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Advance smart cities through Digital Twins: expanding the knowledge and management capacity of public buildings stock for energy efficiency rehabilitations

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ABSTRACT

In a new vision of smart cities, one of the ambitious challenges for Public Administrations is to expand the knowledge framework (smart data/smart governance) on public building stock supporting a new advanced management capacity for renovation and energy efficiency rehabilitation. The paper shares the experience of the international project Med-EcoSuRe (Mediterranean University as Catalyst for Eco-Sustainable Renovation), specially the methodology of Digital Twin experimented in the Pilot Project of Santa Verdiana, merging both the building performance with indoor environmental data and well-being characteristics. The vision of the project is very ambitious and aims to represent a comprehensive methodology and tool dedicated to PA for a sustainable and smart governance - programming, planning, managing - of energy in public buildings, supporting the evaluation of retrofitting scenarios, decision making on cost-effective and innovative energy rehabilitation actions in Med contexts.

KEYWORDS

Smart governance/ Energy Efficiency / Digital Twin / public buildings retrofitting

ABSTRACT

In una nuova visione di smart city, una delle sfide più ambiziose per le Pubbliche Amministrazioni è espandere il quadro conoscitivo (smart data/smart governance) relativo allo stock di edifici pubblici, per una nuova e avanzata capacità gestionale ai fini della ristrutturazione e riabilitazione energetica. L'articolo condivide l'esperienza del progetto internazionale Med-EcoSuRe (Mediterranean University as Catalyst for Eco-Sustainable Renovation), e in particolare la metodologia Digital Twin sperimentata nel Progetto Pilota di Santa Verdiana, che unisce le prestazioni dell'edificio con i dati sull'ambiente interno e le caratteristiche di benessere. La visione del progetto è molto ambiziosa e punta a una metodologia e uno strumento comprensivi dedicati alle PA per una governance sostenibile e smart dell'energia negli edifici pubblici – programmazione, progettazione, gestione –supportando la valutazione di scenari di retrofitting e processi decisionali per azioni di riabilitazione energetica innovative e convenienti nei contesti mediterranei.

KEYWORDS

Smart governance/ Efficienza Energetica / Digital Twin / retrofitting di edifici pubblici

1. The challenge: how to expand the knowledge and management capacity of public buildings stock

Reflecting the conditions of the surrounding built environment, public buildings in the Mediterranean area are often obsolete, also in terms of Energy Efficiency (EE): they are outdated, sometimes historical, in any case inadequate to the growing comfort demand of the occupancy, such as the cooling one, and to the sustainability targets. The result is uncomfortable public buildings using a large amount of fossil energy, with a high impact on the environment in terms of CO2 emissions. Moreover, the energy status of public buildings is often unknown, such as its potential of improvement.

The high fragmentation of public buildings data that influence EE (geometry, envelope, MEP systems, consumptions, end-users' feedbacks, etc.) is the main barrier to implement strategic EE plans and to intercept funds for large retrofitting and rehabilitations of public buildings stocks: knowledge and integrated management is indispensable for the strategic programming and planning of energy rehabilitations.

To address this challenge, many years ago an international and interdisciplinary research group, led by DIDA/ABITA researchers of the University of Florence, shared the vision that digital advancements in the building sector (such as BIM and Digital Twin) represent a unique occasion for Public Administrations to manage public buildings stocks, driving towards an overall innovative and open approach to EE, based on institutional capacity building, knowledge&skills and pro-active participation of all the stakeholders. The first idea was to design a smart platform for building data collection and management [I_Building Platform], creating a "building identity card" where all the information and data of existing public buildings (the project focused on schools) are collected according to the same criteria and validation process and managed in a more integrated, collaborative and transparent way, serving more efficient processes. The platform becomes a tool to manage the knowledge framework and could work as decision support system, very useful to guide the process of enhancing the existing building stock, aiming at a more efficient data management, with a logic of access and sharing of "open data" on a user-friendly platform (Fig. 1).

The Med-EcoSuRe project (financed by ENI CBCMED Programme) offers the opportunity to implement and investigate this challenge in the framework of Mediterranean context, experimenting the methodologies of the Digital Twin in the local pilot. The project is setting collaborative learning schemes to foster scientific progress on innovative energy renovation solutions within the university's immediate neighbourhood, which is the university building. The main concept behind the project is that working with stakeholders can produce more effective innovative solutions: the idea is to stimulate participatory processes, supporting university building manager with predictive tools and enhancing their capacity to plan and implement sustainable energy mix strategies and technologies for the Mediterranean climatic and social contexts. Based on the Living Lab approach, the purpose is to create a collaborative platform for research, development, and experimentation of product and service innovations in real-life contexts, based on specific methodologies and tools, and implemented through concrete innovation projects and community-building activities. Pilot buildings in different Mediterranean countries are becoming Local Living Labs, connected by the overall Cross-border Living Lab.

In charge to manage the Med-EcoSuRe Cross-border Living Lab, and within the Space BEXLab[1], the research proposes, through its outputs, significant and vibrant changes in the MED region:

1. optimize/innovate the knowledge framework and management of the public buildings stocks, as basis for cost-effective energy mix plans, with toolkit for BIM/Digital Twin to support the digital transformation of the building sector and Public Administrations;
2. reinforce the cooperation among stakeholders (universities/research centres, companies, public authorities, end-users) both at local and Cross border level, opening EE processes in Living Labs for more inclusive and participated processes;

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[1] The Space BExLab (Real and Virtual Space for Building Environmental Experience) has been established as a laboratory of the Department of Architecture (DIDALABS) of the University of Florence with the aim to experiment with augmented Digital Twins for interdisciplinary research and didactics on predictive planning and design.

3. promote awareness and a more pro-active social behaviour, thanks to real data interaction on EE in pilots/Living Labs and experimenting the best comfort experiences.

2. Energy efficiency through digitalisation: the renovation of public buildings

Within the global race to reduce the effects of climate change, the European Union is operating for a transition towards a clean energy society: for the next ten years, the ambitious target is to reach at least 32,5% of energy efficiency, 40% cuts in greenhouse gas emissions, and 32% renewables in energy consumption (European Commission, 2019a).

Improving the energy performance of the construction sector is crucial, since buildings are the larger energy consumers, accounting for approximately 40% of the energy consumption and 36% of carbon dioxide emission, performances that can be explained by the fact that three quarters of the EU's building stock were built when EE requirements were limited or non-existent and the rate of renovation is just of 0,4-1,2% per year (Agora Energiewende, 2019).

A relevant role in this challenging process is played by the public sector: even if publicly owned or occupied buildings occupy about the 10-12% by area of the EU building stock, they have a strategic role as best practice for the overall sector, where innovation can be collectively tested and proposed to the wider public. Public bodies should set the example and give impulse for the creation of the necessary know-how for the rest of the country, with the implementation of public nZEB (nearly Zero Energy Building) both in the case of new buildings and for the renovation of existing ones (EUROSAI, 2018).

Both the two main directives driving the building sector's EE transition, the Energy Efficiency Directive (2012/27/EU - EED) and the Energy Performance of Buildings Directive (2010/31/EU - EPBD), consider the leading role of public buildings. Article 5 of the EED sets binding renovation targets for public buildings[2] and stresses that governments shall undertake an exemplary role in the energy retrofit of their countries' building stock. In the same direction the EPBD, which fixes minimum energy performance requirements for all buildings, considers additional conditions for the public sector: mandatory energy performance certification and public display of certificates, as well as an earlier date at which all new buildings owned and occupied by public authorities should be nZEB.

To reach the ambitious clean energy objectives, the amended EPBD (2018/844/EU) clearly indicates to turn on the renovations of existing building, to be transformed in nZEB by 2050, and on digital technologies, promoting smart systems and digital solutions as a means to achieve energy savings in a cost-efficient manner[3]. Digitalization is one of the EU priorities[4], but even if important progress has been made in digitalising Europe, still a lot needs to be done to ensure the EU industry will fully seize the digitalisation opportunities. This evolution is globally relevant for the construction sector, second less digitalized sector after agriculture, which is largely dominated by Small and Medium Enterprises (SMEs), characterised by decreasing innovation, low rates of technological adoption and diminishing efficiency (European Commission, 2019b).

From a policy perspective, the EU Directive on public procurement (2014/24/EU) is the only policy instrument that clearly refers to the use of digitalisation technologies in the construction sector, in particular to BIM (Building Information Modelling). The Article 22 of the Directive stipulates that "For public works and design contests, Member States may require the use of specific electronic tools, such as of building

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[2] The article states that Member States shall ensure, since January 2014, that the 3% of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year to meet at least the minimum energy performance requirement, or alternative measures (such as behavioural change of occupants of public buildings or installation of energy management systems).

[3] The amended Directive also refers to "smart readiness indicators" to measure the capacity of buildings to use information and communication technologies and electronic systems to adapt the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings.

[4] The 2015 "Strategy for a Digital Single Market" outlined the path for the EU to build the right digital environment.

information electronic modelling tools or similar". The transposition of the EU Directive at national level varies greatly across Europe: eight Member States (Austria, Denmark, Finland, Germany, Italy, Luxembourg, Spain and the UK[5]) have made the use of BIM mandatory in the procurement of public works. At international level, where the use of this digital technology is accelerating in the global construction market, and in particular in the North America, BIM is defined as "shared digital representation of physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions" (ISO 29481-1:2010).

According to the European Commission (2019b), and beyond BIM, the digitalisation of the construction sector encompasses at least six digitalisation technologies, which should be integrated in BIM: additive manufacturing, robotization, drones, 3D scanning, sensors and IoT (Internet of Things). Yet, the diffusion of BIM is very thin because several gaps in the construction sector are still in place, such as the limited obligatory digitalisation targets at national level, the lack of investment for SMEs, of trained employees, of investment in research and development and, more importantly, a lack of a holistic vision for the research needs, not only related to BIM but to the full set of digital technologies and potentials (ibid.).

As for EE, the public sector plays a leading role also in the digitalisation of the construction/building sector, as sustained by the EUBIM Task Group. According to them, government policy and public procurement methods are powerful tools to support the positive change in the building sector. As non-competitive, transparent and non-discriminating, the public sector can encourage to fully grasp the digital opportunities, providing better public services, with an increased transparency of building performances, and in turn better value for public money and better quality of the built environment (EUBIM, 2017).

3. The Digital Twin

To face the ambitious clean energy objectives related to the built environment, it is even more recognised as strategic to take full advantage of the several technologies spreading in the digital domain, overcoming the single BIM digital technology. Nearby BIM in fact, digital technologies are advancing at an ever-increasing pace, exploiting the even more smaller, cheaper and integrated sensors, the Internet of Things (IoT) and more experimentally, Artificial Intelligence (AI) and its recent advancements (big data analysis, semantic web, machine learning, deep learning) (Boje et al., 2020). Sustained by adjacent digital technologies (i.e. sensors and IoT), a new concept of Industry 4.0. is circulating in the building sector, born in the field of product lifecycle management, and firstly expressed by Micheal Grieves in 2003: the Digital Twin (DT). Grieves (2014) describes the DT as consisting of "three main parts: a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together" (p. 1). The idea is to associate a digital representation to a physical product and to create a bi-directional data connection between the physical and the virtual, in order to improve the physical twin.

Expanding the DT concept to the physical world, this means real entities, such as buildings, with data collected through sensors and, in the digital side, models and tools where data and information can be analysed and processed, to be used to improve the physical assets. It is easy to capture the potential of such twinning (which is the act of synchronising): exploiting digital technologies, DTs can optimise the understanding of buildings' functioning as basis for decision-making. The interaction of the built environment with semantic 3D models, enriched with real-time data fed by sensors, provides the opportunity for a real-time monitoring and data acquisition, processing and re-introduction of data in the buildings' lifecycle. According to Khajavi et al. (2019), the DT of a building can be used for predictive maintenance, resource efficiency improvement, enhancement of tenants' comfort, what-if analysis for optimization of the building design and enabling closed-loop design to transfer learnings from a building to the future ones.

Due to this functionality, DTs are strategic for the challenges related to the energy renovation of existing buildings, with the possibility to capture and elaborate real-time data on EE, also related to the human experience (through IoT), i.e. to predict and simulate the most cost-effective building interventions. In this

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[5] Due to the recent Brexit, UK is not more an EU State Member, but it is still a reference for the BIM national adoption.

field, BIM has already evolved in BEM (Building Energy Modelling) to simulate energy performance, evaluate energy needs and optimize buildings' physical and technical assets, but principally referring to the design stage. The DT possibility to manage energy data in the operation stage and to share them with all relevant stakeholders (from energy agencies to citizens) represents an opportunity for a better EE management. The structured and functional amount of data on buildings can overcome the traditional approach to renovation design, opening towards an evidence-based and data-driven decision making across all the building's lifecycle (and in particular in the use phase), supporting more collaborative schemes.

Yet, if BIM is seen as the starting point for the DT, BIM development towards DT (by the addition of sensing capabilities, big data and the Internet of Things from site to building operation) is still very low, as noticed before, due to the delay in the BIM general adoption.
According to the DT maturity spectrum developed by IET et al. (2019) in the evolution of BIM towards DT, going further the nD BIM models, it is time to handle real-time data from sensors and to integrate IoT, in order to improve the operational efficiency also in relation to human behaviours (Fig. 2).

4. Experimenting the Digital Twin in the Med-EcoSure project

As an experimentation within the Med-EcoSure project, the Italian team is developing a Digital Twin of the pilot university building under renovation, tackling the open digital challenges in the construction and building sectors.

The selected pilot building/Living Lab is located in the Santa Verdiana building complex, School of Architecture of the University of Florence, which sits in the UNESCO city-centre (*quartiere* of Santa Croce). Transformed into educational centre in 1986, Santa Verdiana was a former convent (1395) and female prison (1865), which required over the years a series of radical restoration and adaptation interventions to fit the new use. In particular, the pilot is a more recent building block added in the north side of the historical cloister, study room in the ground floor and classroom/laboratory in the first (Fig. 3).

Starting from the survey data, collected by the Space BExLab, a 3D BIM model has been developed in order to fulfil the BIM uses for 4D (time), 5D (costs), 6D (facility management), 7D (sustainability) and for communication and interaction with the stakeholders (academics, Public administration entities and technicians, professionals, economic operators and end-users) along the development of innovative strategies for the building energy renovation. The survey information loaded into the model contains, apart from the geometrical and physical information(materials), the energy performance information collected on the energy audit. Both geometrical and information level of development/detail is LOD C (Level of Detail corresponding to "definite object", according to the UNI 11337-4), level of development needed for the information transfer for the energy analysis and energy simulations as BEM (Building Energy Model). For this scope, and thanks to interoperability (gbxml format), simulations in dynamic regime will be carried out using dedicated software (e.g. TRNSYS, Design Builder and EnergyPlus).

Based on the Living Lab principles, the team is introducing a collaborative approach which exploits the potentialities of BIM/DT for the decision making along the design, construction and operation phases, since the pre-measurement of the intervention (e.g. data on envelope and technical system, monitoring, sensors, IoT, end-users feedbacks on behaviour and comfort, etc.). Supported by the DT, the objectives of the local pilot renovation are:

- to assess that the building operates according to quality standards on sustainability (e.g. energy performances) and comfort (e.g. indoor quality);
- To highlight the criticalities and gaps and planning to modify the operational systems (physical and technical assets, but also behaviours) in order to improve their performances;

- To create n. “what if” scenarios and test strategies and materials to evaluate how the different economic, environmental and social conditions influence the energy performance of the public building, in order to reduce its negative impact.

5. Monitoring indoor environmental quality and well-being characteristics

At this stage of the project, the team is working on the monitoring set-up of the pilot building, process that serves both the pre and post renovation of the site for the refurbishment and use phase.

A complex measurement system will be developed to create an information map of 2 rooms used for different scopes at the School of Architecture. The collected data will describe the thermo-physical, the air quality and other well-being characteristics that change as a function of time and boundary conditions.

Some sensors of the same type will be installed in different spots, covering a uniform grid with the objective to detect the spatial distribution of monitored parameters. The rooms were properly selected as a significant sample of “common” academic living place relating to their orientation, urban context, building manufacture, usage. The first measurement layout is meant to be redundant, at least, because physical phenomena need to be verified from different points of view since no background data are available. Furthermore, the sensors’ correct installation has to be confirmed with multiple crossed measures.

The first year of data monitoring is fundamental for understanding the site behaviour and the response of sensors’ set-up. In this context the measurement layout could be also optimized suggesting the minimum number of devices which is useful to characterize the environments in an exhaustive way.

It is important to mention again that one of the aims of project is defining procedures and methods for the Digital Twin process (experimental part) which would be repeatable in a very large range of different possible applications (public and private building stock). The measurement set-up should be adaptive, modular and plug&play to facilitate the research without compromising accuracy. This led to consider the overall signals chain starting from the sensitive elements, that must be non-intrusive and easy to connect and supply, up to the data concentrators and transmitters. Even the communications protocols are chosen with the same principles taking into account the need of cables and the suitable wireless publishing tools. At the moment, commercial solutions are preferred for the ease and speed in installation, but in parallel, the overall control and data management logics, which are going to be implemented in detail, will be also approached towards open source programming languages. In the next future, another room at the same boundary conditions could be equipped with a new full customised measurement system aiming at a comparison with the commercial one in terms of capability, flexibility and costs.

As well known, the intended use and the level of occupancy play a key role in the energy performance and well-being of a building. From one side, human behaviour modifies the operative conditions strongly (for instance the temperature through the heating plant); from the other side the occupants experience the continuous variation of the internal parameters in terms of comfort or discomfort (illuminance, air exchange, etc..).

It is important to underline that people, in general, are rarely informed about the connection of those concepts at an upper level beyond temporary feelings. No complete tools are available for the managers that handle buildings, with the lack in defining strategies of intervention wherever is needed and plans for long term administration and maintenance.

A revolution in terms of awareness is necessary with the development of decision methods, primarily derived by quantitative parameters extrapolated on field, and then used for validating predictive models. The living laboratory makes a complex measurements database available to the researchers, which represents the springboard for the design of post-processing procedures. They will let to convert the acquired values from sensors into useful information at different levels of aggregation and synthesis.

On a microscopic point of view, the analysis of the signals helps in understanding the details of actions-reaction relationships between the building system and the external forcing (weather conditions as well as occupants). As a following step, an overall macroscopic view is needed to summarize results for a clear and effective dissemination up to the draft of guidelines for a smart management and usage.

6. Open challenges and future works: the strategic vision of augmented cities

The Pilot Project of Digital Twin/Living Lab will be helpful to demonstrate its scalability to the entire heritage building stock, providing Public Administrations with a powerful method for the energy rehabilitation of public buildings to be supported by Digital Twin, with monitoring data on indoor quality, real performance of building envelope as well as the contribution of end user behaviour.

This will also make it possible to outline a procedural model that can be extended on a large scale and that can be used throughout the territory (bottom up) and thus be able to design an intelligent urban network; it will be possible to create a large-scale global database/dashboard on which information regarding buildings (public/private), as well as the services connected to them, can be stored and analysed. Such possibility opens towards a qualitatively better and more efficient government of the territory, from the scale of the single building to the entire city. The development of buildings' DTs, and the flux of data they bring, can intercept, and be intercepted by, the smart city's objectives (e.g. data for smart grids) to address the SDGs on affordable, reliable, sustainable and modern energy for all and on make cities and human settlements inclusive, safe, resilient and sustainable.

The implementation of DTs in fact allows the integration of real-time data on buildings in even more hyper-connected digital systems, which can support a better management of the economic, environmental and social resources interacting in the built environment.

The possibility to manage even more high quality and integrated data represents an opportunity for public sector to be more socially responsible for the global climate change challenges: firstly, the availability of integrated energy data can to enhance the capacity of PA to plan more innovative and performative buildings, such as NZEB, leading to the best cost-effective renovations (e.g. scenario simulations); secondly, managing several DTs consent to prioritize EE interventions in public buildings stocks (e.g. schools), neighbourhood or even at city scale; finally, the human interaction on data (i.e. living labs, IoT, apps or simple monitors) is strategical to educate citizens/end users to a more conscious behaviour in relation to energy savings (understanding needs and benefits) and environmental protection.

Nevertheless, as mentioned above, DT is not a static model based on a single digital technology, but rather a responsive system made of a "constellation, or ecosystem of technologies that work and connect" (IET, ATKINS, 2019), which need to be systematised and transferred to the large use, starting from the public one: it is emerging the need of methodologies and user-friendly tools for the management of DTs.

Looking more forward, DTs have the potential to evolve into autonomous systems with less human intervention, through AI-enabled design and control. Through data and feedbacks, both simulated and real, a DT can develop capacities for autonomy and to learn from and reason about its environment: in this perspective, "a digital twin will not only lead to better decision making, but it will make better decisions" (ARUP, 2019, p. 16).

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Note

The paper is written jointly by Antonella Trombadore, Gisella Calcagno, Giacomo Pierucci. Referring to the individual chapters, they have been written as follows:

Trombadore A.: | 1. | 4. |

Calcagno G.: | 2. | 3. |

Pierucci G.: | 5. |

Trombadore A. & Calcagno G. | 6. |

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Figures

Fig. 1: Vision for a smart management of public buildings stocks (author)

Fig. 2: Functioning of the Digital Twin for buildings (author)

Fig. 3: First floor plan of Santa Verdiana and the pilot building (author)

Fig. 4. Implementation of the pilot Digital Twin (author)