A smart toolbox for the digital transformation of buildings

Sofía Mulero-Palencia
Energy Division
CARTIF Technology Centre
Boecillo, Valladolid Spain
0000-0002-0474-9065

Susana Martín Toral
Energy Division
CARTIF Technology Centre
Boecillo, Valladolid Spain
0000-0002-1867-878X

Dimitrios Rovas
UCL Bartlett School of Environment, Energy and Resources
University College London
London, UK
0000-0002-5639-6783

Georgios Kormpakis
Decision Support Systems Laboratory
National Technical University of Athens
Athens, Greece
0000-0003-4052-4549

Vangelis Marinakis
Decision Support Systems Laboratory
National Technical University of Athens
Athens, Greece
0000-0001-5488-4006

Ali Vasallo Belver
Energy Division
CARTIF Technology Centre
Boecillo, Valladolid Spain
0000-0003-3802-6479

***Abstract*—New net-zero energy policies and the potential to improve the efficiency of existing buildings necessitate significant transformational action. Combining digitalisation and smart technologies can lay the groundwork for affordable, adaptable and close-to-market solutions. With this aim in mind, this paper presents a generic and replicable solution for transforming buildings to higher levels of smartness, which is being developed within the context of the Horizon Europe BuildON project. We introduce a Smart Transformer Toolbox – a set of components and tools to facilitate the integration of heterogeneous systems, enable automation and control and unleash the potential of artificial intelligence in modelling and optimisation strategies. The solution includes simplified interfaces to bridge the gap between technology and end users, providing functionalities to continuously Monitor, Assess, Predict and Optimise (MAPO services) building performance while supporting informed decision-making.**

Keywords— Smart Readiness Indicator, smart building, Artificial Intelligence, Digital Twin, Energy Management System

I. INTRODUCTION

Buildings play a crucial role in the transformation of our living spaces. The building stock accounts for approximately 40% of total energy consumption and 36% of CO_2 emissions in Europe [1]. The potential for mitigation is significant, and comprehensive action in the sector is needed to achieve the climate and energy goals of the Paris Agreement. The actions promoted by the European Union with the Green Deal [2] or the Renovation Wave [3] are driving this change, aiming to accelerate the renovation of buildings to reduce carbon and energy intensity while improving citizens' quality of life.

Almost 75% of buildings do not meet current energy standards, and a large portion of these will still stand in 2050 [4]. Although improving the energy efficiency of buildings is one of the key actions to achieve the EU's carbon neutrality target for 2050, such renovations are often not feasible for several reasons (i.e., legal aspects, high investments), leaving this annual renovation rate very low [5].

The current context, therefore, calls for more energy-efficient practices, and digitalisation can help achieve this transformation by applying strategies for optimal control of building operations to improve energy performance. Moreover, since the 2018 revision of the European Energy Performance of Buildings Directive (EPBD), the potential of smart technologies has taken on a pivotal role. Smarter buildings could support the transition towards digitalisation and decarbonisation to benefit occupants, owners, and the overall energy system, achieving zero emissions and a fully decarbonised building stock. To enhance the implementation and facilitate the adoption of smart technologies, the EU has supported the development of the Smart Readiness Indicator (SRI) [6], which measures buildings' smart preparedness level. This indicator was introduced in the 2018 revision of the EPBD Directive and provides an integrated assessment and recommendation framework to support implementation pathways using digital automation and monitoring technologies to improve the ability of buildings to detect, interpret, communicate and respond to changes efficiently.

Many unresolved cross-cutting issues are holding back the adoption of such technologies, starting with the lack of knowledge and evidence on the potential of building technologies and the associated benefits. Likewise, the rapid evolution in smart building technologies means that existing solutions are not always tailored to the needs of the current and legacy contexts and are, therefore, not scalable and easily replicable.

From this perspective, a combination of heterogeneous technologies for data access and management (advanced metering infrastructures), system automation and control, as well as for data analysis and learning (Artificial Intelligence (AI)/ Machine Learning (ML), energy simulations) will pave the way for buildings to fully enter the digital era. The integration of these technologies will enable real-time monitoring, assessment, prediction, and control to optimise the energy performance of buildings and support users' decisions through informative solutions.

To this end, this paper introduces the concept of an SRI-driven smart transformer toolbox to improve smart building readiness levels for better energy performance. This toolkit aims to provide a generic solution to deliver smart building services, facilitate the integration of heterogeneous systems and technologies and thus directly contribute to delivering the next generation of smart buildings. This solution leverages the capabilities of buildings to manage themselves efficiently and interact with their users and the wider energy environment.

Based on a combination of predictive and descriptive analytics and automation and control strategies, articulated through a unified representation of the building and its systems to maximise interoperability, the building could be managed efficiently, and users could make better-informed decisions.

The paper is structured as follows: following Section I Introduction, Section II presents the background and explores the state of the art of the core components considered within this field. Section II describes the methodological approach to be followed to validate the proposed solutions, while Section III outlines the concept of the BuildON solution and delves into the details of the functionalities provided and how they can contribute to improving the smart readiness of buildings. Finally, Section V includes some concluding reflections and remarks.

II. Background

Numerous definitions have been coined to describe what constitutes a smart building [7], although no standard or widely accepted definition [8] exists. However, two aspects appear to be recurring in the literature. Firstly, critical elements of associated technologies are often linked to data and the communication network that connects diverse technological devices and systems with energy management systems and end-users [9] [10]. Secondly, for a building to be considered smart today, it must be aware of its surroundings, meet user needs, and possess the ability to adapt to the changing environment autonomously [11]. Both aspects are considered in the concept of data-driven smart building proposed by the IEA Annex 81 [12], which presents it as a building that uses digitalisation technologies to optimise its operation dynamically.

Home Energy Management Systems have emerged as crucial components of smart home applications in recent years, integrating communication between appliances and energy systems into a unified communication network [8]. Building Energy Management Systems play a similar role for non-domestic buildings, ensuring that various building systems and services are operated appropriately to ensure comfort while ensuring parsimonious energy use. Taking this further, integrating energy efficiency, distributed energy generation technologies, and demand flexibility into buildings has the potential to advance the state of the art in grid-interactive control buildings [13].

One of the main barriers to adopting smart building technologies is related to social aspects, from the lack of user-friendly products to the deficcient technological knowledge of users [14]. Most of the existing low-cost solutions on the market are of limited capability or too sophisticated for non-expert users, generating distrust and confusion among many, such as building residents. In addition, there are still many applications for particular functionalities, and there is a need to harmonise these solutions. From a high-level perspective, applications such as smart home systems are presented as an option that incorporates increasing homogeneous capabilities, with the advantage that they can be controlled by devices such as smartphones or voice [10].

The harmonisation problem entails seamless integration and coordination between software and hardware components within the management system. Several market solutions enable smooth data exchange and simple communication between service providers and end users. However, traditional lock-in practices, individual access to data and management architectures, with their specific interfaces and intricacies, are still commonplace and should be removed progressively. Aspects such as interoperability, standardisation and data availability for services to be implemented at the edge are key to progress in this field [15]. At the same time, solutions must be deployed both in the cloud and the edge to enable broader applicability and replicability.

The use of AI in developing services to improve building capabilities is becoming increasingly widespread, partly because there is a growing amount of data to exploit due to increasing monitoring levels [16]. A wide range of building-related activities, such as energy consumption and production forecasting, energy profiling and trend identification, energy flexibility management, comfort applications, anomaly detection, optimisation strategies, control applications, etc. can be addressed by AI-based solutions covering the entire building value chain [17]. Such analytics can support decision-making in a general way, aiming to improve energy efficiency [18]. However, smart solutions are not only about technology; changes must also be acceptable to users, as they must be actively involved in user information and advice to adopt energy-conscious behaviour, and users need to be empowered to use these tools effectively through training.

Furthermore, in most cases, smart management solutions remain at an analytical level, as mentioned above. Existing solutions can propose improved performance scenarios, but in most cases, the facility manager manually controls these scenarios. The challenge is to develop optimal control strategies for a holistic set of energy systems and subsystems that can be easily adapted and replicated in other building typologies and with different energy systems and climatic conditions [19].

Finally, Digital Twins (DT) have the potential to provide visual support to these predictive capabilities. They can be considered as virtual representations of objects or systems, updated using real-time data, and they use simulation tools, machine learning, and reasoning to support decision-making. Therefore, DTs can be used to monitor and control actions, facilitating data collection and information exchange between physical and virtual assets. In particular, when assessing the energy performance of buildings, they can help operators identify factors that contribute to higher consumption. Despite growing interest, their use remains limited [20]. The literature shows how DTs have been used in large tertiary and industrial buildings but are less common in more modest scenarios where the costs outweigh the benefits [21], while there are currently not enough commercialised tools and services related to building energy assessment and digital twins.

Digital Building Twins face several challenges due to their inherent building characteristics [22]. They require a robust IT infrastructure that enables communication with field devices and data analysis capabilities; addressing any privacy concerns is also an important consideration. The difficulty in developing useful digital twins stems from the complexity of buildings, with heterogeneity in equipment setup and configuration, as well as a wide range of management and oversight practices. Such concerns create challenges in the development of useful and scalable digital twins. However, Digital Twins are expected to play a significant role in developing smart buildings, requiring further bridging of physical and virtual data for real-time decision-making. Issues such as the lack of standardised methods for integrating real-time data into building BIM models and interoperability between software and monitoring vendors are slowing its adoption. Thanks to its reliable predictive capacity, DT technology can provide accurate feedback from sites and optimal control strategies for various energy services: improvement of Indoor Environmental Quality (IEQ), management of renewable energy sources for comfort or flexibility, detection of anomalies, etc. Combining the analytical capabilities offered by AI services and the control capabilities can help promote the widespread adoption of smart building solutions.

A. *Progress beyond the State of the Art*

Action is needed, building on the technologies and digitisation already described, to move towards increasingly smart-ready buildings. This paper introduces the concept of a Smart Transformer Toolbox to address current barriers and take a step forward. More specifically, in the proposed approach:

- A set of tools focused on improving the level of smartness is introduced to help users learn and explore the capabilities of their buildings.
- Putting users at the centre, we propose accessible and easy-to-use –even by non-experts– applications to monitor and analyse the performance of their building.
- Users are empowered to become active participants in the energy management of the building and get involved in the decision-making process.
- An interoperability framework for data access and bi-directional communication with buildings addresses fragmentation issues and the challenges of interfacing with heterogeneous and multi-protocol systems.
- A set of holistic, AI-based, archetype-driven control services assists in adapting and replicating optimal control strategies.
- Reusable system-level approaches for Digital Twins enable optimal control design and data-driven, AI-enabled predictive services.

III. Methodological Approach and Value Chain

The proposed solution applies to many building typologies, from residential to office, educational and commercial, helping unlock the potential of building

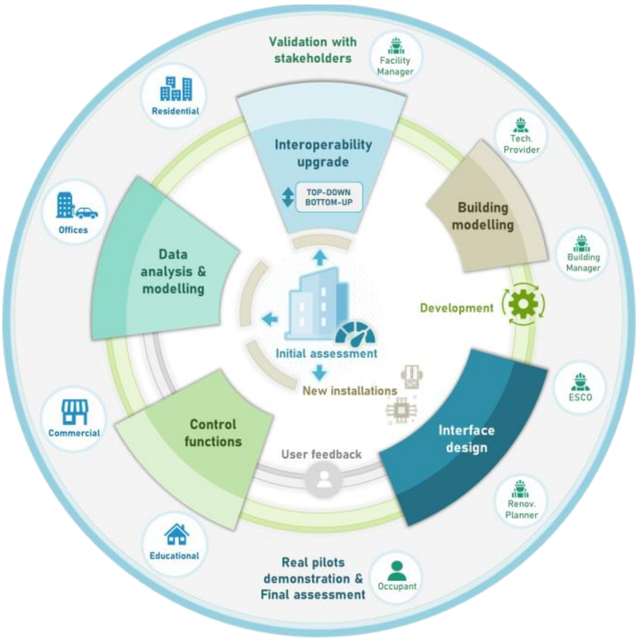

Fig. 1. The BuildON methodological approach.

digitalisation in the broad building sector. In addition, when developing out approach we considered the needs of different stakeholders who can benefit from these enhanced smart applications (i.e., facility and building managers, technology providers, ESCOs, renovation planners, investors, and occupants).

A top-down and bottom-up approach is followed to understand the problem statement, technological constraints, and expectations and to propose the final solution tailored to the needs of the building without losing sight of a generic and replicable perspective, as summarised in *Fig 1*.

1) *Initial assessment:* this first step identifies the domains of the building with potential for improvement and the necessary upgrades to be made.

2) *Technological upgrade:* new installations to be implemented to facilitate the smart readiness enhancing process are defined.

3) *Technical exploration:* activities from the perspective of the different technical blocks are carried out in parallel to

TABLE I. SERVICE CONTRIBUTION IN THE REAL-LIFE DEMONSTRATION SITES.

Service category	***Type of building***	***Main capabilities***	***Monitoring***	***DHW***	***Heating***	***Cooling***	***Cooling***	***Ventilation***	***Dynamic envelope***	***Lighting***	***Electricity***	***eV charging***
Analytic services	Residential	Monitoring, assessment, profiling, prediction	X	X	X			X		X	X	X
	Tertiary	Monitoring, assessment, profiling, fault detection and operation and maintenance	X		X		X	X		X	X	X
Optimisation services	Residential	Visual comfort control, optimal indoor environmental quality, optimal renewable energy generation and distribution, flexibility		X	X					X	X	X
	Tertiary	Visual comfort control, optimal indoor environmental quality, optimal thermal comfort, flexibility			X		X	X		X	X	X
Digital Twins	Residential	Performance simulation, building operation	X	X	X					X	X	X
	Tertiary		X		X		X	X		X	X	X

analyse the information, confirm the objective of the problem under study (data analysis and modelling), design the automation and control modes (control functions), and define the set of actions for the generic interoperability upgrade.

4) User feedback: as an active part of the transformation process, users design solutions (data analysis and control technical blocks and end-user interfaces).

5) Development: Implementation activities were carried out for the described technical solution blocks, end-user applications, and building modelling, and user feedback is provided in an iterative way where appropriate.

6) Demonstration in pilots, validation with end-users and final assessment: the impact from the actual application of the solutions within the selected building categories is evaluated while stakeholders validate the contribution.

In particular, the expected contribution per category of high-level applications in the real-life demonstration sites is outlined in Table 1. This table showcases the main SRI domains [6] affected in terms of increased level of readiness, considering the equipment and technologies available depending on the use of the building.

IV. THE BUILDON SMART TRANSFORMER TOOLBOX

With the aim of building the next generation of smart buildings, a solution is proposed by means of a Smart Transformer Toolbox to be developed in the context of the BuildON project [23].

The concept has two main objectives: achieving energy efficiency in buildings and improving the quality of life of the occupants, managers and operators. This will be achieved by utilising ICT/IoT technologies to connect systems, communicate with the electricity grid and heating networks, and enable automated operations. The Smart Transformer Toolbox aims to cover a wide range of SRI domains, including monitoring, domestic hot water, heating, cooling, ventilation, lighting, electricity, and electric Vehicle (eV) charging. Its goal is to have a positive effect on several impacts, from occupant information to energy savings, maintenance, comfort, convenience, grid flexibility, and storage.

The system consists of a combination of technologies that work in layers, as depicted in *Fig 2*. These are supported by an interoperability framework as a cornerstone to ensure a unified and abstracted representation of the building, connecting heterogeneous and multi-protocol systems with higher-layer functionalities. The applications provided are described below:

1) The MAP services: a set of AI-analytics with monitoring, predictive and prescriptive capabilities, where these are required.

2) The O services: automation and control modes driven by optimisation services covering different building domains.

3) Digital Twins: physical and/or data-driven models for simulation and control abilities.

4) User tools: end-user applications to empower and support decision-making.

Considering the heterogeneity of building typologies and uses, climatic conditions and energy systems available in the building stock, the listed applications need to be generic but sufficiently configurable to ensure wide replicability.

A. The MAP services

The first level of functionalities is provided by a set of adaptable and easy-to-install services aligned with the SRI methodology to continuously Monitor, Assess and Predict (MAP) building performance. These AI/ML and rule-based analytics support maintenance and control processes. More specifically, the capabilities described include:

- Advanced visualisations for monitoring and controlling building performance.
- Benchmarking, based on a set of KPIs tailored to specific building categories.
- Building energy profiling.
- Data-driven forecasting capabilities.
- Operation and maintenance for anomaly detection.

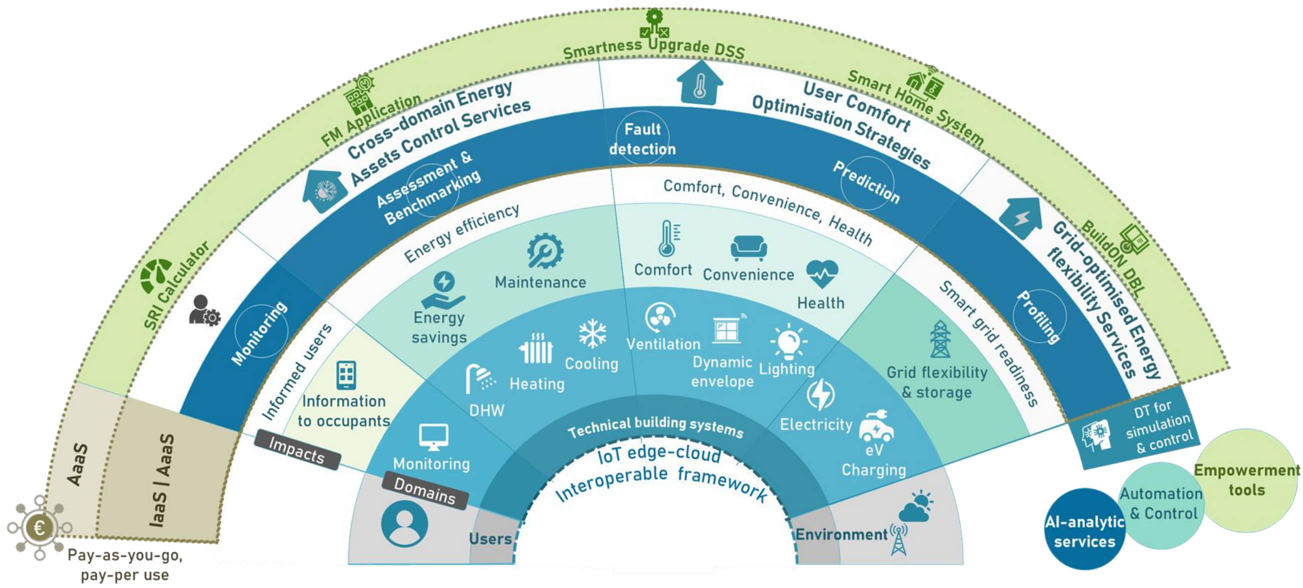

Fig. 2. The BuildON Smart Transformer Toolbox solution.

B. *The O services*

On top of the analytical layer based on an incremental approach, Optimisation capabilities are offered for smart automation and control. Three categories are envisioned, focused on improved environmental conditions, optimal control of heating and cooling energy assets, and flexibility between building and grid. The main functionalities delivered are outlined below:

- Visual and IEQ comfort strategies.
- Control of energy assets for heating and cooling generation and enhanced management.
- Flexibility for occupants and grid congestion management.

C. *Digital Twins*

The ability to reproduce how systems evolve over time makes the physical and/or data-driven models offered by Digital Twins powerful tools for inferring future behaviour, based on expected changes in the systems themselves or the environment. These capabilities are exploited at two different levels:

- Digital Twins for performance simulation, to predict building behaviour and support co-simulation in combination with analytical capabilities (Maturity Level 3 or Open-Loop Digital Twins, OLDT).
- Digital Twins for building operation, aiming at smart optimal control of building performance, based on predictions to control the multiple domain assets (Maturity Level 4 or Closed-Loop Digital Twins, CLDT [24]), thus achieving a bi-directional interaction with the building.

D. *User tools*

As part of the core concept, the top layer is covered by user applications, to involve stakeholders and encourage their active participation. A dual perspective is envisaged: firstly, to support the affordable smart upgrading process, and secondly, to enhance the human-smart assets interaction.

- A Decision Support System (DSS) centric approach aids in the assessment of the smart readiness of the selected buildings. Moreover, it provides insights into the application of different action plans or operational strategies to facilitate better informed decision-making.
- Tailored interfaces allow heterogeneous actors involved in the various categories of buildings to use building management applications in an accessible and user-friendly way, breaking down the barrier between technology and end-users with different levels of technological literacy, expectations and needs.

V. CONCLUSIONS

Although the smart building concept was first used several decades ago, many barriers still exist before actions can be widely implemented to make it a reality. Today, smart buildings must incorporate a higher level of automation in terms of technical building systems and consider their surroundings and the needs of related stakeholders. Technological advances have powered this evolution to enable seamless coexistence and sharing of resources and capabilities.

Digitalisation can drive this transformation and help improve energy efficiency by exploiting the potential of smart technologies. Several actions have gone in this direction through policies, such as introducing the SRI. This indicator, together with the advancement of technologies to data access, promotes the use of advanced automation and control of systems that exploit the potential of artificial intelligence. Modelling and optimisation strategies, can support improved decision making paving the way for the next generation of smart buildings.

This works aims to provide a generic solution to increase the smartness levels of buildings. Firstly, the methodological approach described allows to pose the problem, evaluate the constraints and needs and incorporate the most beneficial technologies iteratively and incrementally. This shows the potential behind and its versatility within different categories of buildings according to their use and configuration while underlying the benefits that can be brought to the whole building value chain. Secondly, the advancement beyond the state of the art of the proposed solutions is described towards a new situation in which technology barriers are minimised, opting for accessible and easy-to-use applications up to enhanced participatory scenarios transparently driven by cutting-edge technologies for no necessarily expert end-users.

The conceptual solutions presented are currently in a preliminary definition and development phase. Following the described methodology, building upgrades and implementing the described solutions will accommodate real-life application scenarios. In addition, continuous evaluation and interaction with stakeholders will enable subjective and objective validation of the solution to extract meaningful insights at a future and later stage of the strengths, risks and replicability potential for adopting the outlined solutions on a broad level.

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