of the hybridisation of ideas that leads to experimentation, and to prototyping in a real-world setting (Compagnucci *et al.,* 2021).

Living Labs have proven to be one of the most promising approaches to engage and stimulate stakeholders in co-creating innovative solutions for green energy and sustainable growth (Marksel *et al.,* 2024). The growing interest in applying this approach in various sectors, including energy efficiency and sustainability, can facilitate collaboration among citizens, businesses, institutions and other stakeholders, accelerating the development and adoption of innovative technologies and practices.

*Living Lab for building renovation*

The innovation development phases of the LL methodology, based on exploration, experimentation and evaluation (Malmberg *et al.* 2017), have been adapted to the building renovation process, structured into five stages (Trombadore *et al.,* 2024) (Fig. 1). The exploration phase can be considered as the 'pre-measurement' before the intervention, with the collection of data and information describing the knowledge framework of the building and the analysis of criticalities. The experimentation phase corresponds to the planning and design of renovation scenarios (mix-of-technologies) and the intervention on the existing building. The third and final phase refers to 'post-measurement' after the intervention and the post-management stage.

From a strategic point of view, the setting up of the local LL (called beXLab – building environmental eXperience) required the definition of a common mission for renovation. Looking beyond energy efficiency, the mission of the local LL is to consider renovations holistically, also accounting for their environmental impact (focusing on the integration of renewable energies and NBS), the social aspects of comfort and well-being, and architectural quality.




From a more practical point of view, the setting up of the LL required the selection of a physical space for the pilot building renovation, as well as the creation of a virtual space for the DT experimentation. The strategic location of the LL in a historical heritage context and in a School of Architecture has been calibrated in the project targets that strongly emphasise socio-cultural aspects, while respecting the architectural values (authenticity and integrity) of the site (Fig. 2).
In line with the LL features, the multi-actor methodology adopted accounts for the involvement of a wide set of actors in the renovation process. The adopted engagement methods and tools are the object of the following paragraph.
The methodology has been iteratively adjusted/adapted across the project thanks to the contribution of partners and implementation of the pilot project, serving as official trial to validate its effectiveness. The tested methodology has been capitalised in a dedicated project's output for further scaling up and replication (Renovation Toolkit[3]).

**Methods and tools**

The research team developed several methods and tools to engage the wide range of actors in the LL activities (Fig. 3), facilitating the collective exploration of the DT of the real-case pilot building. According to their role, for each group of actors (researchers as promoters, building and energy managers as customers, companies and institution as stakeholders, and students as "special" users), the specific activities organised and performed are presented to follow:

*Researchers*
As LL promoters, researchers (PhDs, post docs, seniors) led the design and management of all the LL activities, the operative development of the pilot project, as well as the definition of all the project's outputs. In particular, they were in charge of the experimentation with the DT. To initiate it, the interdisciplinary research group (architects, energy engineers and information engineers) focused on the following tasks:
- develop the BIM model of the pilot building to renovate;
- design a protocol for a real-time monitoring system (IoT sensor networks) to collect data on a specified set of environmental parameters influencing indoor comfort, and installing it within the LL spaces;
- customise the DT into an ICT hosting platform[4].

Exploited for the definition of the renovation pilot project (Calcagno et al, 2023), the DT continues to stimulate cross-disciplinary collaboration (for example, service designers are working on the definition of user-friendly interfaces for DT platforms), and it is operative for further research.

*Building/energy managers*
Customers of the LL's outcomes as main people responsible for the management of the university building stock, building/energy managers (from decision makers to technicians) have been involved since the beginning of the project through a dedicated survey (conducted at cross-border scale). This initial survey has been constructed to self-assess current facility management practices, giving particular attention to the identification of information and collaboration barriers. The most relevant findings highlighted common issues, including inconsistencies in building data uniformity, standardisation, and availability, as well as fragmented processes and very low adoption of digital tools. These results have been disseminated in the context of a dedicated cross-border webinar series, to enhance awareness about the common challenges, and to exchange best practices with peers. The series had the objective of sharing knowledge about the benefits of digital models in improving data reliability, fostering collaboration, and supporting informed decision-making.
At the local level, building and energy managers supplied the essential data to initiate the development of the DT. They actively participated in all technical meetings for the definition of the pilot project, conducted around the DT. These sessions highlighted the DT's potential, showcasing its ability to improve project management and predict renovation outcomes.
Given the lengthy and complex administrative and procedural processes inherent in public procurement, technicians observed that the Digital Twin (DT) significantly enhanced project delivery. It enabled seamless collaboration among diverse professionals involved in the integrated project (including architects, as well as

| 03

energy, structural, and safety engineers), while accelerating project updates, speeding up the development of the executive project, and ensuring effective control over the construction process. Moreover, decision-makers were actively involved throughout the project. At its inception, they collaborated to strategically select the most suitable university building for establishing the LL, installing the monitoring system, and implementing the pilot renovation. Regularly updated on the progress of the DT and pilot project, they facilitated a smooth authorisation process. At the end of the project, they formalised their commitment to transitioning the university building stock toward more digital and sustainable renovation practices by signing two dedicated document/project outputs, precisely a long-term renovation strategy and an action plan. Based on a EU to local policy appraisal and on a technical assessment of the existing university building stock, the first is a roadmap to identify priorities and the best renovation opportunities. The action plan listed a structured agenda of 10 key actions to drive process innovation in the management of the university building stock, focusing on collaboration and digitalisation.

*Companies*
A variety of private companies contributed to the LL, each playing a key role in the DT experimentation and pilot renovation:

- IoT and software companies: the development of an experimental environmental monitoring system of the environment required close contact, support and communication with companies to select the optimal set of sensors and activate the DT's data exchange;
- Manufacturing companies: designing and implementing a state-of-the-art pilot renovation involved the integration of innovative technologies and materials (notably, innovative photovoltaic panels). From the design phase, the DT was used both as a communication tool to engage with manufacturing companies and as an operational tool to manage customisation;
- Construction companies: even the construction process had to be innovative. Given the location in a historical building, the continuity of university activities, and the innovative technologies adopted, the worksite required special features. The DT facilitated smooth communication between the contracting station and construction companies, while also supporting worksite organisation;
- Consultancy companies: the adoption of innovative technologies necessitated expert guidance to manage procurement logistics and proper installation, acting as a bridge between manufacturing companies and the contracting station.

Tab 01 | KPIs for the different types of impact generated by beX Living Lab.

| Type of Impact | KPIs | Achieved results |
|---|---|---|
| Societal | % of coverage of the quadruple helix | 100% |
| | Number of of relevant stakeholders/users involved | > 20 researchers<br>> 10 local building and energy managers > 30 Med level<br>> 5 local institutions<br>> 1000 students |
| Environmental | % of energy requirements satisfy by RES | Related to renovation results (Fig. 04) |
| Economic | % of reduced energy costs | Related to renovation results (Fig. 04) |
| Technological | % of increase in TRL of innovated technologies | DT: from basic research (TRL 1) to technology convalidated in a relevant environment (TRL 5) |
| Regulatory | Number of of adapted/implemented policies or directives | n. 1 signed long-term renovation strategy<br>n. 1 signed short-term action plan |
| Academic | Number of scientific papers and/or publications/articles | > 10 scientific papers |

| Tab. 01

*Public organisations and institutions*:
The experimental LL renovation process has been actively disseminated locally through dedicated events, targeting key organisations and institutions to showcase the potential of DT in driving sustainable and innovative renovation practices. The dialogue with the municipality, as the owner of the pilot building, and with the local cultural heritage superintendence, given the architectural constraints of the pilot site, has been stimulated by detailed technical reports, containing DT-generated data-rich renovation scenarios. This approach facilitated a favourable environment to obtain the necessary authorisations.

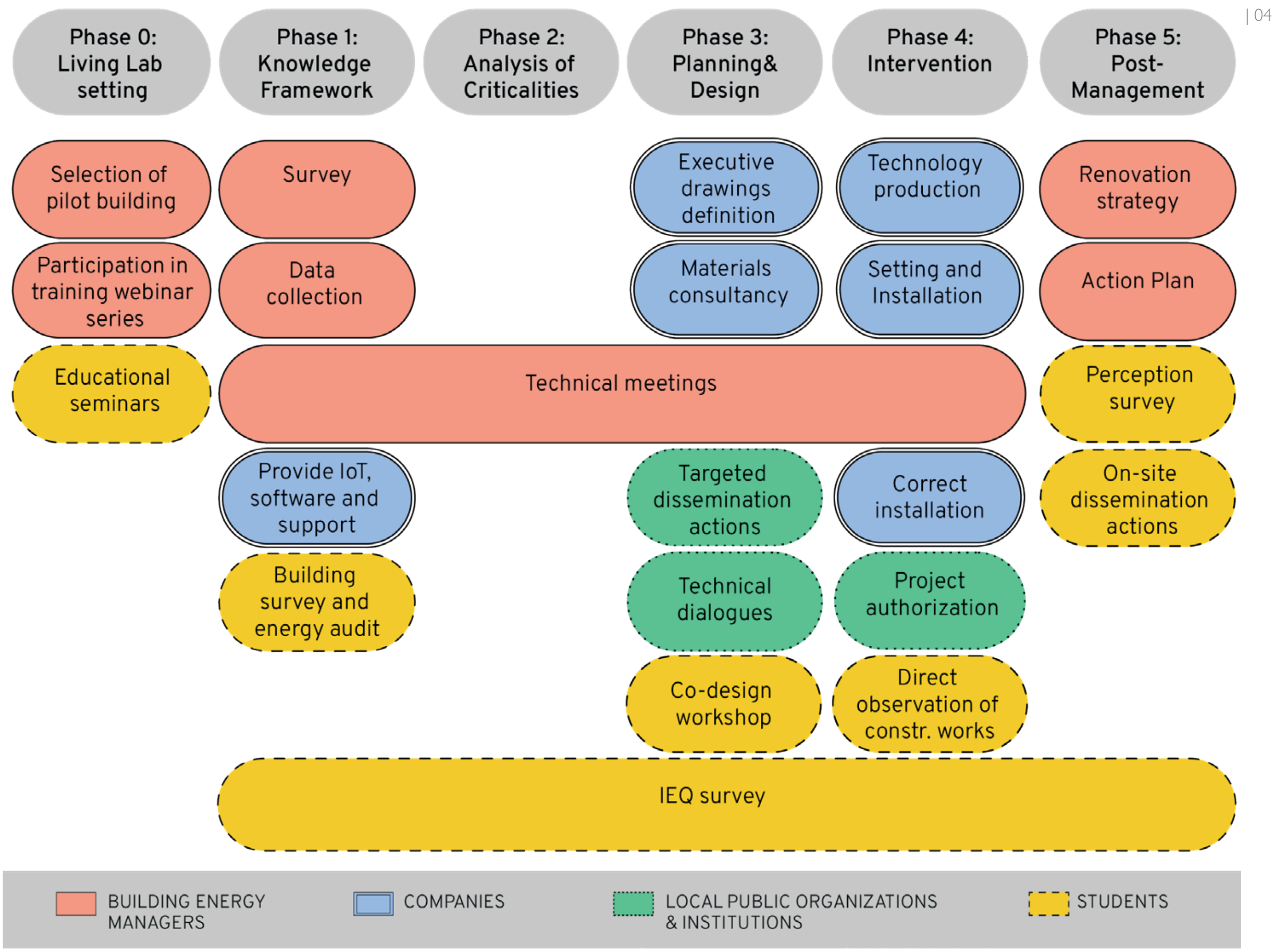
*Students:*
As special users of building, students of architecture have been involved in several LL activities, contributing and benefitting from the DT experimentation:
- dedicated seminars, also with international partners, advancing their knowledge on building renovation and DT, usually relegated to researchers;
- data collection to create the DT (building survey and energy audit);
- qualitative survey on the perception of indoor comfort in the LL (open space for students), stimulating a reflection on the importance of environmental indoor quality, and to retrieve qualitative data for the DT (matched with quantitative data);
- dedicated co-design workshop (see Trombadore *et al.* 2023), handling the BIM asset model of the pilot building to design, simulate and evaluate integrated renovation scenarios;
- direct observation of the pilot project's construction works, adopting advanced techniques (e.g. modularity, prefabrication);
- on-site education conveyed through dedicated posters in proximity of the pilot project and the LL, where all the process, the technologies adopted and the obtained results are detailed in an easy form;
- perception surveys on the pilot project for developing critical thinking about the architectural impact of innovative renovation measures (i.e. solar active structure, see results).

Beyond the project duration, the LL, the DT and the pilot project continue to serve as both real-life and virtual learning resources accessible to students, stimulating their interest in innovative, sustainable and digital practices.

## Results, limits and discussion

Making the most of the contribution of all actors, and supported by the exploitation of the DT, the co-creation in the LL context consented to reach an ambitious renovation project in terms of innovative process and achieved renovation results.
The impacts generated by the LL have been assessed using specific KPIs, defined on the basis of Vervoort *et al.* (2024) (Tab. 1). In particular, the project reached a high societal impact, with 100% of the quadruple helix covered, more than 1000 people involved at local level, and project results increasing positive behaviour towards more sustainable practices. A good technological impact has been reached both with the validation of the DT in a relevant environment, and the full scale installation and operation of the innovative pilot project. Good results also regarded both the regulatory impact and the academic one.
In particular, the pilot project achieved important results in terms of energy efficiency, environmental impact, improved comfort and well-being, highly considering architectural quality (Fig. 4). This last point was of particular interest, given the quality of the historical heritage context of the pilot project, where the need to improve the social acceptance of renovation measures, in particular the integration of renewable sources, is more challenging.
The main intervention of the pilot project resulted in the definition of an experimental 3D steel structure positioned to the south side of the pilot building, and hosting innovative photovoltaic panels (semi-transparent and amorphous). Standing as an active solar shading device, the iconic new façade highly influences the indoor environmental conditions, augmenting energy efficiency while reducing the energy costs and the environmental impact by producing clean energy. The persistence of the pilot in the School of Architecture acts as a tangible result, daily showing the future generation of professionals and citizens the potential of renovations, such as the creative and the aesthetic quality of renewable technologies integrated into architectural solutions.
Beyond the pilot action, the most important result achieved by the project is that all the actors involved experienced in the LL a different way of renovating buildings, namely community-driven and bottom-up, acknowledging in a real-case application the role of collaboration in achieving innovative and satisfying results. Moreover, all the actors entered in contact with

04 | Pilot project results divided by renovation fields (photo credit: ETA Florence)




the DT. This allowed to spread awareness, and to educate, towards the most advanced digital technologies and opportunities. It also offered researchers the opportunity to retrieve information about the limits and challenges of the digital transition. In particular, limitations emerged in the possibility of fully developing a DT for the management of the university building stock. Indeed, even if DT technologies are almost ready to be implemented, more effort is required to advance the digital knowledge and skills of technicians in the public sector. The experience-led learning process activated by the LL, both for building/energy managers and for students, such as the produced educational outcomes (e.g. Toolkit) is a step in this direction.

**Conclusions and future works**

Augmenting the LL methodology with the DT is an innovative transformative path to boost the renovation of public buildings, addressing the green and digital challenges through a renewed collaborative and participative spirit. Beyond the analytic and predictive possibilities enabling advanced decision-making, DT is a valid support tool for more collaborative and engaging practices, whose experimentation in LLs is an opportunity for mutual learning and awareness raising. Beyond energy efficiency and short-term results, an innovative renovation of public buildings combining LL and DT can be an occasion to reinforce the role of actors from the bottom, laying the foundation of a cultural shift by truly supporting the urgent green shift and its persistence in the long term.

The local LL experience in Florence, with the pilot project as evidence, demonstrated the quality deriving from more collaborative and innovative processes. However, the LL adventure is just at the beginning, with a lot of future work in the pipeline. Adopting a broader perspective, the replication of the LL experience in other university contexts[5] and other typologies of public buildings (i.e., schools), is on agenda. At local scale, the didactic potential of the monitoring system, of the DT and of the pilot project should be improved by advancing the sharing of project data and results. This requires more effort in terms of communication, and the simplification of complex data in a user-friendly way. The collaboration with the service design experts is working in this direction, with the short-term idea of creating informational totems for the fruition and navigation of the DT. The long-term perspective is to develop a dedicated app for its full exploitation, both for the university building/energy managers (expert users), with the possibility of managing the building portfolio, and for the building's end-users (not expert users), oriented to stimulate more proactive behaviours toward a more sustainable use of buildings. This is strategic in the education of young architects/citizens.

The created LL/DT, physical and digital infrastructure, is accessible for further research, looking at new collaboration and development opportunities with other disciplines and stakeholders.

## NOTES

[1] Available at: https://www.enicbcmed.eu/projects/med-ecosure (30/11/2024).

[2] Available at: https://enoll.org/living-labs/#living-labs (30/11/2024).

[3] The draft version of the Toolkit is available online at: https://medbexlive.org/. The final version is the subject of an ongoing dedicated publication.

[4] Available at: https://www.snap4city.org/dashboardSmartCity/view/Baloon.php?iddasboard=MzQyNA== (30/11/2024).

[5] The creation of a network of LLs is one of the objectives of the cross-border Living Lab activated in the context of the Med-EcoSuRe project, called Med-beXLive. Available at: https://medbexlive.org/ (30/11/2024).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## ATTRIBUTION

This article has been jointly developed by the two authors. Paragraphs were written as follows: Introduction: G.C. & L.M.; Methodology: L.M. & G.C.; Methods and Tools: G.C.; Results, limits and discussion: G.C.; Conclusions and future works: G.C. & L.M.

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