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***Abstract*—In recent years, the research about energy waste and CO_2 emission reduction has gained a strong momentum, also pushed by European and national funding initiatives. The main purpose of this large effort is to reduce the effects of greenhouse emission, climate change to head for a sustainable society. In this scenario, Information and Communication Technologies (ICT) play a key role. From one side, advances in physical and environmental information sensing, communication and processing, enabled the monitoring of energy behaviour of buildings in real-time. The access to this information has been made easy and ubiquitous thank to Internet-of-Things (IoT) devices and protocols. From the other side, the creation of digital repositories of buildings and districts (i.e. Building Information Models - BIM) enabled the development of complex and rich energy models that can be used for simulation and prediction purposes. As such, an opportunity is emerging of mixing these two information categories to either create better models and to detect unwanted or inefficient energy behaviours.**

In this paper, we present a software architecture for management and simulation of energy behaviours in buildings that integrates heterogeneous data such as BIM, IoT, GIS (Geographical Information System) and meteorological services. This integration allows: *i)* (near-) real-time visualisation of energy consumption information in the building context and *ii)* building performance evaluation through energy modelling and simulation exploiting data from the field and real weather conditions. Finally, we discuss the experimental results obtained in a real-world case-study.

***Index Terms*—Building Information Model, BIM, Internet of Things, Software Architecture, Thermal Energy Modelling and Simulation, Smart Building**

1. Introduction

The COP21 conference highlighted that the need of reducing energy consumption and CO_2 emission has become mandatory in order to reduce the effects of greenhouse pollution, climate change and to move forward to a low-carbon and sustainable society [1]. Information and Communication Technologies (ICTs) have been recognised as key player for reducing energy consumption and to move forward to a more sustainable and smart society [2].

The building sector is responsible of the 40% of energy consumption and 36% of CO_2 emission in Europe [3]. Because 35% of existing buildings are older than 50 years, increasing their energy efficiency could reduce the energy consumption from 5% to 6% and the CO_2 emission of about 5%.

Recent improvements in ICTs offer an archipelago of devices, software and communication paradigms that can enable the deployment of real smart-buildings and cities. Devices, such as low-power Wireless Sensor Networks (WSNs) for environmental monitoring, and novel smart-meters for electric load profiling and recognition, give the possibility of monitoring and characterisation of energy consumption behaviour of buildings and dwellings. On the other hand, recent improvements in Building Information Models (BIMs) [4] makes possible to physically model the buildings considering their construction materials, subsystems and usage behaviour. Furthermore, thanks to the widespread diffusion of Internet-of-Things (IoT) technologies, monitored information (e.g. Temperature or Electricity consumption) can be integrated with BIM models. This integration provide an answer to the European Community requirements for achieving energy efficiency and smart data management. In fact, it enables: *i)* Energy modelling and simulation, for evaluating the actual efficiency of buildings or the effectiveness of possible retrofitting actions; *ii)* Contextualized (near-) real-time visualization and monitoring of energy consumption and environmental parameters coming form deployed sensors and meters. In order to perform this integration, a cloud-based software solution is required.

In this paper, we present an IoT software infrastructure that integrates heterogeneous IoT devices with BIM and GIS technologies. The integration of geo-referenced information with IoT devices and BIM models allows to validate building energy models with real data and evaluate their accuracy. Moreover, the simulations can take advantage from real weather information retrieved by third-party services. Facility- or energy-managers can exploit this information to highlight malfunctions or inefficient usage of building structures and plants. Furthermore, once trusted models are available, building-managers can exploit the infrastructure to monitor the efficiency of buildings and their environmental parameters in (near-) real-time. The rest of the paper is organized as follows. In Section 2, technologies for enabling smart energy management are presented and discussed. Section 3 presents a literature review of energy modelling platforms and available technologies for smart-buildings implementation. In Section 4, we present our software infrastructure to integrate heterogeneous data-sources, both hardware and software, for buildings energy modelling and monitoring. Section 6 presents the experimental results obtained by performing energy simulations in a case-study building where the presented infrastructure has been deployed. Finally, Section 7 provides the concluding remarks.

2. Enabling technologies for Smart Energy Management

This section presents the latest enabling technologies to be implemented for a smart energy management in buildings. Specifically, it provides an overview of the latest IoT and BIM technologies that can be applied to move forward the Smart Building and Smart City views.

2.1. IoT for Energy Monitoring

Contextually to the development of Smart Cities and Smart Buildings, researchers have addressed many challenges to facilitate the deployment of *Smart Meters* and *Wireless Sensor Networks* (WSN), which are IoT technologies. Generally, these allow to realize seamless, energy efficient, reliable and low-cost remote monitoring and control solutions in smart applications.

Smart meters are advanced internet-connected devices able to provide information for billing, monitoring and controlling purposes [5]. Furthermore, the information is also used to supervise systems (from operator's viewpoint) in order to monitor and prevent contingencies, faults and unconventional behavior. Generally, the main functionalities of smart meters are: *i)* data collection/recording, *ii)* two-way communication, *iii)* programming capabilities and *iv)* load control [6]. Usually, the most common communication technologies are: *i)* Radio Frequency (RF) and *ii)* Power Line Communication (PLC) [7]. One of the most innovative uses of these devices is the Non-Intrusive Appliances Load Monitoring (NIALM), a technique of disagregation signal processing [8]. The NIALM technique is able to discerns energy consumption of appliances from the aggregated data acquired from a single point of measurement (i.e. the smart meter).

A WSN is defined as a network of devices (called nodes) working cooperatively to communicate gathered information from a monitored area [9]. This type of network works through wireless links. The gathered data are sent to a concentrator that uses these data locally or sending them to other networks (e.g. Internet through a gateway). In the Smart City domain, WSNs can be divided in three main subsets [10]: *Home Area Networks* (HANs), *Neighborhood Area Networks* (NANs) and *Wide Area Networks* (WANs). An *HAN* creates a communication path among smart meters, home appliances and plug-in devices. These networks can enable end-users to collect information on the environment where they live. Due to the low power and bandwidth requirements, HANs applications, need low-cost communication technologies and protocols (e.g. Wi-Fi, Bluetooth, ZigBee and Spirit). Differently, a *NAN* is established between data collectors and smart meters in a neighborhood area. Usually these networks are short-range communication typologies (they use Wi-Fi and RF mesh technologies) and they are used to collect data from smart meters and transmit them to a data concentrator. Lastly, a *WAN* creates a communication path between service provider data center and data concentrators. In general, these networks are based on LTE, mobile networks (i.e. 2G or 3G standard), fiber, power line communication networks. The deployment of WSN technologies offers numerous advantages such as, lower costs, scalability, reliability, accuracy, flexibility in a wide range of applications [11]. Exploiting heterogeneous devices introduces a lack of interoperability among them. This is a well-known problem in the Internet-of-things context. To cope with this issue, we employ a middleware approach that abstracts hardware functionalities into web services (see Section 4.1). This also allows also a transparent access to IoT resources through unified API (Application Programming Interfaces) [12].

2.2. Building Information Models

Nowadays, increasing the energy efficiency of buildings is one of the most interesting and challenging research areas to test the potential of Building Information Modelling (BIM) methodology [4].

BIM is intended: *i)* as a working method based on cooperation between different professionals involved in the construction process from a shared database and *ii)* as a digital three-dimensional representation of a building, based on objects with associated information. BIM is the central element for the building life-cycle: *i)* design, *ii)* construction, *iii)* management and *iv)* deconstruction. *Sharing, integrating, tracking, and maintaining a coherent Building Information Model will affect all processes and participants that interact with that data* [4]. Hence, the digital model is not a simple drawing but it becomes the starting point for a multitude of possible representations.

In a Smart Building scenario, BIM is used to analyse the existing building stock to promote a better management and retrofitting actions. The architectural BIM model can be used to generate the geometry of the energy model, minimizing misinterpretations and improper approximations encountered in practice [13]. This is the main advantage of using BIM for energy modelling. BIM provides the opportunity to easily simulate different optimization scenarios, both in the design and refurbishment phases. This aspect is guaranteed by the possibility to validate the building energy model based on the real data gathered from monitoring activities and energy bills.

Exploiting BIM model for energy simulations allows the interoperability and data exchange among different software (i.e. modelling, management and simulation software). In this view, exchange data-formats used in the energy sectors are the Industry Foundation Classes (IFC) [14] and green building eXtensible Markup Language (gbXML) [15]. However, such interoperability is still an issue and needs improvements to maximize the whole building life-cycle. As an example, data about systems are not maintained, therefore they must be entered manually. *Although most parties agree that there is much potential in the process, variables such as the type of software and/or analysis being performed, level of experience of the modeller, physical properties of the building, and personal preferences in terms of workflow are currently dictating the level of adoption* [16].

3. Related Works

In recent years, many research works are focused on energy modeling and monitoring in Smart City domain, at both district and individual building levels, in order to reduce energy consumption and CO_2 emission.

In this context, a key challenge is to achieve a complete interoperability between heterogeneous devices. Service-oriented architectures (SOA) seem to be promising along this direction [17], [18]. The project *SOCRADES* [19], [20] aims at developing a modular, adaptive, and open infrastructure for next-generation industrial systems, exploiting the SOA paradigm both at device and application level. Most of SOA solutions focus on enabling ubiquitous computing and IoT applications. *SOCRADES* targets to smart energy-efficient buildings and aims at providing reusable distributed components in order to integrate building automation technologies with UbiComp. The *aWESoME* [21] middleware infrastructure, designed for Ambient Intelligence environments, allows interoperability between heterogeneous devices providing a system that enables buildings automation and energy savings.

Within their research project, Kim et al. [22] describe an ICT solution based on a data-centric middleware able to decentralize the monitoring and control, exploiting a publish/subscribe model [23]. The limitation of this solution is the need to provide an additional request/response communication approach. In this way, possible supply services can retrieve information without waiting for new events.

In a Smart City context, there are different middleware solutions in order to integrate heterogeneous data sources. *ReActOR* middleware [24] allows the seamlessly integration of different devices with a tiny footprint. Thus, it can run in a low power single-board computer (e.g. Raspberry Pi board). However, this architecture is limited to hardware devices and it does not support the integration of different data sources (e.g. Database Management Systems). At district level, authors [25], [26] present an IoT software infrastructure that enables energy management and simulation of new control policies. This through the interoperability and correlation of (near-)real-time building energy profiles with environmental data from sensors. The innovation is represented by the IoT platform able to realize a virtual model of the district in order to provide Smart City services. However, data coming from IoT devices deployed across the energy distribution networks must be correlated together with geo-referenced informationd about buildings. In this context, the DIMMER project can be considered as one of the most significant experiences that takes advantage of these new technologies and methodologies. The DIMMER platform creates a virtual model of a urban district by integrating BIM, GIS (Geographic Information System) and energy distribution networks (both heating and power) together with real-time data coming from IoT devices. Thus, BIM models are needed to better model and simulate control systems [27].

Regarding the interoperability across various application domains, many research projects have been conducted. The *IoT-A* project [28] innovative system that allows the description of an IoT solution by using shared building blocks. The *oneM2M* organization [29] aims at developing technical specifications for a common M2M (Machine to Machine) Service Layer that can be readily embedded within various hardware and software, using existing IoT and Web standards. The *FI-WARE* research project [30] aims at building a sustainable ecosystem around public and open source standards for Future Internet visions. The platform provides a rather simple yet powerful set of APIs (Application Programming Interfaces) for IoT and Smart Applications.

Our contribution consists on a software infrastructure for management and simulation of energy behaviours in buildings that integrates and correlates heterogeneous data-sources, such as BIM, GIS, IoT devices and meteorological data. This integration allows: *i* (near-) real-time visualisation of energy consumption information; *ii* building performance evaluations through energy modelling; *iii* simulations exploiting real weather conditions and building environmental data coming by IoT devices; *iv)* creation of GIS energy maps of the city with specific energy-demand and energy-supply for each building. Furthermore, with respect to literature solutions, we run simulations exploiting more precise BIM models in terms of stratigraphy. Finally, current solutions performs energy simulations based on Typical Meteorological Year (TMY). Whilst, we exploit real weather information to better simulate the building performance according to climate changes occurred in recent years. Our results can be conveniently applied to many contexts. For instance, they can be integrated and correlated with the Building Management System (BMS) through the proposed software infrastructure. In addition, we keep all stratigraphy of building components (i.e. walls, ceilings and roofs) to reduce possible changes to the architectural model.

4. Integrated Solution for Smart Buildings Management

The objective of our research is a cloud-based software architecture that integrates heterogeneous hardware and software components for monitoring and modelling buildings energy behaviour. The platform exploits pervasive geo-referenced IoT devices to collect environmental and energy related information. IoT devices are integrated with BIM, GIS and weather data exploiting middleware technologies. It allows energy simulations to evaluate both efficiency performances of buildings and effects of possible refurbishment actions. Furthermore, the data provided by the IoT devices can be used also for (near-) real-time monitoring and control of both environmental and energy parameters of buildings.

4.1. Middleware for Smart Buildings

Figure 1 shows in detail the three layers of the middleware that is in charge of enabling the interoperability between the heterogeneous data-sources of our solution. The bottom layer is the *Data-sources integration layer*, that integrates heterogeneous hardware and software technologies, by abstracting their features into Web Services. The different hardware technologies are integrated through IoT gateways that are middleware-based software components to abstract device features into web-services. Specific gateways have been developed for different standards and protocols, such as *ZigBee* and *Spirit*. BIM, GIS and weather stations are software data-sources. Their integration is allowed through middleware-based software adapters. BIM models are needed to monitor and model the energy performance of the analysed buildings. GIS provides geo-referenced information about building, distribution systems and deployed IoT devices. Whilst, meteorological information are retrieved from the nearest weather station via third party services.

The core of the middleware is the *Services Layer* that offers the components for developing generic applications and distributed services. This layer is composed by the following modules:

- The *Network Manager* creates a peer-to-peer (P2P) connection between the middleware components and applications enabling a direct communication between theme. Calls to web-services are routed through the Network Manager, which creates a SOAP (Simple Object Access Protocol) tunnel to the endpoint of the required service.
- *Trust e Crypto Manager* is in charge of creating a secure communication between trusted peers. In detail the Trust Manager verifies if a peer in the middleware network is trusted or not. This implies that in the middleware network only trusted peers can invoke web-services and receive informations. The Crypto Manager is able to encrypt messages exchanged between the various peer using both symmetric and asymmetric encryption and digital certificates.
- The *Message broker* provides a data-centred model based on the publish/subscribe approach [23]. Such model increases scalability by decoupling the production and consumption of information. It eliminates the explicit dependencies between applications and middleware components in the network.
- The *Semantics Framework* provides functionality to store, access and update the semantic knowledge (ontology) of one or more domains. Exploiting the ontology, the *Semantic framework* is able to correlate the different data sources together by using semantic attributes. For example, it is possible to know which type of sensors are present in a building or in a specific room, having details on sensors metadata, such as characteristics and measured parameters.
- *Rule Manager* allows the development of control policies completely flexible based on basic rules.
- *Store Manager* is in charge of collecting the data coming from the IoT devices and from the models. Furthermore, the store manager feature provides the collected data to the other components of the infrastructure.

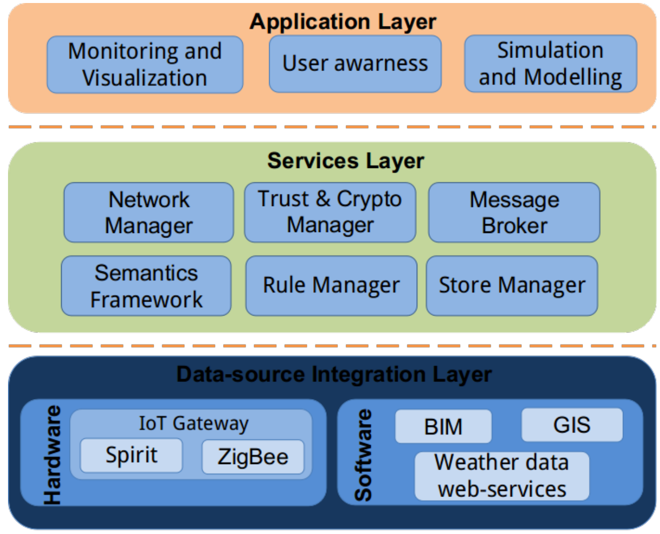

Figure 1. Architectural schema of the proposed software infrastructure.

Finally the *Application Layer* provides a set of API and tools to develop distributed application for building management and to post-process collected information. Thanks to this layer, pervasive applications with various scopes, depending on different stakeholders, can be developed, as described in Section 4.2.

4.2. Application for smart building management

The applications for building management are mainly devoted to facility- and energy-managers. Final user can exploit our solution to retrieve (near-) real-time and historical information on environmental parameters of buildings and rooms, also to provide user-awareness on energy consumption. Furthermore, a set of applications for both monitoring and modelling of energy performance can be exploited by facility- and energy-managers. Such applications are briefly described in the following:

- *Visualization and Monitoring*: Managers and end-users can visualize in BIM model environmental data provided by the related IoT sensors. Thus, they can check comfort parameters and increase energy efficiency by having knowledge of their consumption.
- *Temperature and consumed energy simulations*: Managers can simulate, exploiting real weather data, the temperature profiles in the rooms of the building or the consumed energy in a certain period. This simulation can be used to check the overall efficiency of the building or to check if final users have virtuous behaviours. Furthermore, through user-awareness applications, users can be notified on bad behaviours and suggestions can be given to promote green behaviours.
- *Load scheduling simulations*: Managers can exploit this simulation to evaluate if a change in the heating cycle schedules will provide the same comfort level to end users. Furthermore, managers can validate this applied changes exploiting the real-time data provided by the IoT sensors.
- *Refurbishment modelling*: Managers can run simulation to asses refurbishment actions. For example, they can modify the BIM by changing the characteristic parameters of window fixtures or insulation coating and evaluate the possible energy savings.
- *Building Efficiency Comparison*: A manager that handles more than one building can make comparison of energy efficiency between buildings that share same characteristics in order to understand possible malfunction or wrong user behaviours.
- *Non intrusive load monitoring*: Managers can exploit advanced Non-Intrusive Appliances Load Monitoring (NIALM) techniques to extract from the electricity data coming from smart meters the load patterns of each appliance in the bulging. With such knowledge managers can provide building users with suggestions to reduce or optimize electricity consumption.

4.3. On-site deployment in smart building

Figure 2 shows the principal components that are deployed on-site. Buildings are equipped with a: *i)* Wireless Sensor Network (WSN) with low power micro controllers that monitor indoor temperature and air humidity in rooms; *ii)* with a smart-meter that monitors electricity consumption data by communicating with classic Low-Voltage meter exploiting Power-line communication. Both WSN and smart meters are connected to a gateway that sends data to the Cloud, in particular to the *Store Manager*. The interoperation

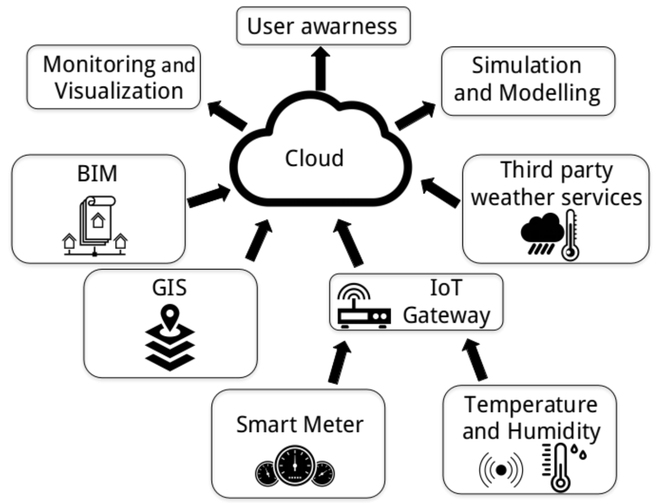

Figure 2. Schema of on-site deployment for the proposed solution.

between collected data in the cloud, weather information, BIM and GIS models is given by the middleware-based software adaptors (see Section 4.1) that provides users with: *i)* simulation and modelling of building energy performance; *ii)* building status monitoring and visualization of collected data; *iii)* user awareness.

5. Proposed methodology for thermal energy simulation

In this section, we describe the followed methodology to perform energy simulations starting from BIM and correlating IoT data within an integrated process. The building energy modelling and monitoring approach is one of the most challenging topic in Smart City scenario. In this context: i) BIM establishes a proper knowledge of the buildings; ii) technical investigations aimed at energy efficiency are required by EU Energy Performance of Buildings Directive [3]; iii) IoT links different domains and provides real data from the field. These factors constitute the key issues for this research development.

To achieve it, BIM models have been developed with *Autodesk Revit 2016* [31] starting from on-site surveys. They include: *i)* accurate building envelope characterizations in terms of correct stratigraphy, thermal and physical properties; *ii)* facility management information (e.g. room type and occupants); *iii)* materials nomenclature standards. Thus, they become a significant repository of graphical and alphanumeric information useful for energy analysis. To properly set the model to perform energy simulations, the BIM needs simplifications by removing excessive details in the architectural model, such as decorations and staircases (see Figure 3). These details are unnecessary and get slow the simulation or can even include inaccuracies in final results. Figure 4 shows the *Energy Analysis Model* (EAM) that consists of rooms and analytical surfaces generated from the BIM model and exported by *Revit* in gbXML

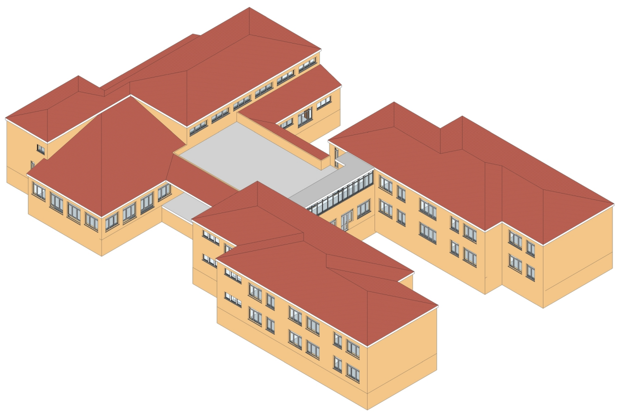

Figure 3. BIM model.

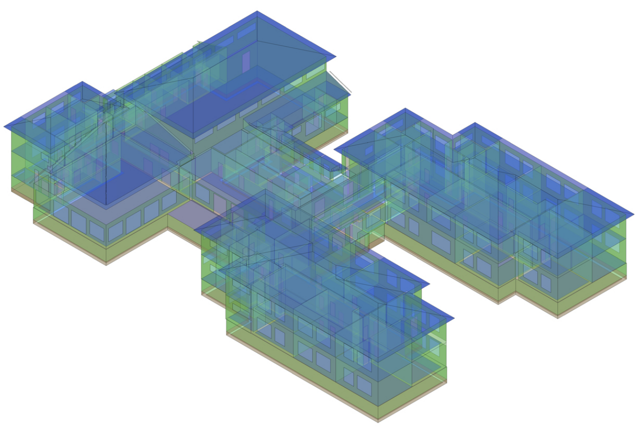

Figure 4. Energy Analysis Model (EAM).

data-format. Figure 5 reports the proposed energy modelling optimization process. The **EAM Simulation Engine** block performs building simulations using EnergyPlus [32]. It needs the following inputs:

- *Geometry and materials* of building components (e.g. stratigraphy and shades) and their thermal and physical properties. These come from BIM models;
- *Real weather data* such as *i)* air dry-bulb temperature, *ii)* solar radiation and *iii)* average air temperature;
- Data retrieved from *Heating Ventilation and Air Conditioning systems* such as *i)* nominal power and flow rate of radiators, *ii)* nominal power and efficiency of boiler, *iii)* climate control unit, *iv)* on/off profile of the heating system;
- *Occupancy* of rooms, including number of users and time-shifts.

The outputs of the *EAM Simulation Engine* block are radiant, operating and indoor temperature. It also provides the energy consumption profiles of the building. Traditionally

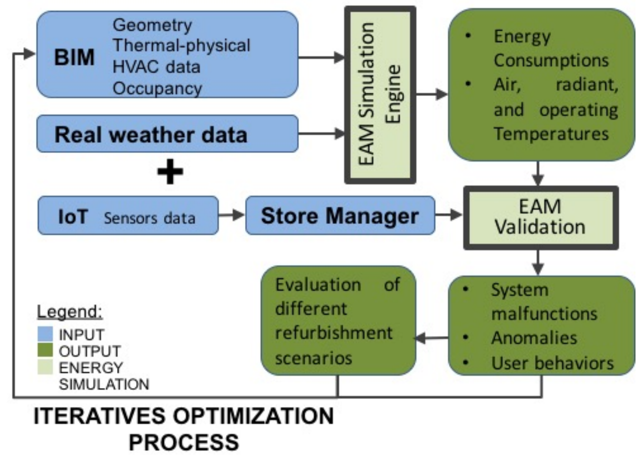

Figure 5. Proposed energy modeling optimization process.

energy simulations with EnergyPlus are performed using Typical meteorological year (TMY). TMY is obtained by averaging hourly meteorological measurements collected for 10 years. Thus, it does not represent real weather conditions. As a strong point of our simulations, we integrated in our software platform (see Section 4.1) third-party weather data-source from the nearest weather station. Hence, real weather information (i.e. solar radiation, outdoor air temperature and humidity) are considered in the simulation process replacing the default TMY.

Indoor air temperature and humidity are sent every 15 minutes by IoT devices and collected in the *Store Manager* of the proposed platform (see Section 4.1). Such data are needed by the *EAM Validation* block in Figure 5 to validate the performed simulations. This validation is done by comparing the results of the *EAM Simulation Engine* with the real measured values coming from the deployed IoT devices. Analysing temperature and consumption trends, factors that may affect the energy model can be identified, such as user behaviors, malfunctions and anomalies in the system. For instance, user-awareness applications can help in minimizing not energy efficient behaviors. Whilst maintenance activities can be planned to monitor and solve identified anomalies (e.g. by comparing measured and simulated data, it is possible to discover irregular trends of real indoor temperatures due to faults in on/off schedules of the heating system or efficiency losses of the building-system).

In addition, BIM models can be used to evaluate different design and/or refurbishment scenarios (see section 4.2) (e.g. external/internal coat application, fixtures replacement and power peaks regulation). Thus, this updated BIM model is a new input for the energy modelling optimization process. This process is iterative and can help building- and energy-managers in evaluating the best solution for both energy performances and Return of Investment.

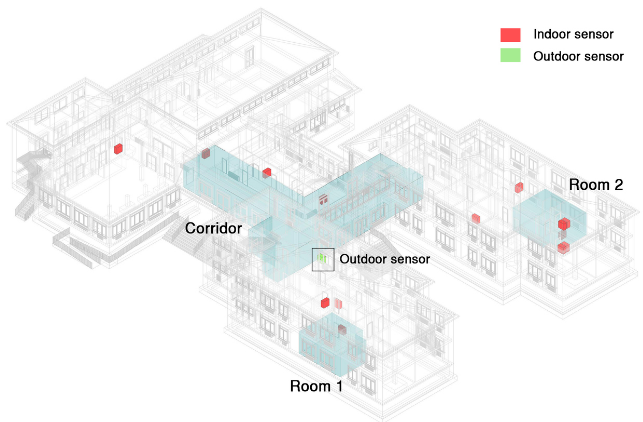

Figure 6. Sensors positioning and reference rooms for the energy simulation within the case study.

6. Case study and experimental results

As case study, the methodology described in Section 5 has been applied on a primary school. It is a public building of about $14,500\ m^2$ spread on two floors (see Figure 3 and Figure 4) with brick walls facades, double glazed windows and pitched roofs. The building is connected to the district heating distribution system. During working-days, the heating system cycle is from 4:00 a.m. to 7:30 p.m.. To ensure a comfortable environment for users the ignition of Monday is anticipated on previous Sunday at 11:00 p.m..

The building has been equipped with 16 IoT devices, 15 indoor and 1 outdoor (see Figure 6), to send air temperature and relative humidity. Sensors have been installed in the most meaningful building zones according to its intended use, construction type and floors number (i.e. main entrance, classrooms, gym and student canteen). The Wireless Sensor Network has been evaluated to optimize the employed IoT devices with respect to the good result of the energy simulation. In this study, indoor devices have been placed in comparable rooms in terms of use and dimension characterized by a different orientation. Instead the outdoor device has been placed at the worst solar exposure to detect the minor outdoor temperature. The symmetrical shapes and the regular internal distribution of the building have allowed us to select some reference rooms to collect enough data for energy analysis.

The energy simulation has been performed for the whole heating season. In this paper, we present the results from January 9$^{\text{th}}$ to January 15$^{\text{th}}$ 2017. The validation model is achieved by comparing the Temperature trends, as described in Section 5. For this purpose, we have analysed three selected rooms in the building (see Figure 6). These rooms have been chosen in relation to building shape and their occupancy during the week, as described in the following:

- **Room 1** is a classroom in the east part of the building occupied by 21 people. It is located in correspondence of thick trees that act as solar shield for the building.
- **Room 2** is a classroom in the west part of the building occupied by 22 people.
- **Corridor** is at the entrance of the school in a central position of the building. It is characterized by a very large environment with many openings and glazed windows. It does not have a constant occupancy during the day.

Both east- and west-oriented facades receive substantial contributions of thermal energy due to solar radiation. This is an advantage during winter season. Vice-versa, this translates into increased heat load during summer season, which would necessitate air conditioning. As the school is not equipped with such conditioning system, our simulations cover only the winter period.

Figure 7 reports three air temperature trends for the observation period: *i)* measured data coming from IoT devices (green line), *ii)* simulated with TMY Weather condition (red doted line) and *iii)* simulated with real-weather conditions (blue dashed line). The daily trends identifies the different phases of the heating cycle: *i)* ignition of the heating system (04:00 a.m.); *ii)* school entering (8:30 a.m.); *iii)* lunch break with opening windows for air circulation (12:30 a.m.); *iv)* school exiting (4:30 p.m.); *v)* shut-down of the heating system (07:30 p.m.). The air temperature chart highlights that measured data and simulation results with real-weather conditions have similar trends. On the contrary, the trend of TMY simulation results has the worst correlation with real samples. Especially during night hours, the temperature trend decreases to around $10\ ^{\circ}C$ with TMY simulations, while both measured and real-weather trends reaches about $16\ ^{\circ}C$. This because TMY refers to meteorological conditions, in terms of temperature and solar radiation, significantly different to daily weather samples. Both simulations with real-weather data and TMY show a quicker slope of increase and decrease in the temperature trend when the heating system is switched *on* and *off*. This quicker response is related with the modelled heating capacity of the building. Indeed in the development of the BIM model the stratigraphy of the walls has been hypothesized fallowing the suggestions in [33]. Those hypothesis were necessary due to a lack of information on real wall stratigraphy data in the building documentation.

To evaluate the performance of our simulations three indicators of dispersion have been used:

- *Mean Bias Difference* (MBD) measures the average squares of errors between simulated and measured values;
- *Root Mean Square Difference* ($RMSD$) represents the standard deviation of differences between simulated and measured values;
- *Mean Absolute Difference* (MAD) is defined as the average of the absolute difference of two variables X and Y.

Table 1 details the error rates given comparing measured data with simulations performed with both real-weather and TMY conditions. As shown in Table 1, real-weather

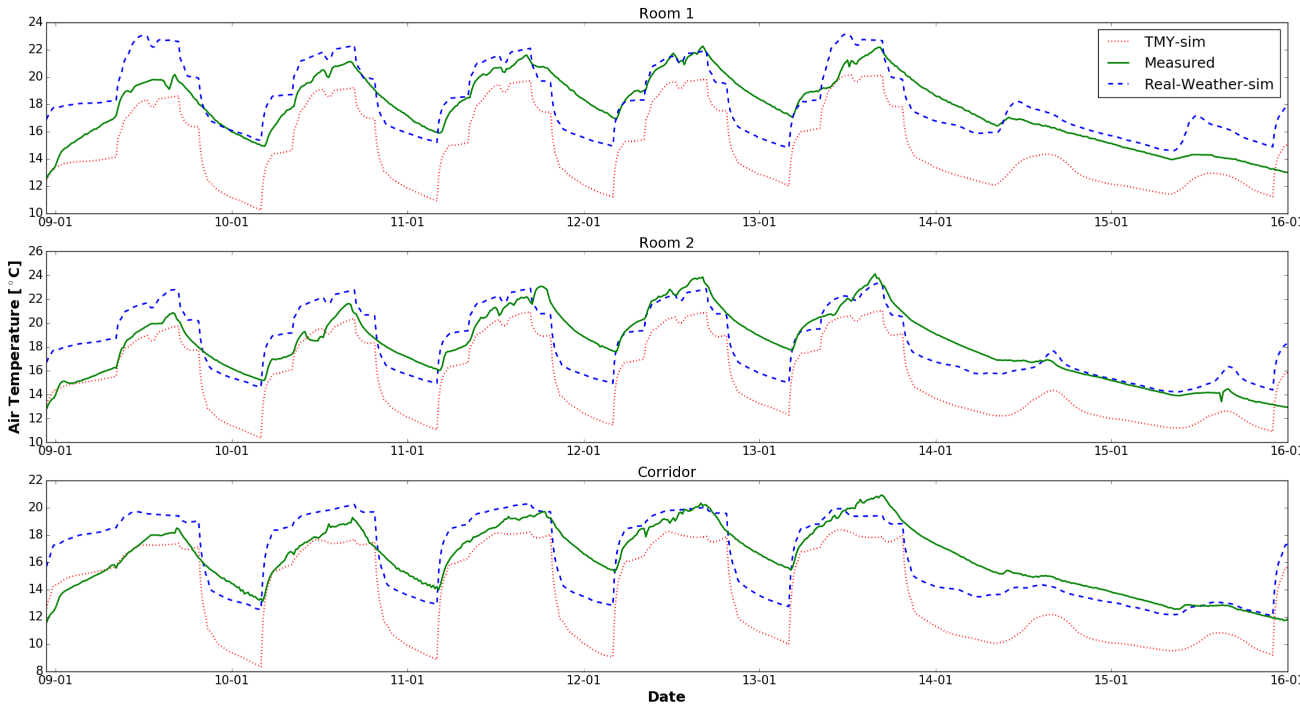

Figure 7. Simulated and measured indoor air temperature trends between 9th-15th of January 2017.

TABLE 1. DISPERSION INDICATORS OF SIMULATED INDOOR TEMPERATURE AGAINST REAL MEASURED VALUES

Rooms	Indicator [%]	Real-weather Sim vs Measured	TMY Sim vs Measured
Room 1	MAD	8.02	16.82
	MBD	2.18	-16.64
	RMSD	9.78	19.01
Room 2	MAD	9.07	18.55
	MBD	0.10	-18.34
	RMSD	10.83	20.74
Corridor	MAD	9.35	16.94
	MBD	-0.17	-16.06
	RMSD	11.52	20.85

information improves the simulation results drastically with respect to TMY. Indeed, MAD, MBD and $RMSD$ have lower values with real-weather conditions. In particular in *Room 1*, we obtain a MAD of 8.02% against 16.82%; a MBD of 2.18% against -16.64%; a $RMSD$ of 9.78% against 19.01%. Similar results have been obtained for the other two rooms.

7. Conclusions

In this paper, we presented our software infrastructure for management and simulation of energy behaviours in buildings. It correlates different information by integrating heterogeneous IoT devices and meteorological services together with BIM and GIS technologies. This solution provides building-, facility- and energy-managers with tools for: *i)* (near-) real-time visualization of energy consumption information; *ii)* simulations of temperature trends and energy consumptions. Through simulations, the managers can also check and evaluate the efficiency performance of the building, energy behaviours of users and possible refurbishment actions.

The presented experimental results showed that our solution simulates with a good accuracy the heating performance of the case-study building. With respect to literature solutions that consider TMY weather data, our results highlighted that the integration of real weather information into the simulation process strongly increases the accuracy of the simulation itself. The methodology presented in this study will be replicated, within the same research project, on different existing buildings in terms of construction typology, year, intended use and occupancy to demonstrate the usefulness of the simulation packages.

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