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Smart Home applied to historic buildings
A real case study

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***Abstract*—Smart home is increasing in popularity within the IoT applications. This thanks to its ability to change house equipment into being more intelligent and interconnected and thus, delivering a connected life experience to the user. This paper investigates the literature and state-of-the-art on the smart home. Then, the paper presents a real case study that describes how smart home concepts have been applied to a heritage building, raised in 1922 and located in the City of Turin (Italy).**

***Index Terms*—Smart home, Heritage building, Green building**

I. INTRODUCTION

In the last decades, the Internet of Things (IoT) evolution spreads rapidly, unleashing new applications and services [13, 14]. They aim at improving the quality of life of people, delivering a connected life experience. The smart home is one of the several applications. As the authors in [2] point out, developing smart homes is crucial for smart cities' success.

Smart home, also known with the terms *home automation*, *home network* or *connected home*, refers to a residence equipped with a communication network, high-tech household devices, appliances, and sensors that can be remotely accessed, monitored, and controlled. Moreover, these technologies provide services responding to the residents' needs [3]. Indeed, Artificial Intelligence (AI) and IoT-enabled home devices (e.g., intelligent personal assistants, smart sensors) allow smart homes to become interconnected, interactive, intelligent, and to remotely control systems (e.g., lighting and heating). A study by Mordor Intelligence [30] highlights that the global smart home market is expected to grow to 119.26 USD billion by 2022 [30]. Indeed, smart home devices have been massively launched on the global market during the last years, especially by suppliers that are well known in the technology field.

There are several papers in the literature that address the topic of smart homes. Despite the great interest, smart home services have not been widely accepted [24]. According to [33], a reason relies on the lack of technology to establish the infrastructure of a smart home. This can be particularly relevant when a historic building becomes smart. These buildings are subjected to several restrictions aimed at protecting their architectural or historic merit. For example, the historic buildings are aligned to the others in terms of energy efficiency. However, they could avoid this regulation if meeting the target would alter their characteristics or appearance. Given these limitations, few applications of smart home concepts to historic buildings are present in the literature and state-of-the-art.

This paper overcomes the gap in the literature on smart home, with the following two contributions:

- we propose a review of the literature on smart home with an analysis of the historic building;
- we present a case study concerning a real application of smart home concepts, under the refurbishment of a historic building, raised in 1922 and located in the City of Turin (Italy).

The paper is organized as follows. Section II reviews the literature on smart home and its applications, while Section III discusses a real case study. Finally, in Section IV we summarize the paper's results and the contributions.

II. LITERATURE REVIEW

As stated in the Introduction, a part of the IoT and related technologies domains is represented by smart home applications. Despite the growing interest, a definition of the smart home seems to be challenging. In the literature, the response to this matter comes with a waterfall of definitions. The authors [29] define a smart home as a residence equipped with smart technologies that provides tailored services for users. In their review, they found that the various definitions include three concepts: technology, intelligent system, and the ability to satisfy users' needs. Recently, the concept of smart home has been extended and improved. Although the three aspects mentioned before are still present, new definitions insist on the communication among devices, and thus, on the status of being a part of an IoT system [31, 36]. Just a little attention has been paid in the literature to heritage building. To overcome the limitations, we analyze the applications of smart home concepts in the literature, identifying the main patterns and trends.

A. Methodology

From a methodological point of view, we started to retrieve information and case studies on smart homes from peer-reviewed journals, books, and conference proceedings, as the source of home literature. In doing so, we used the keywords “smart home”, “smart home applications”, and “smart building”. This yields a first sample of papers from 2001 to 2020. Then, we added other keywords to consider the potential objectives of the applications (e.g., “privacy”, “energy management”, “risk”, “environment”, “monitoring”, “control”) and to focus on the buildings with historic or artistic value (e.g., “historic building”, “historical building”, “heritage building”). We then reduced the entire set of selected papers by restricting the topic area. In particular, we filtered the studies that cope with a specific application of smart home concepts and related features. Moreover, we removed the papers for which all the information about the application is not fully available. These filters allowed to reduce the noise of information, excluding non-specific, more general, and less reliable documents, discussing the smart home topic indirectly and marginally. Finally, to gather information on technological and social development, we accepted articles without imposing temporal constraints in the search phase, but then a screening on the most recent literature has been performed. The literature included in the study appeared between 2014 and the first months of 2020, with a peak between 2018 and 2019. The growing attention on smart homes received in this period can be easily justified by the diffusion of the technology and the increasing requests for efficiency by householders and legislation.

This process yields a selection of about 61 papers: 77% in journals, 13% in conference proceedings, and 10% book chapters.

We analyzed the selected papers according to the following aspects:

- Objective. This category refers to the main goal of the smart home application.
- Display, Applications and User Interface. It addresses the relationship between the user and the devices to understand how the system communicates and provides information to the user.
- Devices. It provides an analysis of the main devices used to equip a smart home.
- Heritage building. It analyses the state of the art around the re-qualification of historic and heritage buildings through the creation of smart home.

B. Key findings and discussion

In this section, we review the literature on the smart home concept, with a focus on the frameworks mentioned in Section II-A.

First, concerning the objective, the greatest part of the analyzed papers (29%) deals with the adoption of the smart home concept to improve energy efficiency and energy management. About 16% of papers focus on the adoption of smart home devices in relation to the understanding of the consumers’ behaviors and how they respond to the innovation. Sustainability emerges as another relevant objective. Indeed, 10% of papers analyze solutions to improve the environmental sustainability of the building, also considering the refurbishment of historic structures, which are typically not environmental-friendly. While 9% of papers investigate smart home applications to provide benefits to the health condition of the users. At the date of this analysis, a little research has been conducted to analyze the economic perspectives, taking into account the costs of these technologies and the payback period of smart home solutions; and to the application of smart home concepts to protect a historic building for aging and needed refurbishments (3%, respectively).

As above-mentioned, a huge interest in the literature is dedicated to the energy consumption of smart home applications from different perspectives. Some authors (e.g., [16]) investigate the possible clusters of connected devices infrastructures to control and manage energy efficiency. Other contributions (e.g., [17, 32, 37, 39]) are devoted to understanding whether the shift from traditional homes to smart home systems can generate energy savings. For example, Tirado Herrero et al. [39] state that, although smart home equipment manufacturers claim to reach up to 30% reduction in energy consumption, the actual energy saving estimates account for a modest 10-12%, in the United States. Similarly, Ford et al. [17] notice that the residential energy demand reduction has not been proved yet, with the expected energy saving not founded in actual applications. The authors in [37] investigate the potential energy savings and the improvement of historic buildings’ livability. Several papers in the literature deal with the reduction of energy consumption while improving efficiency, proposing different approaches: (i) simplifying the user approach through new user interfaces and new system architectures with tools like Arduino [15, 22, 28, 38]; (ii) suggesting simple but effective precautions to save energy such as appliances auto-play in low energy load moments or controlling device consumption while turned on and in sleep mode [16, 21]; (iii) creating heuristics and decision-support algorithm [19, 23, 34]; (iv) trading the energy among homes [1].

Concerning the category on display, applications, and user interface, different papers in the literature address the communication between user and devices. This relationship is commonly seen as an important characteristic of the smart home. The active role of the user is recognized as effective by different sources, underlining the importance of both real-time feedback and historic data in increasing awareness [8, 28]. For example, Nilsson et al. [32] discuss the role of real-time feedback into smart home energy management systems to allow the user to understand its actions and manage them. Ford et al. [17] analyze 19 in-home displays and notice how 17 of them allow access to historic data and 6 provide predictive use. Expanding the time horizon from the present toward both past and future provides a clear benefit to the users’ awareness. Finally, other contributions in the literature discuss the need for the development of software and applications to support the relation between user and devices [11, 25].

Across the literature, there are some attempts to describe the main technologies composing a smart home system. For instance, Li Jiang et al. [26] provide smart appliances that would make users’ life more comfortable. Some examples are a smart bed able to wake the user up with combinations of preferred sounds and smells; a smart mat that sensing the body weight and recognizing the footprint is able to identify the user, recording who is at home while removing the dust and bad odors. More in general, commonly recognized smart home devices in the literature are the following: (i) smart thermostats that collect data with sensors, from temperature to humidity and outdoor weather; allow programming of time points with setpoints temperatures, reducing heating when not needed; (ii) smart plugs/switches able to sit between the electricity source and the appliance, providing information and control functionalities to non-smart appliances; (iii) smart lights composed by sensors, microprocessors and remotely controllable switches based on led lamps technology that offer the users remote or automated control functionality of lights. Other discussed devices are other sensors, micro-controllers, web-cams, and the communication medium, connecting the smart devices to the wired or wireless control unit [17, 20, 23, 35, 38].

With the increasing interest in preserving historic and heritage buildings given their architectural and historic value while improving efficiency, several papers in the literature apply technology to these constructions. More in detail, Capella et al. [7] install a set of low power sensors to guarantee early detection of problems, protecting the historic value of the building. Other authors [4, 9] adopt a conservative approach using technologies, e.g., laser, infrared, and sensors, during the restructuring phase of a historic building. Costanzo et al. [9] and Biagini et al. [4] debate through a case study the importance of non-invasive analysis and non-destructive refurbishment techniques on historic buildings. They perform an analysis of the building structure through scanners and composed a 3D model, a sort of digital twin of the building to be digitally analyzed before the intervention, understanding how a specific part of the structure is raised, and its possible weakness. Finally, some contributions [5, 6, 10, 12, 18, 27] are focused on the re-qualification of ancient buildings, especially under what concerns the energy efficiency (e.g., heating and lightening) according to the European environmental legislation.

III. CASE STUDY

In this paper, we consider a real application of smart home concepts to a historic building located in the Mirafiori district of the City of Turin (Italy). The building has a relevant historic value specifically recognized as historic-environmental value. It was raised in 1922, and it is composed of an underground floor (the basement), a ground floor, a first floor, and an attic, for a total of 190 m^2. Regarding efficiencies and carbon emissions, the building original heat system accounted about 271.06 kWh/m^2year of energy performance, and 82.42 kg/m^2year of CO2 emissions, before re-qualification. This low-efficiency performance overcomes the threshold set by the European regulation on the efficiency clusters at 175 kWh/m^2year, assigning the building the G-Class.

The building recovery plan is part of the collaboration with ABSE Studio Srl and is composed of: (i) architectonical project and internal restructuring; (ii) home automation system; (iii) roofing restructuring and photovoltaic system installation.

In the remainder, we provide a detailed description of these phases.

A. Architectonical project and internal restructuring

The first phase is devoted to performing different interventions, e.g., first-floor slab consolidation, insulation of external walls, electric system refurbishment, hydraulic system refurbishment, and finally, reduction of thermal dispersion due to fixtures. It has a twofold aim: first, to solve structural weaknesses, recovering the effects of time, and second to allow access to the first floor.

A set of installations have been conducted to increase the energy and heating efficiency of the home while reducing waste. The first installation of the heating and conditioning system took place in the basements. The choice was a thermal system with energy generation based on a pellet stove. Then, for the rest of the house, radiant panels on the ceilings of the ground and first floor have been selected to allow the heating of three floors with just two series of panels. The panels have been applied to the false ceiling (Figure 1) to protect the load-bearing structures. The false ceiling leaves 5 mm of blank space to the ceiling, and it is 27 mm thick, supporting the 15 mm thick panels with a metal structure. The application of stucco and painting allowed the hiding of the panels to the residents' eyes. The chosen thermic plant is a reversible air-condensed heat pump, which can be used to both condition and heat the panels of the ground and first floors. Figure 1 depicts the panels heat generations.

Fig. 1. Installation of the heating system (left) and thermography picture of the panels while working, by means of a thermoscanner (right)

Then, a key role is played by the adoption of nanotechnologies to obtain energetically-efficient insulation of perimeter walls. The insulation, applied after an anti-mold treatment, was performed through a coating on the inner face of the walls. The coating material was composed of a fiberglass mesh with a thermal skin coat constituted by lime, perlite, cocciopesto, and hollow glass spheres (based on expanded silicates). On the one hand, this solution is ecological as the materials are bio compatible. On the other hand, it gives to the structure both mechanical resistance and high breathability, allowing to resolve the humidity reduction that typically affects historic buildings. The steam resistance is characterized by a factor $\mu < 8$. The thermal conductivity of cellular glass ranges between 0.040 and 0.050 W/mK. This value, associated with a thickness ranging between 4 and 5 mm, leads to a thermal resistance equal to 0.45 m^2K/W. A thermographic assessment of the walls showed that the average external wall temperature goes from 14°C before the treatment (Figure 2) to 18°C after the nanotechnology-based insulation (Figure 3).

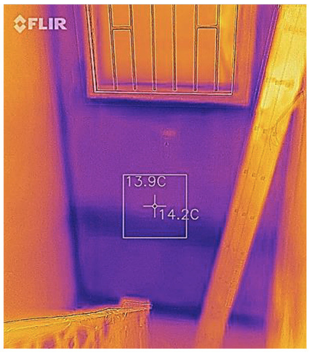

Fig. 2. Thermography of an external wall before the nanotechnology-based insulation.

Fig. 3. Thermography of an external wall after the nanotechnology-based insulation.

During the house refurbishment, the wall radiators have been removed and a brand-new system has been created. The electric system switchboard that is supplied by the photovoltaic modules is connected with all the household plugs and appliances and the heat pump. The reversible heat pump generates the domestic hot water (DHW) used both in household utilities and in panel heating.

Finally, the windows and the other fixtures were replaced with newer, and most effective insulation solutions.

B. Home automation

In order to allow the creation of a stable connection to the Internet, the project determined the installation of an optic fiber connection. A Mesh Wi-Fi network based on the Netgear system was chosen since it does not need reconnection while moving from an access point to the other. Besides, it is always effective in minimizing the peak load due to the simultaneous connection of different devices. The system connection capacity is 550 Mbps. The installed smart home system is based on Amazon Alexa. For the house security improvement, surveillance cameras are placed across the house. The control of the smart home system is performed through the Alexa App and the distribution of Amazon Echo devices (i.e., smart speakers) in different rooms. The user can control the domestic electric system through smart plugs and some smart applications. The integrated lighting system, which communication is based on Zigbee protocol, is controlled by the Alexa Skills extension. This is a simple update available on the Amazon Alexa smartphone app. Just select the app extension the user can improve its Alexa automation system with the so-called Skills, which similarly to a smartphone application or a personal computer program, allows the user to manage the desired device. The house security relies on a system of surveillance cameras, model Arlo Pro by Arlo. One of their more interesting features is the fact that their control through the Arlo Alexa Skill, allows householders to access the surveillance cameras at any moment, managing them from the in-house speakers or the smartphone application.

C. Roofing restructuring and photovoltaic system installation

The last step of the project was the refurbishment of the roofing, together with the installation of a photovoltaic plant (Figure 4). The plant composition is of 18 modules for a generated nominal power of 6 kilowatt-peak (kWp), with a production of 7780 kWh per year in an estimated condition of annual solar radiations equal to 1640 kWh/m^2. The roof acting as a base for the photovoltaic modules has a slope of 35° for both the tilt and the orientation angles. Then, the power generated by the photovoltaic modules reaches the inverter. The electric meter provide information about energy production. This generated energy is exploited in substitution of the external energy supply when possible, both for the conditioning plant and the household utilities. Unused remains of energy enters into the electricity grid.

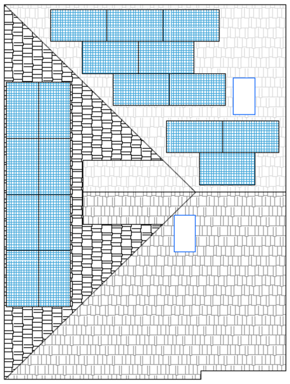

Fig. 4. Photovoltaic panels project.

IV. CONCLUSIONS

In the case study, the transformation from traditional to smart home allows gaining better performance. Indeed, the original energy efficiency of the building was very low, corresponding to the lowest class of the energy ranting system.

The refurbishment project leads the house from the G-class to A1-class, moving the energy performance index from 271.06 kWh/m^2year to 68.52 kWh/m^2year (-74.7%).

Moreover, the CO2 emissions after the re-qualification are expected to account for 15.22 kg/m^2year, signing a reduction of 77.8%, also due to the utilization of the photovoltaic system.

The better performance is also expressed in term of reduction of the household total consumption. According to the estimations performed by technicians assessed, this value is around 80,790 kWh/m^2year before the refurbishment, distributed in thermal energy consumption equal to 73,190 kWh/m^2year and electrical energy consumption at 7,600 kWh/m^2year. The post-refurbishment scenario, despite its increase in electrical energy consumption due to the heat pump installation, foresees a drastic reduction of the total value, down to around 32,280 $kWh/year$, with a split of 18,580 kWh/y on thermal energy and 13,700 kWh/h on electric energy. Since the photovoltaic system allows to produce the 54.8% of the electrical energy, the computed CO2 total emissions are reduced by 87.9% ranging from 22,140 $kg/year$ to 2,675 $kg/year$.

From an economic perspective, the total cost of the energy efficiency and smart home project accounted for 75,000 € over a total of 190,000 € (i.e., 394.74 e/m^2 over 1000 e/m^2). Although the relevant initial capital expenses, 27,690 € of which related to the smart technologies and systems, their adoption would provide benefits in the medium-long run. Indeed, the project is expected to reduce household energy requirements from 5,712 €/year to about 2,500 €/year. Moreover, due to the improved efficiency savings, the payback horizon is estimated to be of just 4.31 years.

The case study highlighted as adopting smart technologies can improve the environmental and economic sustainability of heritage buildings while maintaining their historic and architectural value. All the planned interventions have been implemented and concluded. Two activities that will be performed in the future are the constant integration of additional functionalities and remote controls with Alexa and the revision of the coating to monitor the thermal performance and make eventual adjustments (e.g., expanding the thermal coat) if needed.

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