THE EFFECTIVENESS OF AN INTERNET OF THINGS-AWARE SMART VENTILATED INSULATION SYSTEM

by

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The considerable thicknesses of common insulation systems, applied to the internal or external building envelope, can be inappropriate in the Mediterranean climates for improving buildings' energy efficiency and their internal comfort at the same time; in fact, the high thicknesses of insulating material provided by legislation standards can be cause of environments' over-heating and formation of condensation. In this framework, the S-MUnSTa system is an innovative dynamic ventilated insulation system able to overcome condensation and overheating phenomena, also exploiting Internet of Things technologies; the main characteristic of the proposed smart insulation is that the ventilated external layer is equipped with dynamic valves of insulating material, for opening and closing the air channel, with the aim to optimize the thermal performance. In order to guarantee the expected performance of the system, as it has been patented, in this paper an innovative fixing system to install the insulating panels is presented. This new method allows a rapid and easy installation, without any specialization required and with low maintenance costs.

Key words: *energy efficiency, ventilated insulation system, Internet of Things, wireless sensor networks, CoAP, dry mechanical connection*

Introduction

Buildings energy efficiency plays a key role in terms of reducing energy consumption and improving the internal comfort. Buildings, in fact, are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU. It has been demonstrated that thermal insulation of the house envelope can reduce heating bills for about 50-80% [1]. For this purpose, since 2005, legislation standards regulate the use of different insulation systems based on the use of considerable thicknesses of insulation, placed to the internal or external building envelope. The insulation systems have evolved into two main typologies. In the first type, the insulating panels (of different materials) are adjacent to the internal or external side of the envelope. However, in Mediterranean climates, in many cases, the use of high thicknesses of insulating material impedes the vapour transmission and led to the consequent formation of condensation [2], creating also a thermos effect in the summer period [2-5]. Instead, the second type, called dynamic systems, involves forced and natural ventilation mechanisms. The advantage of using

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these solutions has been demonstrated by many studies, which deepen on ventilated façades [6, 7], Trombe walls [8] and dynamic insulations [9-11]. However, even if the ventilated systems reduce the condensation phenomena, these solutions are not able to overcome the over-heating problem, as occurred in traditional external insulations.

In order to solve the described problems of the existing insulation systems, in 2013, a pre-assembled ventilated insulation system (registered trademark MUnSTa©) [2, 5, 12] was patented; the invention led to a considerable technological simplification: MUnSTa© insulation system, in fact, consists of a few number of simplified components, hence allowing a fast and easy assembly. This innovative system, while using considerable thermal resistance (for the winter), is able to overcome the summertime over-heating problems and the condensation phenomena with the use of a ventilated external layer. The system, in order to optimize the thermal performance, is equipped with valves of insulating material, for opening (in summer) and closing (in winter) the ventilation channel.

This paper is an enhancement of the work presented in 2016 [13], where the effectiveness of the proposed system has been demonstrated through a numerical validation. In the same paper, an implementation on the opening/closing of the valves of the insulating solution, through the aid of a wireless controller system based on Internet of Things (IoT) technologies, was carried out. This new system composed of both the innovative MUnSTa© and the innovative control system is called *S-MUnSTa*. Starting from these *conforting* results, the main aim of this research work is to *engineer* the MUnSTa© application, so as to make possible the mass-production of the system. In order to do so, in this work a further implementation of the MUnSTa© fixing system is presented, that guarantees the expected performance of the patented application. Here the insulating panels are mechanically dry connected to a sub-structure realized in pultruded material, which in turn is fixed to the external walls through a specific system able to guarantee the correct positioning and calibrations. With respect to the original fixing system, the new technology allows compensating for any unevenness of the external walls, and the dry connections avoid the durability issues linked to the use of the adhesives [14]. The installation is rapid, easy, and any specialization is required. Furthermore, all the components are available on the market, therefore both the production and maintenance costs are advantageous.

In addition, this work presents a comparison among S-MUnSTa and other insulation technologies available on the market, with the aim of describing which are the benefits that this innovative system can guarantee. Finally, a brief description of the IoT-aware services that the system can provide is presented, showing all the different modalities the end-user can interact with them.

The S-MUnSTa system

The MUnSTa© is an innovative thermal buildings insulation applicable on any configuration of walls and roofs (even with windows and doors), both in existing and in new constructions. This system adapts dynamically to the external climate conditions, improving the comfort and energy savings during the whole year. In this system, the insulation panel is separated from the wall or the roof, by *spacer wedges* of the same insulating material, hence creating an air gap, on the contrary of the traditional one, where the panel is in contact with the façade.

The channel can be either ventilated during the summer or closed hermetically during the winter. The ventilation is controlled by movable valves, equipped with electronic control, positioned at the top and at the bottom of the air gap. The system could also be completed with sensors for automatic opening based on external temperature. Through numerical simulations, previous studies [2, 5, 12], individuated the appropriate periods for valves movement: the opening in the first days of May and the closing in the last days of September.

Patrono *et al.* [13] demonstrated the effectiveness of the proposed system through a numerical validation; in this simulation, the internal surface temperature of a real case of study was investigated, with respect to the traditional external insulation and to the configuration without insulation system, proving the best performance of the MUnSTa© system, both in summer and winter seasons. Figure 1 reports the internal surface temperature on a typical summer day of a case of study. The best performance was registered by the MUnSTa© solution, obtaining a temperature reduction up to 2.5 °C. The valve opening, in fact, led to the decrease of surface temperature. On the contrary, the use of a traditional external insulating system caused overheating phenomena in the central hours of the day.

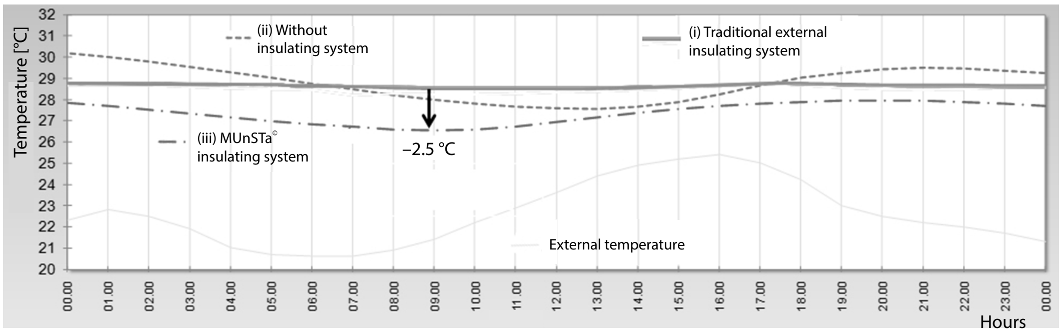

Figure 1. Effectiveness of the MUnSTa© system with respect to a traditional insulation system

In the same paper, an implementation on the opening/closing of the valves of the insulating solution, through the aid of a wireless controller system based on IoT technologies, was carried out. This new system composed of both the innovative MUnSTa© and the innovative control system is called *S-MUnSTa*. Figure 2 shows the overall logical architecture of the proposed smart ventilated insulation system, including the power backbone and the tools to interact with it, both locally (smartphone application) or remotely (web dashboard), as explained in later sections.

The insulation system includes special panels (SP) and standard ones (without valve and control system). Both types of panels are spaced from the building envelope to create an air gap between walls and the insulation layer. The SP are positioned according to a predefined pattern, and the valves allow the user to control the ventilation channel according to his/her needs, without involving sophisticated control algorithms and in several ways (both locally and remotely).

The central control unit (CCU) is a module handling user commands destined to actuators, managing the power source coming from the photovoltaic system and communicating wirelessly with the wireless panel controller (WPC) included in the SP, in order to open or close the linear actuators of each SP. The CCU provides in output the power line backbone for each SP.

The SP plays a key role in the system, since it is equipped with a movable valve and, in order to control the opening/closing of the valve, it contains a wireless controller, a linear actuator and a battery that powers it (fig. 3). The WPC consists of a low-rate wireless PAN node and implements the logical functions of actuator and battery controller. The SP are connected to the power line backbone coming from the CCU to power their batteries and WPC.

This control infrastructure makes the insulation system an integral part of the IoT, offering a generic physical infrastructure upon which several custom applications can be implemented according to user needs. This approach follows the recent trend in the IoT context, which allows interconnecting physical objects to the Internet by means of the so-called smart objects, *i. e.* sensing or

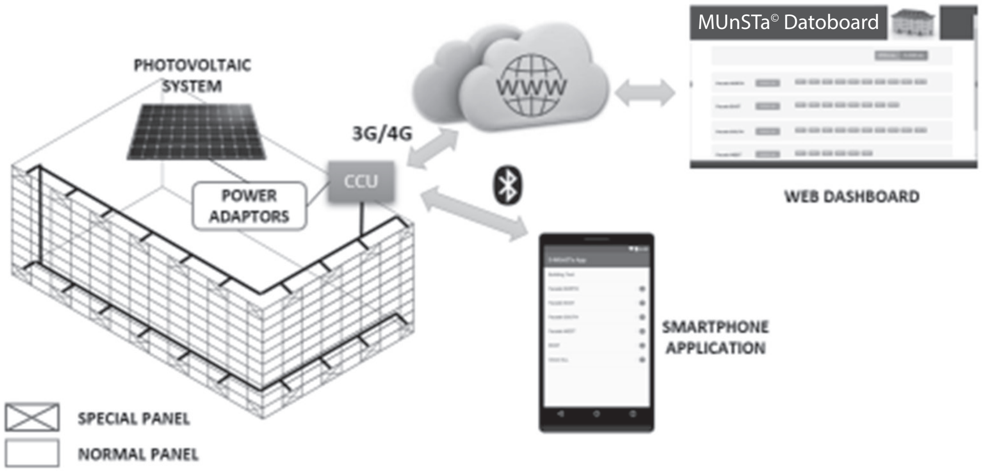

Figure 2. Logical architecture of the smart ventilated insulation system, power backbone and the tools to interact with

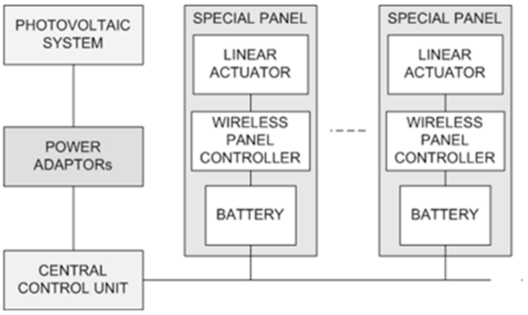

Figure 3. Smart ventilated insulation system overall logical architecture

actuating devices able to communicate each other by using standard Internet protocols. In this way, starting from smart objects based on energy efficient wireless sensor networks [15-18] and by exploiting mash-up engines or rule-based application platforms, it is possible for the end user to develop high-level applications without dealing with low-level hardware and protocol details. These patterns have been recently exploited by several studies in the literature [19-21], even though none of them address similar solutions in the field of external insulation systems.

Methodology and research design

As shown in fig. 3, the two main building blocks of the smart control system are the WPC, included in each SP, and the CCU, installed inside the building.

The logical scheme of the WPC is depicted in fig. 4. It is a typical node of a low-rate wireless personal area networks (LR-WPAN) which implements the logical functions of actuator controller and battery controller.

The first function is in charge of executing the opening and closing of the linear actuator, responding to commands sent by the CCU. The second function deals with the management of the battery charge level. It is worth noting that the WPC is powered by the same battery used to power the actuator (with a proper power adapter). From a technological point of view, the WPC is built upon an IoT-compliant protocol stack, based on the constrained application protocol (CoAP) Group Communication [22] standard at application layer and the IEEE 802.15.4 protocol (IEEE 802.15 WPAN™ Task Group 4, http://www.ieee802.org/15/pub/TG4.html) for the physical and media access control layers of the communication stack. This protocol, in fact, provides a multi-hop communication pattern among nodes of a wireless mesh network, *i. e.* a communication in which two or more wireless hops are needed to convey information from a source to a destination that cannot communicate directly. Intermediate nodes act as a relay to forward messages between those nodes. This is the case of insulation systems for large buildings, where the distance between a given WPC and the CCU can be greater than their radio range (which is approximately 10 meters). Moreover, radio range can also be reduced by walls attenuation.

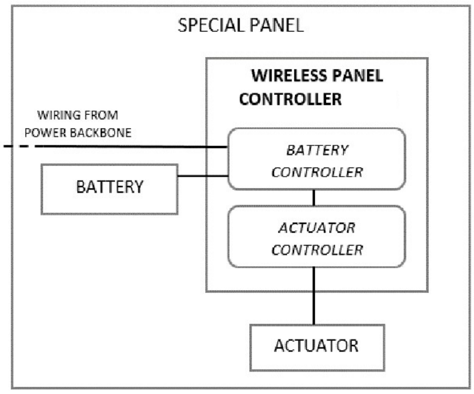

Figure 4. Logical scheme of the WPC of a SP

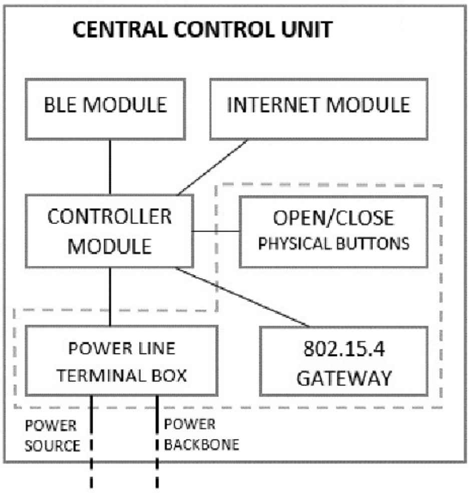

Figure 5. Logical scheme of the CCU

The logical scheme of the CCU is illustrated in fig. 5. Its main functionalities are:

- handling user commands destined to actuators and triggered in different modalities,
- managing the power source coming from the photovoltaic system, and
- communicating wirelessly with the WPC to open or close the actuators of each SP.

User can act on the valves system in three different ways. The most common way is to use physical buttons on the CCU: once the user pushes the OPEN or CLOSE button, the controller starts the opening or closing routine, which implies interacting with WPC until all actuators are in the desired state. The second way to interact with the system is by exploiting the Bluetooth Low Energy (BLE) transceiver of common smartphones. By means of a dedicated smartphone application, users can communicate with services and characteristics offered by the BLE module of the CCU to issue commands to change actuators' state. A screenshot of the smartphone app is shown in fig. 2. The third mode of interaction is the Internet remote control, by exploiting the 3G/4G module for Internet access of the CCU. It defines a web application reachable from the Internet thanks to the small web server hosted on the CCU and its public IP address. The application defines some REST API, accessible only by authorized and authenticated users, which allow to interact with all valve actuators at once, with subsets of them, or even directly with each single actuator. Therefore, it represents the most powerful and flexible way to interact with the smart system. A remote user, in fact, can connect to the system simply by opening a web browser and by typing the URL of the system: once logged in, the user, through the visual interface, can trigger commands to the desired actuators in order to open or close them. This is fully compliant with the IoT approach. In future versions of the system, further information will be able to be displayed by the visual interface, such as the current values of some ambient parameters (temperature, humidity, insolation, *etc.*) or some statistical information about the opening/closing of the valves over time. In fig. 2 an example of the Web application interface is also depicted.

The communication with the WPC to trigger actuators state change is carried out by including an IEEE 802.15.4 interface that acts as a gateway for the wireless communication.

It is worth noting that the CCU has a modular structure. In fact, it is possible to install more than one IEEE 802.15.4 gateway, power line terminal box and/or command buttons, according to the size, the topology and the position of the building. This allows WPC segmentation at network level (by using different gateways), batteries segmentation at power level and the possibility to interact with a subset of WPC with dedicated buttons.

Regarding the sizing of the battery in each SP, it directly depends on the chosen linear actuator, which is the most power consuming device, whereas the consumption of WPC is negligible (in the order of tens of milliampere) with respect to the actuator. Moreover, taking into account that the actuator activation happens on average two times per year for less than 1 minute, for a linear actuator working at 12 V and 0.95 A, a battery with a capacity of 2500 mAh can last for more than 1 year.

Wired alternative solution

In buildings where a wired electrical system is available, it can be exploited to power each linear actuator of the SP through a wired connection. Indeed, a power adapter must be used anyway in order to adjust the voltage and waveform of the electrical network signal to match actuator input requirements (*e. g.* from 220 V AC to 12 V DC). In this case the battery on the SP can be removed and the power of each actuator can be managed by the CCU, together with commands issuing. The controller module in the CCU, in fact, can activate the output line of the terminal box and control the polarity of the output signal at the same time, in order to open or close the attached actuators. The number of actuators connected to the same power line depends on the capacity of the power adapter attached to the input line of the terminal box. By doing so, groups of actuators can be actuated at the same time from the CCU, without the use of panel controllers. This solution can decrease the cost of the overall system, but cannot provide individual actuator control.

Table 1 illustrates a high-level comparison of the proposed solution with the illustrated wired alternative solution.

New mechanical dry connection of the insulating panels

In this section, the implementation of the MUnSTa© fixing system is presented, which guarantees the expected performance of the patented application. In the new solution, the insulating panels are mechanically dry connected to a pultruded profiles sub-structure. The latter is fixed to the external walls through a specific system (*i. e.* the *plate-spherical knot system*) that sets the correct positioning and calibrations. With respect to the original fixing system, the proper adjustability of the sub-structure is guaranteed in all three directions (x, y, z) and in rotations, in order to compensate for any unevenness of the external walls. Furthermore, the dry connection allows to avoid the durability issues linked to the use of the adhesives [14]. The installation is rapid and simple, and any specialization is required. All the components are available on the market, therefore both the production and maintenance costs are advantageous. As in the original fixing system, every kind of external finishing (plaster or architectural panels) are allowed, also thanks to the tough pultruded profiles sub-structure.

The assembly operating sequence (starting from the single components to arrive to the finished insulation system) with the description of the components, are summarized in the following 6 steps.

The first two passages are done directly in the production workshop, where the *plate--spherical knot system* is fixed to the sub-structures profiles.

Table 1. Comparison of the proposed solution with a wired alternative solution

Functionality	Proposed solution	Wired alternative
Power source	Photovoltaic system	Wired electrical system
Power adapter	Sized according to battery input requirements	Sized according to actuators input requirements
Battery charge level control	On SP with WPC	–
Actuator power source	Battery on SP	Wired backbone with adjusted tension and waveform from the CCU
Actuator input polarity control	On SP with WPC	On CCU
Actuator open/close control	Triggered by CCU and managed by WPC	Triggered and managed by CCU (through output power line activation)
Panel controller	IoT-compliant WPC	Unnecessary, actuator and power controls are performed by CCU
Individual actuator interaction	Yes, through WPC	No
Group actuator interaction	Fully, through CoAP Group communication	Partially, through wired backbone segmentation

- *Step 1*. The sub-structure profiles, T-section pultruded profiles, (75 × 75 × 8 mm), are cut out according to the architectural design. The composites materials are employed because of their advantageous properties: high mechanical performance, lightness, durability and thermal and electrical insulating properties [23].
- *Step 2*. The T-section pultruded profiles are connected to the *plate-spherical knot system*. The latter is the subject of a patent application and it is composed of two elements made of galvanized steel as depicted in fig. 6: a plate (60 × 40 mm^2) with 18 drills, where a bearing sphere is welded and C-shaped plate (80 × 80 mm^2) with 4 drills, where a threaded tube (diameter of 30 mm) is welded. The two plates are joined through the clamping of the sphere in the appropriate circular accommodation with the aid of the bolt.

Figure 6. Assembly of the *plate-spherical knot system*

This system guarantees the calibration of the rotations. The *plate-spherical knot system* is positioned in the proper point of the T-section pultruded profile and fixed trough four thread screws (fig. 7).

The installation phase is finished in the construction site; the positioning of the MUnSTa© anchorage system is carried out in *Steps 3* and *4*, while in *Steps 5* and *6* the insulating panels are connected to the sub-structure and the external finishing is applied.

- *Step* 3. The positioning of the MUnSTa© anchorage system is done through laser alignments and, in the external walls, the tracking of horizontal and vertical lines is performed with the objective to place L-section aluminium profiles. These guides are useful to install vertical frames and they are connected to the walls through expanding steel anchors, fig. 8.
- *Step 4*. The sub-structure is connected to the L-section aluminium profiles. Firstly, in order to calibrate the z position, a threaded bushing connected to a drilled plate, is screwed to the expanding steel anchors and connected to the L-section aluminium profiles, fig. 9.

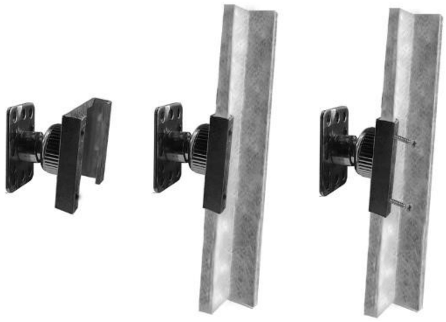

Figure 7. Assembly of the *plate-spherical knot system* with the T-section pultruded profile

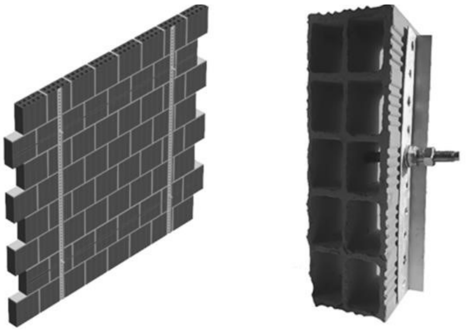

Figure 8. Positioning of the L-section aluminum profiles in the building external walls

Secondly, in order to calibrate the *x*, and *y* positions, the drilled plate is connected to the *plate*-*spherical knot system* through plastic rivets, fig. 10. The calibration of the rotations is guaranteed by the sphere in the *plate–spherical knot system*.

- *Step 5.* The insulating panels (both the normal and the special types) are connected to the pultruded sub-structure through steel clips, fig. 11. These latter represent the best rapid and cheap connection methodology, also ensuring high load carrying capacity (up to 90 kg per each clip). Furthermore, this system is durable also in aggressive environments.
- *Step 6*. The external finishing is applied on the insulating panels. Every type of cladding could be adopted, according to both architectural and structural choices. In order to guarantee the structural integrity, the proper fixing method is recommended.

Comparison with different insulation technologies

In tab. 2, different insulation technologies available on the market are compared with the MUnSta© dynamic system equipped with both the IoT and the new fixing technologies. For this purpose, several parameters are considered. The vapour breathability, the yearly comfort and energy saving are important criteria for ensuring the efficiency of an insulating system. Furthermore, the adaptability to every building typology, the ease and speed of installation and maintenance and, finally, the cost-effectiveness, are not minor factors for the end-users' choice.

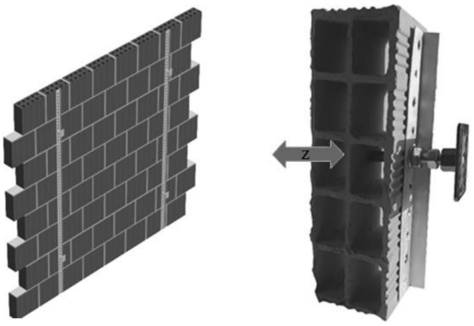

Figure 9. Connection of the threaded bushing – drilled plate to the L-section aluminum profiles

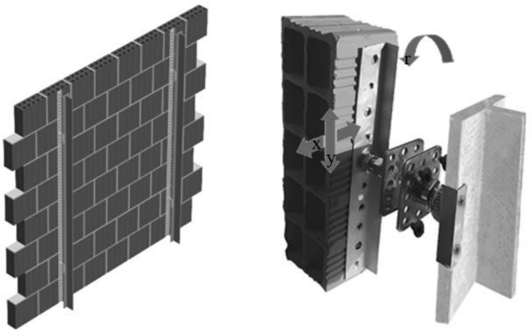

Figure 10. Connection of the threaded bushing – drilled plate to the *plate-spherical knot system*

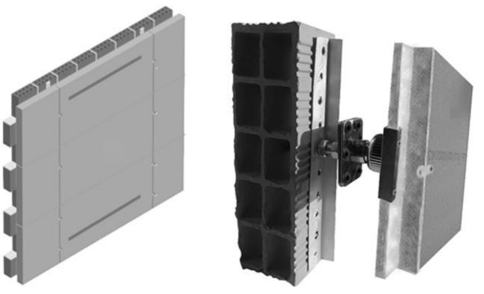

Figure 11. Connection of the insulating panels to the pultruded sub-structure

From the analysis of this table it is evident that the MUnSTa© insulating system satisfies in a single product every chosen parameter, unlike the other methods. In particular MUnSTa© system is the only one that guarantees both summer and winter comfort and energy saving, together with an easy and speedy installation, as explained in the previous section. On the contrary, in the external insulating systems the high thickness of the panels prevents the vapour emission, causing condensation phenomena. In summer season, in our Mediterranean climates, this system also led to overheating problems, with consequently discomfort situations [2-5]. In addition, both climate and human factors should be considered during the installation phase. In fact, it was demonstrated that both atmospheric agents and human errors could affect the durability aspect of the insulating system [14]. Also passive systems (Trombe walls) present overheating problems during the summer period and, for this reason, additional ventilation systems are necessary [8]. Furthermore, these systems require specific buildings configuration and orientation, in order to allow the natural ventilation and both the construction and maintenance phases are complicated. In ventilated façades, the ventilated channel reduces the condensation phenomena, but these solutions are not able to overcome the overheating problem, as occurred in traditional external insulations; furthermore, they present installation and maintenance complexity problems [2]. With regard to the dynamic insulation, its application requires careful system design to ensure that the interior surface temperature of

Table 2. Comparison of the S-MUnSTa with other solutions available on the market

Insulation system / Parameters	S-MUnSTa	External insulating systems	Passive systems (Trombe walls)	Ventilated facades	Dynamic insulation systems
Adaptability to buildings typology	✓	✓	✗	✓	✗
Ease and speed of installation	✓	✗	✗	✗	✗
Ease of maintenance	✓	✓	✗	✗	✗
Vapour breathability	✓	✗	✓	✓	✓
Summer comfort	✓	✗	✗	✗	✗
Winter comfort	✓	✓	✓	✓	✗
Summer energy saving	✓	✗	✗	✗	✗
Winter energy saving	✓	✓	✓	✓	✗
Cost-effectiveness	✓	✗	✓	✗	✗

a room is at an adequate level. If the air flowing through a dynamic wall is cold, leading to low surface temperatures, dynamic insulation does not necessarily provide better thermal comfort than conventional insulations [9].

Regarding the cost-effectiveness, an affordable price makes the MUnSTa© system very competitive in the market. In fact, the cost-benefits ratio is advantageous respect to the other insulating systems: the price (65-70 euro/m^2 and 75-80 euro/m^2 with the new fixing technology) is comparable with the External insulation systems (50-60 euro/m^2) and less expensive than the Ventilated façades (100-140 euro/m^2 in relation to the different finishes). Regarding the Trombe walls, these solutions are the most expensive, and the more are the additional expenses, the more are the user's benefits [8].

Conclusions

In this paper, a refinement and an improvement of the S-MUnSTa IoT-based ventilated insulation system, has been proposed. The main aim was to *engineer* the MUnSTa© application, so as to make possible the mass-production of the system, ensuring the expected performance of the MUnSTa© patent. In order to do so, a new fixing system of the MUnSTa© has been presented, according to the technological simplification criteria. Through this new method the insulating panels are mechanically dry connected to a pultruded profiles sub-structure, then the quality is not influenced by the weather conditions and the features of the patented system are guaranteed. This new methodology allows a rapid and easy installation, with any specialization required except for the connecting of the cabling. All the components are available on the market, therefore both the production and maintenance costs are advantageous. As in the original fixing system, every kind of external finishing (plaster or architectural panels) is allowed, also thanks to the tough pultruded profiles substructure.

Furthermore, a comparison among S-MUnSTa and other insulation technologies available on the market has been done, in order to investigate the chance to commercialize the system. The chosen parameters shown the important benefits that this innovative system can achieve with respect to the other solutions available on the market, and the most important are the summer comfort and energy saving and the ease and speed of installation and maintenance.

A high-level description of the IoT-aware services that the system can provide has been presented, showing all the different modalities the end-user can interact with them, ranging from physical buttons switching to local smartphone interaction and remote Internet connection.

Further works consist into the implementation and other validation phases of the proposed system, that are currently under investigation, comprising a prototype of the S-MUnSta system and a new simplified fixing system. The new simplified fixing system will provide a small frame put onto the insulating panels directly in the factory, so to further reduce the installation phases.

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