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Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit

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ABSTRACT

Interoperability issues on networks of heterogeneous devices create a relevant and complex challenge. The Word Wide Web Consortium (W3C) develops a series of specifications, called the Web of Things (WoT), to address this challenge. WoT is focused on integrating smart things into the application layer of a system using on Web technologies. Thus, WoT is expected to have a great impact on the smart retrofit of buildings once data from existing and future planned systems are able to be gathered and analysed seamlessly. In this paper, we (*i*) analyse the application of the W3C WoT on the core of the Building Energy Management System (BEMS) to enable the universal integration of both private and public systems; (*ii*) propose a novel architecture for the BEMS based on the W3C specifications; and (*iii*) present a real-world application based on this architecture. The application covered in this paper allows data gathering from sensors with standard commands, enabling data analysis with a simple collecting process. By applying these specifications, smart building retrofit can be benefited from: (*i*) the ability to merge and scale different systems and devices; (*ii*) the easiness to access data; (*iii*) the reduction of development and maintenance costs; and (*iv*) offering standard interfaces to the BEMS.

1. Introduction

Achieving smart cities requires the evolution of building towards energy efficiency (Dakwale, Ralegaonkar, & Mandavgane, 2011; Kylili & Fokaides, 2015). Existing buildings have great potential for reducing energy consumption, and thus, renovation of existing buildings (Farahani, Wallbaum, & Dalenbäck, 2019) and energy retrofit (Luddeni, Krarti, Pernigotto, & Gasparella, 2018; Tadeu et al., 2016) have an effective role in energy performance optimization (Hashempour, Taherkhani, & Mahdikhani, 2020). Energy efficiency in a building relies on sensors, controllers and actuators that allow the Building Energy Management System (BEMS) to be configured and operated properly, as depicted in Gunay and Shen (2017), Tushar et al. (2018) and Yu, Haghighat, and Fung (2016), where the importance of data gathering and analysis in smart buildings is highlighted. All the appliances of a building can be monitored and/or controlled using specific hardware and software that manage those sensors and actuators (i.e., hot water tank temperature, boiler energy consumption, etc.). Sensors provide the BEMS with the environmental context as well as with information about the real-time status of the appliances. These contextual variables must be measured in strategic areas, acquiring data to extract essential information, directly related to the comfort of the tenants and the operation of the air conditioning and domestic hot water system. Apart from sensors, there are other devices such as controllers and switches with the capability of actuation over different components of the building, applying smart control models, orchestrating all the devices and maximizing the efficiency of the BEMS. Internet of Things (IoT) (Al-Fuqaha, Guizani, Mohammadi, Aledhari, & Ayyash, 2015; Atzori, Iera, & Morabito, 2010; Gubbi, Buyya, Marusic, & Palaniswami, 2013), and more specifically Web of Things (WoT) (Raggett, 2015; Zeng, Guo, & Cheng, 2011), set the foundations to actuate and interact with these devices. The knowledge inferred from the environment is crucial to understand the conditions of the building and allows experts to develop strategies and implement actuation plans to improve the retrofitting of buildings based on realistic models (Ferrante, 2014; Martín-Garín, Millán-García, Baïri, Millán-Medel, & Sala-Lizarraga, 2018; Tushar et al., 2018). The actuation will be closely related to the retrofit system, as it will be able to control the parameters and actuate to maintain them in a comfortable zone.

Nowadays, architecture plans include sustainability actions to maximize both the energy performance of the building and the comfort

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of residents, with a reduction of energy bills and climate fingerprint, as stated in Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings, and Directive 2012/27/EU on energy efficiency. The early design includes the deployment of advanced information systems to monitor and control the status of the premises efficiently. In the case of old buildings, with obsolete or even absent equipment, adopting efficiency measures is a hard task. These old buildings are challenging scenarios to deploy IoT sensor networks and devices (Hannan et al., 2018). These barriers make difficult the development of an IoT-enabled retrofit system.

Another challenge to deploy a retrofitting system is the distribution of sensors. Several approaches to sensor distribution based on optimization algorithms have been proposed (Arnesano, Revel, & Seri, 2016; Yoganathan, Kondepudi, Kalluri, & Manthapuri, 2018). The sensor network must cover relevant areas that usually have diverse physical features (i.e. upper floor rooms, basement, remote storage room, outdoor terrace), and with different protocols and technologies, sometimes dependent on specific vendors, that are not interoperable among them. Even when devices use open IoT standards, the wide range of protocols makes the achievement of interoperability among all the system devices difficult and costly. Therefore, ad-hoc integrations, developing intermediate conversion platforms and gateways, are usually required.

WoT is a paradigm devised by the World Wide Web Consortium (W3C) on top of the IoT concept (Web of Things at W3C, 2019). It provides standard mechanisms to interact with any type of device from any automatic system using a descriptive JSON file called Thing Description (W3C Web of Things (WoT) Thing Description, 2019). WoT offers an interesting approach to solve the issues faced during the design of systems that include legacy devices and heterogeneous technologies. The main differences between WoT and IoT are:

- The counteracting of fragmentation between different sensors and actuators by providing a machine-interpretable description of them.
- WoT brings IoT with machine-readable descriptions of sensors, actuators and controllers, providing it with an interoperability layer and enabling semantic interpretation of systems.
- WoT is designed to work specifically with the World Wide Web protocols, avoiding the technology fragmentation and lack of interoperability between different families of devices.

These features are useful in building monitoring and control, as every device can communicate with each other, triggering actions on the indoor ambient faster and more reliable.

This paper aims at demonstrating the feasibility of the W3C WoT proposals as a solution for an effective integration of heterogeneous IoT-enabled devices in a BEMS. The context of this work is the HEART project (Heart Project, 2019), which aims to design a tool that integrates multiple components of a building, enabling smart retrofit. The W3C WoT recommendations offer a mechanism that can be used as the basis to design and implement a network of sensors, actuators, and other devices for smart retrofit of buildings. In addition, the efficiency of the energy management is improved through both passive (e.g., insulation and use of high-performance materials) and active elements (e.g., predictive air conditioning control, monitoring water temperature). The approach proposed in this paper can be applied not only to new buildings, but also to existing ones, integrating the solution into devices in the current installation.

To the best of our knowledge, this is one of the first works addressing retrofitting of buildings using WoT. Although some solutions based on IoT have been proposed recently (Dzulkifly, Aris, Jorgensen, & Santos, 2020), the use of WoT is really scarce, if present, in this field.

An analysis of the state-of-the-art of IoT and WoT for smart retrofit will be complemented with a proof of concept applied to a real use case, illustrating the feasibility of the proposed approach.

2. State of the art

Monitoring and control of energy consumption in buildings in the context of smart retrofit is a complex task. This task can be alleviated using a WoT architecture to address key issues such as connections of sensors and actuators, data collection and data analysis.

2.1. Building energy monitoring and retrofit

The building sector accounts for almost 40% of the total energy demand in developed countries, becoming the largest greenhouse gas emitter in cities (Liang et al., 2018). The existing building stock accounts for a significant part of the energy demand in this sector. Thus, governments, technicians and scientists are aware of the crucial role of retrofitting existing buildings (Pardo-Bosch, Cervera, & Ysa, 2019). The refurbishment of existing buildings is a low-cost, high-volume approach aimed to reducing building energy consumption while pursuing worthwhile reduction in emissions from the built environment (Labeodan, De Bakker, Rosemann, & Zeiler, 2016). In addition, building retrofitting is essential to tackling energy poverty, one of the most important social problems faced by our society (Pacheco-Torgal et al., 2017). Nevertheless, the refurbishment process of older buildings still presents a number of challenges.

Advancement in Information and Communication Technology does however provide the opportunity to harness yet unrealized energy consumption reduction in existing buildings. Improvement in physical and environmental information sensing, communication and processing, enable the monitoring of energy behaviour of buildings in real-time, allowing building performance evaluation through energy modelling and simulation exploiting data from the field and real weather conditions (Bottaccioli et al., 2017). The access to this information has been made easy and ubiquitous thank to IoT devices and protocols. The development IoT-based sensors has become crucial for analysing and optimizing the energy-performance of buildings (Cascone, Ferrara, Giovannini, & Serale, 2017). Self-organization and modularity of these devices in particular, make them advantageous in achieving fast, cost effective, less-disruptive and unobtrusive retrofit in existing buildings (Labeodan et al., 2016).

However, a number of limiting issues related to the deployment currently impact the scope of IoT utilization, including lack of comprehensive end-to-end standards, fragmented cybersecurity solutions, and a relative dearth of fully-developed vertical applications (Minoli, Sohraby, & Occhiogrosso, 2017).

2.2. IoT and smart retrofit

Several works on smart building retrofit based on IoT are focused on the efficiency of buildings, measuring the energy consumption and the energy loss to guide building renovation (Lee, 2019; Marinakis, Doukas, Karakosta, & Psarras, 2013). These works expose the importance of building efficiency, as it is responsible of a notable part of the electric consumption of a country. Aiming to this direction, in Luo (2019) power consumption is studied based on previous data to predict the day-to-day consumption, based on a sensor grid, a storage layer that accumulates the collected data, a machine-learning predictive model that analyses the data, and finally, a service layer that interfaces between the generated model and the management system of the building. In Liang et al. (2018), the idea that retrofits help to improve energy savings is exposed, either in commercial and residential buildings, and the standardization of the measures is also proposed.

Successful implementations of IoT-based smart retrofit systems, such as Pasichnyi, Wallin, and Kordas (2019), are able to acquire and analyse data from multiple buildings, and generate intelligent data services for multiple building scenarios, exemplifying how the paradigms may change from single building datasets to multiple building data lakes that feeds multiple intelligent services. In Shah (2016), a wireless system for building monitoring in the context of building automation is proposed, using a mobile proprietary IoT system which could be enhanced through optimization algorithms. In Forest and Shabani (2017) an approach of a smart ventilation system is proposed. This approach automatizes the ventilation of a building by adding wireless communication to the air controlling dampers which control the temperature and humidity of the room. In Png, Srinivasan, Bekiroglu, Chaoyang, and Su (2019), an optimization algorithm is used based on a building IoT monitoring system, reducing costs by 20% using a decentralized control system. Other systems, such as Martín-Garín et al. (2018), use a set of accurately calibrated sensors to measure air quality inside buildings, reporting a retrofit in quality of life of the occupants by observing behavioural patterns.

2.3. WoT and smart buildings

WoT is intended to enable interoperability across IoT platforms and application domains (W3C Web of Things (WoT) Architecture, 2019). It is an aggregation of programming patterns and architectures that links real objects and properties as part of the Web. WoT aims to reduce heterogeneity, helping to create IoT solutions formed by wide varieties of devices and platforms. Therefore, WoT needs to scale accordingly and adapt to all the requirements of said devices (Guinard, 2011). The smart cities, and the smart buildings, cannot be devised without automation systems, some of them based on Web technologies and Web-enabled devices (Lilis, Conus, Asadi, & Kayal, 2017).

The Web protocols and standards have been used and applied to IoT in recent years. In Negash, Westerlund, and Tenhunen (2019), a Web of virtual Things is used to manage multiple devices, enabling the interoperability between them. Those Things are virtual representations of a real Thing that are registered in a server, exposing a RESTful API[1] to access them. In Iqbal et al. (2018), a WoT platform based on Web Objects is used to manage devices inside a building, using an aggregator gateway that stores data in the cloud. The Things in this project are identified by URIs, as well sensors and actuators.

An implementation of a Web-based IoT framework that enables the interoperability between devices and sensors is described in Paganelli, Turchi, and Giuli (2016). This framework is based on aggregation and reference principles, creating a browsable graph of information nodes that can be accessed using REST verbs (GET, PUT, POST, DELETE). Lastly, this framework is applied to a smart city scenario. In Bovet and Hennebert (2014), a model based on WoT is proposed to enable interoperability of heterogeneous devices and self discovery applying it to a smart building deployment. For this purpose they use a WoT architecture based on a semantic approach, sorting different devices and properties.

3. Concept design

As reviewed above, there is a lot of research done in the building monitoring topic, IoT in smart retrofit and WoT applied to smart buildings. This work is focused on using the WoT paradigm, together with Web protocols and RESTful services, in a more standardized way, using the recommendations provided by the W3C WoT Working Group (W3C Web of Things (WoT) Working Group, 2019). In this manner, we will be able to identify and expose all the sensors and actuators of a building through Web protocols.

Our case study is framed on the HEART project (Heart Project, 2019), where a complete building energy system (indoor air ventilation system, energy system and water system) is monitored and controlled by a group of smart devices. Firstly, we define the architecture needed for this project; secondly, we provide some detail in the specific components and implementations; and, finally, we present a novel deployment proposal in a real building.

The information that can be gathered from the indoor air, combined with the data acquired from the ventilation system, the energy system and the water pumps enable to create a model for energy consumption, optimization, automation and smart retrofit for the indoor air conditions and energy savings. In Ren and Cao (2019) and Zhang, Li, Zhao, and Rao (2019), the potential use of the collected data of the air inside a building is treated in depth. Although this is the main objective of the gathered data, our focus is on the proper collection, aggregation and exposure of the variables.

3.1. Components

In a smart building equipped with the architecture proposed in this manuscript, each of the monitored appliances is connected to a device that allows data collection and action triggering. These appliances and their associated devices are described below.

3.1.1. Heat Pump (HP)

The HP interoperates with the BEMS by:

- Sharing information: The HP implements a Modbus/TCP server that enables the operation of the device (i.e., operating modes, set point temperatures), as well as getting internal values.
- Sharing thermal energy: The HP is linked to a Phase Change Materials (PCM) Storage. Thermal energy flows from the PCM Storage to the Domestic Hot Water (DHW) tank managed by the HP circulation pump.
- Getting electric energy: The HP is powered by a multiple-input and multiple-output device.

The HP is physically connected to the HP Gateway (HPG). This gateway performs the role of communication interface with the rest of the BEMS. The HP and its gateway are directly connected through Ethernet, creating an ad-hoc local network exclusively for the HP operation. The HPG is in charge of exposing the commands and variables of the HP in form of a WoT TD (W3C Web of Things (WoT) Thing Description, 2019).

The HPG is implemented on an UP Board, a credit-card sized x86 computer with an Intel® ATOM™ Z8350 processor, 4 GB of RAM, Wi-Fi and Gigabit Ethernet, running Ubilinux 4.0 (an embedded Linux distribution) as operating system. It acts as a gateway between the HP and the external clients (i.e., cloud platform and building control logic).

3.1.2. Multiple Input Multiple Output (MIMO)

The MIMO interoperates with the BEMS basically distributing the electric energy from/to the building devices. Likewise the HP, the MIMO is physically connected to the MIMO Gateway (MG). This gateway performs the role of communication interface with the rest of the BEMS. The MIMO implements a Modbus/TCP server that enables the operation from an external device. The MIMO and its gateway are directly connected through Ethernet, creating an ad-hoc local network exclusively for the MIMO operation. The MG is in charge of exposing the commands and variables of the MIMO in form of WoT TDs.

The MG is implemented on an UP Board, as the one for the HP, acting as a gateway between the MIMO and the external clients (i.e., cloud platform and building control logic). The device runs Ubilinux 4.0 as operating system.

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[1] A RESTful API is an application program interface (API) that uses HTTP requests to GET, PUT, POST and DELETE data.

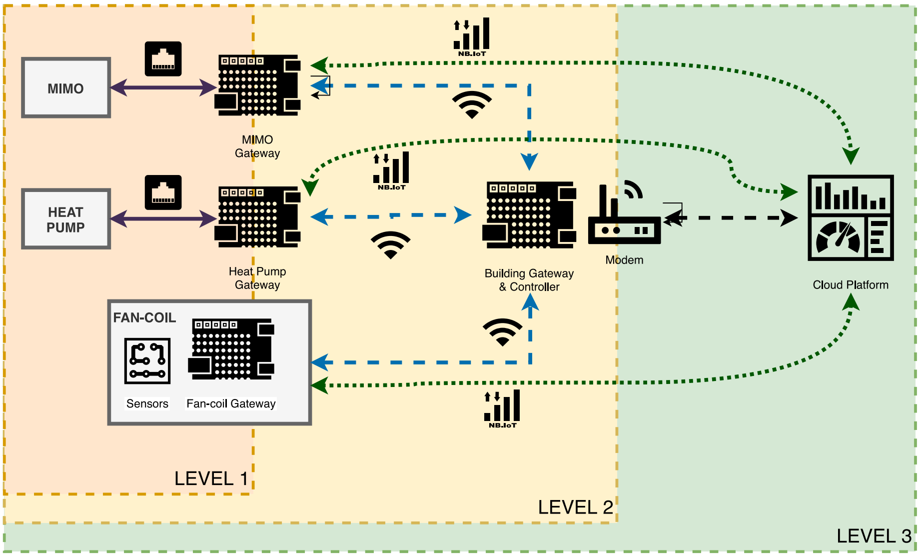

Fig. 1. BEMS logic control levels.

3.1.3. Fan-Coil (FC)

FCs are appliances based on STILLE's commercial solution (Il tuo, 2019), enabling smart functions though either a Narrowband IoT (NB-IoT) or a Wi-Fi module.

There are three types of FC:

- DHW Boiler: It is located in the bathrooms. It measures DHW flow rate and temperature.
- Smart FC: For heating/cooling the main rooms of the building. It provides the BEMS with information about environmental and internal variables, including: air temperature (inlet/outlet); air relative humidity; water flow rate; electric power consumption; and water temperature (inlet/outlet).
- Smart Radiator: It behaves like a smart FC but it only provides heat.

All the FCs have an on-board control system that measures environmental and internal variables useful to achieve BEMS requests. FCs receive control information from the BEMS to adjust their operations using an interface module. The on-board control system is based on an ATmega328P processor that controls the basic operations of the appliance (i.e., on/off, critical situation, season change, and fan speed).

The on-board control system is connected to an interface component, controlled by a Pycom GPy (a Micropython-programmable development board), to support both NB-IoT and Wi-Fi communications. FCs implement a running WoT servient written in MicroPython, that allows to operate with the system. A WoT servient is a software stack that can perform in both server and client role, implementing the WoT functionalities required to host and expose Things and/or consume Things (W3C Web of Things (WoT) Architecture, 2019). Through the Web services exposed by the WoT servient, FCs receive commands from the BEMS (i.e., switch on, temperature set, hourly set point, desired fan speed, and season set up).

3.1.4. Building Gateway & Controller (BGC)

The BGC is the core component of the system in the building. It is connected to the rest of the devices of the building and it is in charge of several control operations. Its configuration is dynamic, since it receives setup information from external services. It acts as a proxy between the devices deployed in the building, such as the FCs, the HP and the MIMO, and the external services, such as the cloud control platform.

This device plays the role of offline BEMS controller, allowing the basic monitoring and control logic of the system when the BEMS components have no direct connection to the cloud platform via NB-IoT. It also acts as a gateway between the building and the Internet, enabling a direct and reliable broadband access to the cloud platform, converting protocols, adapting packet formats, and translating messages between networks.

The BGC is deployed on an UP Squared board with an Intel® Celeron™ N3350 processor, 8 GB of RAM, running Ubuntu Server 18.04.3 LTS as operating system, one Wi-Fi connection and two Gigabit Ethernet interfaces. It meets the requirements of the system, allowing to connect it to multiple networks simultaneously with high bandwidth to attend all the requests. The BGC continuously gathers information about the status of the devices in the building and exposes visual data through intuitive dashboards. It enables the communication with the external tools, such as the Cloud Platform, allowing them to configure some parameters of the system (e.g., set point temperatures, operation limits). The system may also configure alerts depending on specific needs. The offline control is implemented in Docker, a platform as a service (PaaS) solution for operating-system level virtualization to deliver software in packages called containers (What Is Docker, 2019). A Docker container is an isolated environment, similar to a virtual machine but using fewer computational resources, which contains all the tools, libraries and dependencies as one package that can run in any other computer with the Docker environment. This makes the applications portable and modular. The offline control is implemented in Docker containers and perform decoupled tasks as the WoT servient proxy, a local database and the dashboard interface among other systems.

3.2. Architecture

The Building Energy Management System is one of the key components of the platform. The BEMS implements the operation logic to control and distribute the electric energy flux, thermal energy and information, coordinating the main devices – MIMO, HP, Thermal Storage (TS) tanks, Photo Voltaic (PV) and FCs – in the building. The BEMS also enables a direct interaction with the inhabitants of the building, reporting about the building performance in terms of energy, allowing them to monitor and control it.

The main components of the BEMS have interactions among them in terms of electric energy, thermal energy and information. In this section we focus on the information flow. The BEMS is implemented by three different levels of controls, as can be seen in Fig. 1:

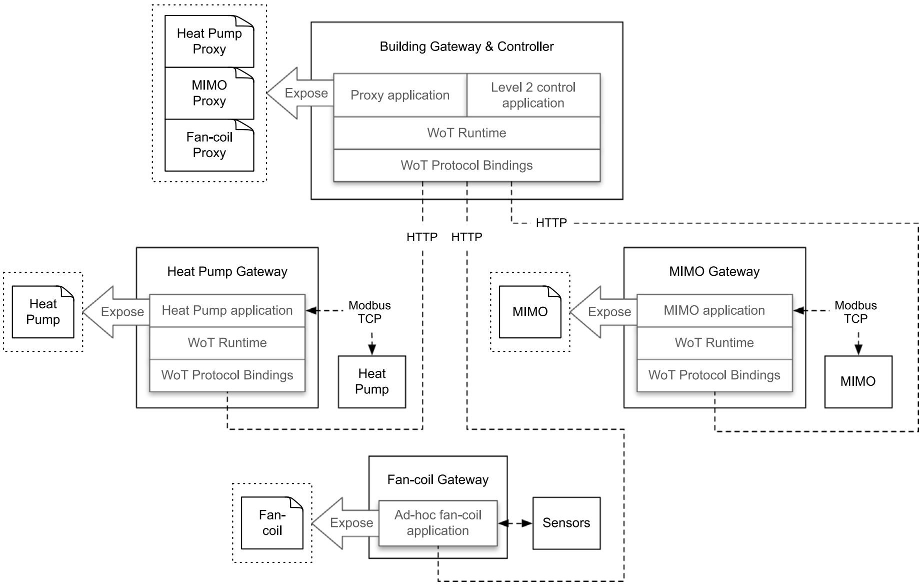

Fig. 2. BEMS WoT architecture.

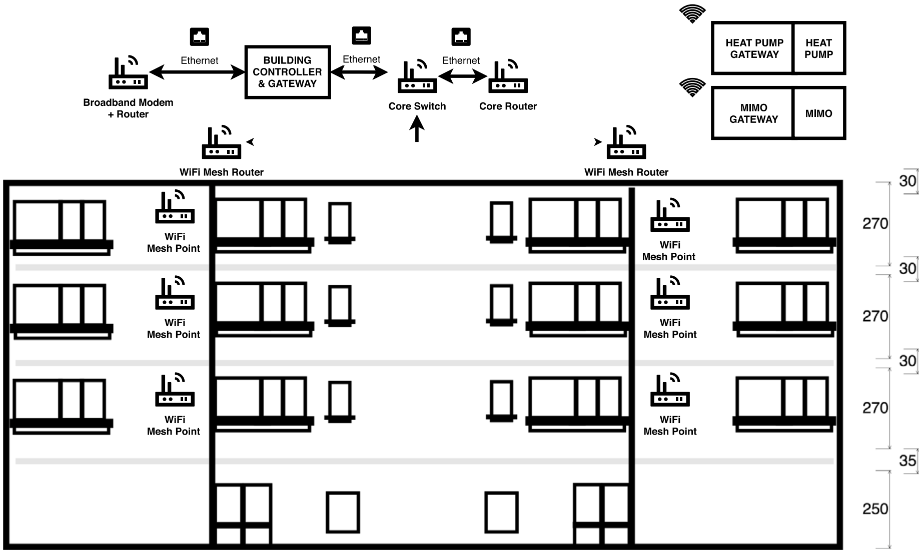

Fig. 3. Italian case deployment schema.

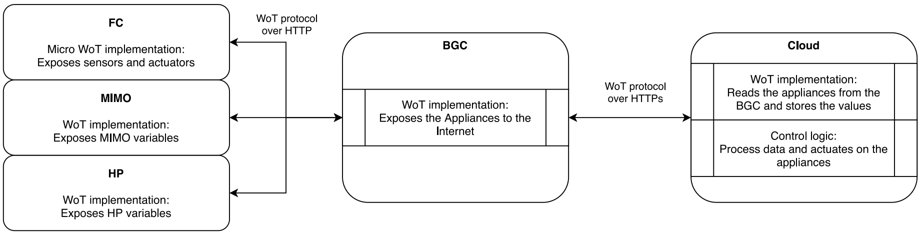

Fig. 4. Italian case deployment software modules.

- Level 1: A root control system (firmware) embedded in each HEART component (e.g. HP, MIMO and FCs); at this level the control is focused on the protection of the operation of the components (e.g. over-temperature, over-current, short circuit) and on the internal management of each appliance.
- Level 2: An offline control logic, physically implemented at building level, in a specific hardware component: the Building Gateway & Controller.
- Level 3: An adaptive–predictive online logic implemented on a cloud platform.

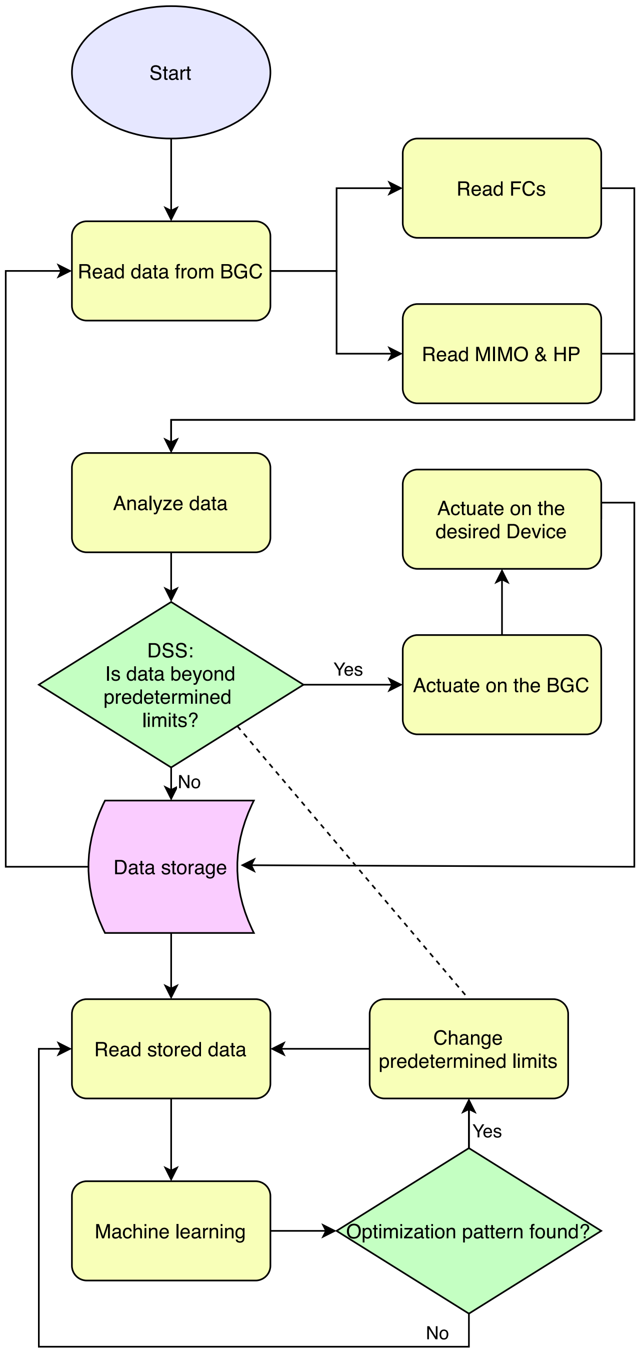

Fig. 5. Italian case deployment software flowchart.

Level 1 is composed of building appliances, like the FCs, the HP and the MIMO, whose properties are exposed through their respective gateways, communicating with Level 2. The BGC is the cornerstone of Level 2, providing the basic functionalities of the BEMS, monitoring and controlling the system in real time. In Level 2, we can also find the internal wireless network which communicates all the gateways. The local BGC is always connected with the appliances of the building to guarantee stability of the system in case of an Internet connection disruption. In Level 3, a cloud platform is responsible for enhancing both the monitoring of the BEMS and its control decisions. It also has access to third party data (i.e., environmental information, weather forecast) that helps in the decision making.

The selection of the main communication technologies of the BEMS is based on the premise of the uninterrupted operation of the system (see Appendix). NB-IoT is selected as one of those that will be implemented due to its novelty and potential, and Wi-Fi is selected for its well tested operation, implementation and robustness. Thus, the system will run over two different communication protocols: NB-IoT and Wi-Fi. This redundant approach will be used within the lifetime of the project; once the project is finished, the system will rely on NB-IoT communications, keeping the Wi-Fi subsystem as a backup mechanism just in case NB-IoT does not demonstrate full maturity and reliability, or just for eventual low coverage. For the data rates and bandwidth, a TD causes a request that consumes 5 kB to 10 kB of bandwidth, while a Property request (i.e., the measurement value from a sensor) uses from 50 to 100 bytes of bandwidth. Any of the protocols described in Table A.1 are able to manage properly such requests.

3.3. WoT architecture

This section describes the architecture of the BEMS from a WoT standpoint. In Fig. 2 each Thing is represented as one entity, but in the real world case there can be more than one of each, specially the FCs of which there may be tens in the same building.

The BGC, the MIMO and the HP are implemented over the full-featured WoT runtime described in Mangas and Alonso (2019). The smart FCs use an ad-hoc MicroPython implementation that is much more suitable for constrained devices (i.e. GPy boards). All components are described in terms of the WoT interaction model (Kovatsch et al., 2019). This means that every functionality (e.g. a voltage reading, the act of increasing the temperature) is represented as either a property, an action or an event.

Each of the Level-1 components exposes a single Thing described by a TD document. Also two distinct WoT applications are deployed on the BGC: one of them implements the Level-2 control logic, acting as a pure WoT client (i.e. does not expose any Thing); the other one exposes a set of proxy Things that represent the Level-1 components.

All communications between components use HTTP as the application-layer protocol and follow the WoT interfaces that emanate from the TDs of each Thing. This is achieved by leveraging the Protocol Bindings layer of each WoT runtime. This layer is able to automatically translate high-level messages that follow the WoT interaction model to the low-level HTTP messages that are actually exchanged between devices.

As mentioned above, the BGC acts as a WoT proxy for the smart FCs, the HP and the MIMO. A WoT proxy is an intermediary that exposes a “mirror” of another Thing. Proxy Things are usually augmented with additional features (e.g. protocols) that are not supported in the constrained hardware platforms of the original Things. Thus, the BGC enables interaction between the devices attached to the private local network and other clients. A catalogue of the WoT Thing Descriptions of the building is also exposed in the BGC proxy. This catalogue provides a list of pairs, where each pair contains the unique identification of a component and a URL pointing to the corresponding WoT TD.

4. Deployment

The system proposed in this paper follows the schema shown in Fig. 3. As described above, the connection technology for this deployment is Wi-Fi. The building will be covered by a Wi-Fi local network, deployed through access points (AP) that create a complete mesh network, where all the devices are attached.

The BGC, the MG, the HPG and the FCs will be connected to the BEMS local area network. All the devices, with the exception of the BGC, will not have access to the Internet in order to minimize cyber security risks. Thus, since the BGC is a vulnerable piece of the system which implements strict security recommendations, including encrypted end-to-end communications and other measures such as limiting the access to other parts of the system. All the BEMS devices and appliances are connected to the BGC. The BGC includes protected

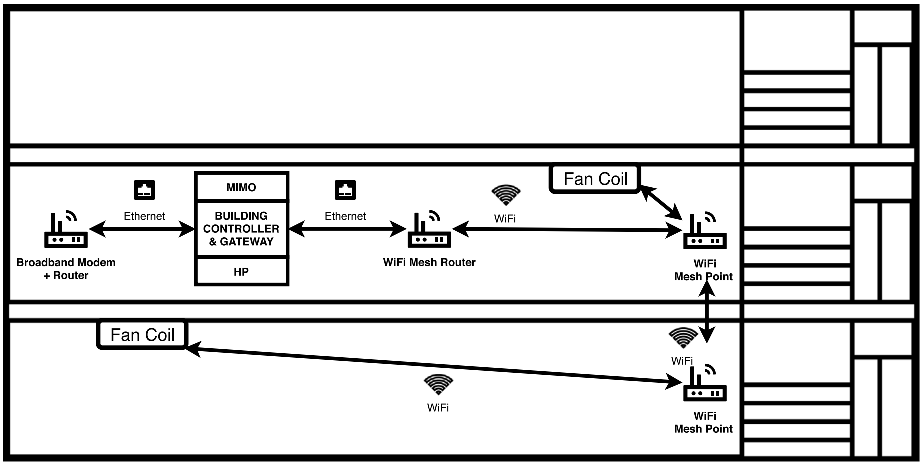

Fig. 6. Experimental deployment schema.

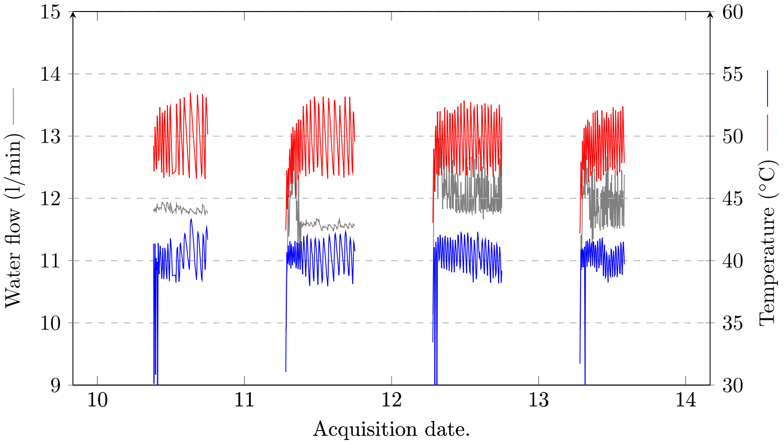

Fig. 7. Water flow and temperature in a FC; four days of operation (measurements acquired in March 2020).

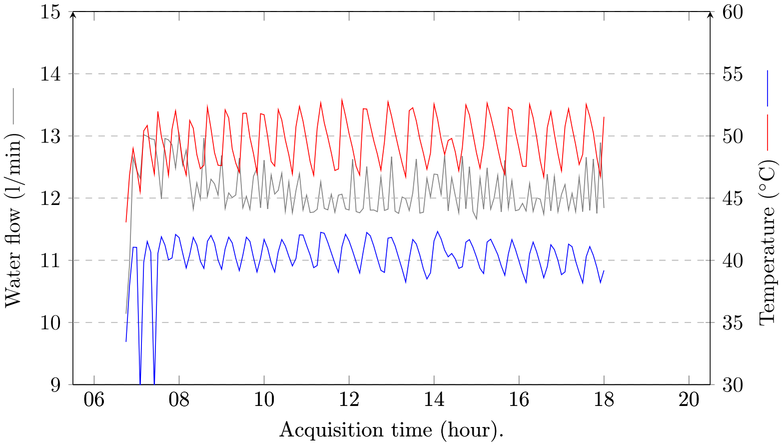

Fig. 8. Water flow and temperature in a FC; detail of one day of operation (measurements acquired on March 12th, 2020).

HTTP services to offer external control over the appliances and the BEMS as a whole.

Concerning the software needed for these deployment, there are three main modules represented in Fig. 4: (*i*) the individual software modules deployed in the building appliances (FCs, MIMO and HP) which expose sensors and actuators; (*ii*) the BGC which contains a WoT proxy server which redirects petitions to the different devices; and (*iii*) one of the key components of the HEART system, the cloud platform including a Decision Support System (DSS) and BEMS. The cloud platform also composes of a WoT reader which consults the appliances and the DSS which decides whether or not to actuate over them. Fig. 5 details the workflow of the process. In future iterations of the DSS, machine learning techniques will be applied in order to change the inner rules, and adapt to the dynamic conditions of a building.

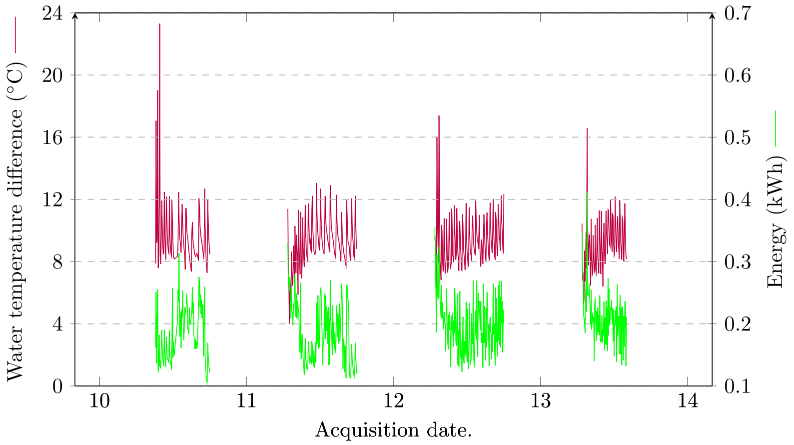

Fig. 9. Water temperature difference and energy in a FC; four days of operation (measurements acquired in March 2020).

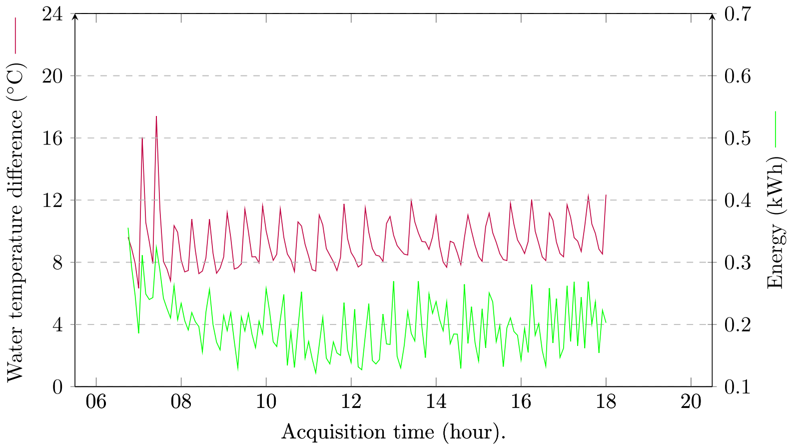

Fig. 10. Water temperature difference and energy in a FC; detail of one day of operation (measurements acquired on March 12th, 2020).

4.1. Experimental pilot

With the objective of testing the system configuration, guaranteeing the performance of the hardware selected, and the communications, a proof of concept was deployed locally at CTIC Technological Centre premises. This pilot aims to checking the uninterrupted operation of the system, monitoring the environmental parameters of the existing FCs, and checking differences with other off-the-shelf accurate monitoring systems. The proof of concept deployed involved the implementation of the following devices:

- 1 × BGC.
- 1 × Wi-Fi Mesh Router.
- 2 × Wi-Fi Mesh Point.
- 2 × Smart FC.

This experimental pilot includes a complete architecture (as shown in Fig. 3) with a reduced number of devices, deployed within a two-storey office building. A BGC finds and exposes all the available FCs in the network. There are two FCs distributed in two floors. The local network is a private mesh Wi-Fi network, implemented with a mesh-shape configuration with two mesh APs serially linked, and connected to the FC.

This pilot also includes an MIMO and an HP, that simulate Modbus servers. Both Modbus servers emulate the MIMO and the HP, providing measurements from sensors and acting on the devices. As expected in the final deployment, the piloted BGC exposes all the BEMS operations and a list of sensors, including all the features of the MIMO, the HP and the FCs.

Fig. 6 shows that the pilot covers all the potential scenarios that the final deployment will face. This includes challenging Wi-Fi mesh communication through floors, an MIMO, an HP, multiple FCs and the main BGC in charge of communicating, exposing and controlling all the internal devices, linking the internal network and the outside systems, such as a cloud platform to monitor the variables and control several variables of the BEMS.

The pilot run experiments for two months, being the system on about ten hours a day, five days a week. The devices monitoring the FCs expose 15 properties that could be accessed at any time. The measurements were acquired each minute, making a request to each property and storing it in a data base. Each request consumed around 100 bytes; hence, a complete reading consumes about 1,5 kB every minute. Giving that there are two FCs, the total bandwidth necessary to monitor all these properties was 50 kB/s. The available bandwidth was different depending on the distance between the FC and the mesh AP: in the first mesh hop, the bandwidth was 7,5 MB/s; the second hop provided a bandwidth of 2,6 MB/s. That bandwidth properly covered the needs of the experiment. At the end of the experiment, about 300 h of operation were collected from each FC.

The two-month experiment gathered data about water temperature in both cold and hot circuits, water flow and energy consumption of the two FCs. The FCs were requested once every 10 min for all the available properties. Fig. 7 shows water flow and temperature measurements of four days of operation (the FC were turned off at night), showing how the FCs start in the morning and stabilizes during the day. Fig. 8 shows the detail of one day of acquired data, for example, the peaks at the beginning of the day, where the water starts pumping and the

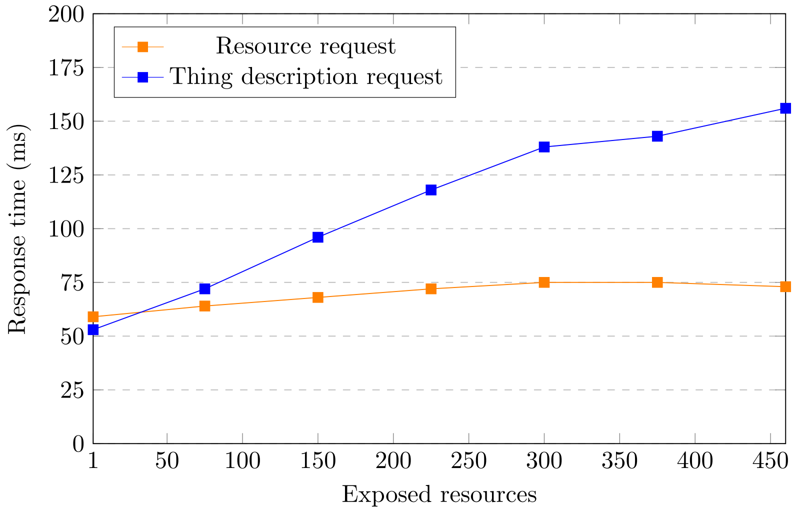

Fig. 11. Average response time of a Web Thing through HTTP using the PyCom GPy processing board.

temperature difference is greater, which causes an increase of thermal energy as shown in Fig. 9 and detailed in Fig. 10 which will be discussed later.

The thermal energy is the difference between the input water temperature and the output water temperature in correlation with the water flow, which translates in a total amount of energy used in the FC system. An accurate number of the thermal energy used in the FCs can be retrieved, expressed as an instant value. The thermal energy consumption in kWh for the hot water circuit, E_w^h, can be computed using Eq. (1) whereas for the cold water circuit, E_w^c, can be computed using Eq. (2), where $FlowR_w$ is the total water flow-rate through the FC during a certain period (l/min); SH is the water specific heat constant (0.0011627); Tin_w is the inlet temperature of the water in the FC (°C); and $Tout_w$ is the outlet temperature of the water in the FC (°C). Using these equations, the FC can calculate the instant thermal energy as shown in Fig. 9. This collecting process shows the capability of the WoT deployment to serve data in a regular basis.

$$E_w^h = FlowR_w \times SH \times (Tin_w - Tout_w) \quad (1)$$

$$E_w^c = FlowR_w \times SH \times (Tout_w - Tin_w) \quad (2)$$

A battery of tests was run concerning the response time of the FC appliances (see Fig. 11) In the context of this work, each data point was obtained as the average of 1000 requests using The Apache Bench tool (ab - Apache HTTP, 2020), with deviations that range from 2.0 ms when the number of properties are low, to hundreds of *ms* when the properties reach the maximum. In addition there were values of >2000 ms due to device internal operations. All the requests are HTTP REST GET request to an URL which contains the property or the TD. As the average number of exposed resources taking properties and actions into account is 20, we can expect a response time under 100.0 ms in the local network, assuming multiple Wi-Fi mesh jumps could slow down the process. The response time, as seen in Fig. 11, is acceptable taking into account that the purpose of this system is not a continuous measurement of the devices, but a slow check over time, which will give plenty of time to make all the desired requests.

5. Conclusions

In this paper we propose an approach for smart retrofit of buildings based on the Web of Things paradigm. The state of the art related to retrofit of buildings, WoT and intelligent buildings was visited to contextualize the problem and provide an adequate solution to its requirements. In this work, the WoT paradigm was found suitable for applications to assure interoperability between different IoT devices in retrofit environments.

A concept design was proposed, describing all the devices composing the building appliances, their characteristics and communication protocols. This design allows data gathering with standard commands directed to simple addresses, enabling data analysis with a simple collecting process. In addition, the use of the WoT standard proposals enables to add sensors or actuators to different appliances with a low impact on the devices, even without turning them off.

Furthermore, we built an experimental implementation of a representative subset of the proposed design. The capabilities and robustness of the system were tested and assured in that experiment. This work can conclude that time and cost are saved when the smart retrofit of buildings is based on WoT, increasing the interoperability among different devices and platforms. The BGC can manage dozens of devices with less than 200 lines of code and a settings file, whereas the smart FCs manage and expose a dozen of sensors with less than 500 lines of code, including sensor reading and wireless configuration.

Future work will be focus on security mechanisms for the BGC, developing the NB-IoT implementation of the WoT protocol and evaluating the possibilities of automatic discovery mechanisms for all the Things connected to the system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Communication technologies and smart retrofit of buildings

The use and exploitation of building retrofit, as a part of the IoT, are based on reliable communication technologies, such as Narrowband, Wi-Fi, LoRa or Sigfox, among others. These communication technologies are key for data gathering and control of remote systems. Three communication technologies have been selected for this approach:

Table A.1
Comparison of communication protocols for smart retrofit of buildings.

Indicator	Wi-Fi	NB-IoT	Zigbee
Standardization	✓ 802.11ax is the latest standard being developed by the Wi-Fi Alliance (2019).	✓ 3GPP formalized this standard in 2016.	✓ Zigbee Alliance released version 3.0 of the standard in 2015.
Robustness	✓ Based on the IEEE 802.11 specifications (2.4 GHz); maturity.	✓ Supports several radio solutions (i.e., GSM, LTE) operating in specific bandwidths; robustness depends on the availability of the network provider.	✓ Based on the IEEE 802.15.4 specifications (2.4 GHz); maturity.
Security	✓ Networks are password secured by the IEEE 802.11i (using Advanced Encryption Standard (AES)).	✓ Devices have a unique SIM card, with credentials and subscriber data. Encryption using 256-bit keys and possibility of establishing an IPsec tunnel (decreasing performance significantly).	✓ Implements the Advanced Encryption Standard (AES-128) at Network and Application Layer.
Device deployment	✓ Range radius of 100 metres from the nearest AP.	✗ Devices do not communicate with each other, but to the cellular system network; indoor, outdoor; coverage range of km.	✓ Range radius of 75–100 metres, indoor.
Develop	✓ Multiple guides and well documented solutions and examples.	✗ No examples or guidelines; development needs to be done from scratch, with little to none documentation.	✓ Multiple guides and well documented solutions and examples
Scalability	✓ Supports hundreds of devices connected to the same network.	✓ Scale depends on the capability of mobile stations (more than 50 k connections per cell).	✓ May support over a hundred of devices connected to the same network.
Data rate	✓ Up to 600 Mbits/s.	✓ Theoretical 250 Kbits/s.	✓ 250 Kbits/s.

- Wi-Fi (Wi-Fi Certified, 2019): The most used indoor wireless connection technology. It is widely tested and there are a wide variety of affordable devices that implement it.
- Narrowband-IoT (NB-IoT) (Beyene, Jantti, Ruttik, & Iraji, 2017; Chen, Miao, Hao, & Hwang, 2017): A Low Power Wide Area Network enabling a wide range of devices and services, specifically focussed on indoor coverage, using third party networks and platforms.
- Zigbee (Zigbee, 2019): A specification oriented to create Personal Area Networks with low-power devices.

A brief comparison between these protocols is shown in Table A.1, highlighting the features that are desirable for the purposes of this work.

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