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Integrated smart system for energy audit: methodology and application

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Abstract

The article describes the design and the application stage of a smart energy audit system, integrated within building, and the methodologies adopted for the detection of malfunctions of the plant. The system is set up as a "black box" consisting of a hardware aimed at logging both energy and environmental parameters and a software for the assessment of building behavior and the management of energy flows. The Energy Signature was chosen as the reference method for the evaluation of the energy performance of building. The system was tested in an existing public office building.

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Keywords: **Energy audit; energy consumption; Energy Signature; logic control; monitoring**

1. Introduction

The high energy consumption of the building sector is a topic discussed and addressed on the tables of all the political and scientific institutions. At the global level, the primary energy consumed by buildings accounts for about 40% and the greenhouse gases emissions for 30% [1]. The awareness of the environmental, economic and social risks related to these emissions were the engine which in recent years has motivated the decision-makers in launching a series of measures to improve building performance [2], [3].

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The European Union is actively involved in the definition of measures aimed at reducing consumption and improving the energy performance of buildings up to the definition of nearly Zero Energy Buildings (and beyond),

with high thermal performance and use of renewable energy sources to meet the energy demand [3]. These concepts are well suited to new buildings, primarily subordinate to design constraints. The situation is rather different if the same requirements are applied to existing buildings, where a further design effort is required in order to consider structural, landscape and environmental constraints which can affect the refurbishment to varying degrees [4].

The European building stock consists for about 70% of residential buildings. The non-residential buildings represent the remaining 30% and constitute a complex and heterogeneous set. The analysis of the time series highlights how more than 50% of European residential buildings were built before the 70th. About 15% of the total was built in the new millennium and just the 4% after 2010 [5]. The Italian situation related to the new buildings shows lower percentage compared to the European average. Finally, the recent international crisis has further reduced the investment in the building stock.

The energy consumption is directly proportional to the age of the buildings [6]. The introduction of energy policies increasingly conservative over the years allows the reduction of buildings energy consumption. Specific studies have highlighted how a systematic procedure of analysis of the state of art and of refurbishment actions can address the national energy policy related to the building sector [7].

Starting from these premises, it is clear how the energy retrofit of the building stock should take a leading role [8] also to achieve the nZEB goals [9]. In Italy, a series of measures to encourage energy retrofits were launched over the years (in terms of tax deductions) stimulating a sector that perhaps more than the others has been affected by the adverse international economic situation. The last available data shows how the actions financed over the years (2007-2015) have produced an overall energy saving of primary energy higher than 13.200 GWh and a CO_2 reduction of about 2.800 kt with a total investment of about 28 billion euro [10]. Although these are encouraging results, they are not enough to achieve the targets. Most of the renovations concerned the replacement of windows, followed by the replacement of the heat generator typically with condensing or high efficiency boilers and the installation of solar panels for Domestic Hot Water (DHW) production. The renovations related to the opaque envelope occupy a marginal position representing about 2% of the total [11], [10]. The choice is often imposed by economic reasons rather than a careful analysis of the overall impact of the intervention.

It is clear how the application of an integrated approach [12], smart devices able to manage the energy and environmental variables [13] and a systematic procedure of energy diagnosis [14] aimed at identifying unusual behavior of the building-plant system and at suggesting the best practices of refurbishment could actively contribute to achieve the set energy requirements for the building sector [15].

The paper describes an automated system for the energy diagnosis of buildings divided into three different levels of analysis: a first level of predictive diagnosis aimed at the analysis of the energy consumption, a second level aimed at the management and optimization of the thermal comfort and a last detailed level aimed at real time monitoring of the energy and comfort variables. A hardware and software architecture for monitoring the energy-environmental variables, for managing the energy flows and for assessing energy retrofit has been realized, tested and optimized in real public buildings. In the present article the focus is on the definition of the methodology of the energy diagnosis for the analysis of consumption and on the optimization and control procedures of energy flows and thermo-hygrometric comfort.

2. Architecture and functionality

2.1. Overview

The system is a multi-level diagnostic tool aimed at investigate a specific feature of the building-plant system. The energy diagnosis in the stricter sense represents the first level of the system.

The need for specific solutions for the monitoring of consumption is satisfied through the use of transducers and smart meters for the measurement and detection of the energy and environmental variables: energy consumption such as electricity, fuel, water and heat, indoor (air temperature, radiant temperature, relative humidity, air velocity, CO_2

concentration, lighting) and outdoor environmental variables (thermo-hygrometric conditions, solar irradiance, wind velocity and direction, lighting).

The measuring devices are equipped with the necessary apparatus for the wireless transmission of data. Two different transmission protocols are used: W-MBus for the energy consumption data and ZigBee for environmental variables. The last one is more adaptable [16] and useful to manage indoor environmental data from a dense network of a Wireless Sensor Network (WSN) by configuring one or more intermediate nodes as router allowing the signal transmission between end device and the coordinator even at long distances. The SCADA application is the “black box” where the data are collected and stored. Finally, the data management software platform is used for the energy-environmental diagnosis and for the identification of any critical situations.

The detected variables are stored in the database and made available for further processing, aimed at the implementation of energy diagnosis and management procedures. This goal is pursued through a software application able to import data from the local database and carry out the diagnosis. In Fig. 1 the system architecture is outlined, consisting of hardware component for the energy-environmental monitoring, software/hardware component for the energy diagnosis and user interface. The various levels are connected through transfer protocols (TCP/IP, FTP, Ethernet).

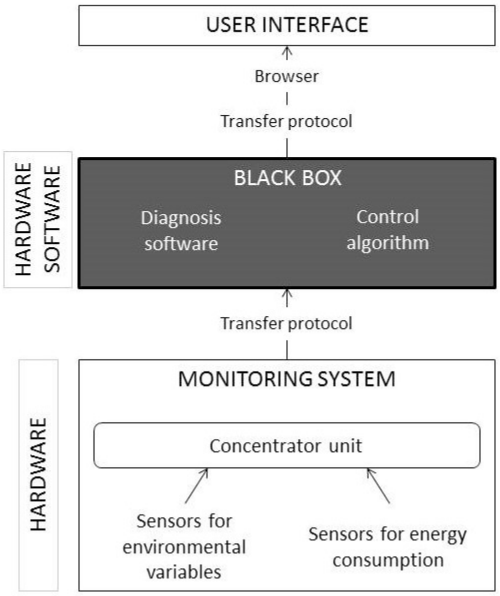

Fig. 1. System architecture.

2.2. Energy diagnosis software

Beside the hardware architecture for monitoring of the energy and environmental variables, it was necessary to realize the software able to analyze the detected data and formulate diagnostic hypotheses on the energy-environmental behavior of the building. A diagnosis method in compliance with the requirements of the “standard audit” was adopted [17]. The choice fell on the Energy Signature (ES) method [18] equipped with automated algorithms that allow the automatic evaluation of the measured data [19]. The overall index is made up of two curves: the Design ES (DES), realized starting from design data of building and the Real ES (RES), made from the on-site monitored data. The ES is graphically represented on a Cartesian plane where the abscissa is an external environmental variable, typically the outdoor air temperature, averaged on a specific sampling interval. The ordinate represents the energy parameter (consumption or power) over the same temporal range. The sampling interval chosen for the system is weekly for the on-site monitored data and monthly for the historical consumption, derived from bill. In this way the system is flexible as a function of the scope and field of application [20].

Beside the graphic representation, which quickly shows the building's energy behavior, the methodology provides physical and statistical indices that analyze in more detail the detected data and return more information of the energy trend and any faults, by comparison with reference values. These indices refer to:

- slope of ES;
- intersection of ES with Cartesian axes;
- dispersion of the detected points;
- outliers.

The analysis of the monitored data related to the thermo-physical, operational and utilization characteristics of buildings, detected through on-site inspection, allows the energy behavior to be assessed and indications on the energy retrofit to be provided.

The energy diagnosis tool can be applied both to existing and new buildings with different purposes. In the former the energy diagnosis is applied with all its function, from monitoring and detection of anomalies in the behavior of the building plant system to checking the performance of any refurbishment works. In new buildings the system allows to verify the correct sizing of the plant respect to the structural and functional requirements of the building on one side and the operational management on the other.

2.3. Benchmarking

The system provides a guided path for the assessment of possible critical issues in the energy building's behavior on the basis of the results of the energy audit and the comparison with benchmarks appropriately defined and parameterized, suggesting macro-areas of intervention to optimize the operation of the building.

The benchmarking phase is carried out: using values defined by technical standard, valid in any context or variables in relation to use of the building, climatic zone, required performance class, etc.; comparing the current state with performance expected in the design phase or with identifiable targets to be achieved (best practices, limit values set by law, etc.). In Table I the considered indices and the related acceptability range are shown.

Table I. Diagnosis indices and benchmark.

Indices	Benchmark		
	Good	Moderate	Poor
Slope - % difference (RES-DES)	< 5%	5 < % < 15%	> 15%
Pearson coefficient ρ	> 0.7	0.7 < r < 0.3	< 0.3
	(> -0.3)	(-0.3 < r < -0.7)	(< - 0.7)
R^2	> 0.95	0.95 < R2 < 0.90	< 0.90
Heating limit	15-17°C	-	-
Outlier	No outlier	-	-

Once the benchmark values are defined, the critical analysis of the result of the diagnosis is carried out in three phases: assessment of the performance obtained for a given index (by defining if the performance falls within an acceptable value range, and how much deviates from the best performance), parallel evaluation of the diagnostic results and the input data (by connecting any performance deficiencies to situations related to one or more specific aspects of the building and identifying what are the critical issues) and identification of the basic strategies (by formulating macro-refurbishment or optimization strategies).

2.4. Control and optimization

In order to define a control system, a simplified thermal model to control the energy fluxes and to improve the performance of buildings was developed. Robust numerical methods are needed for a detailed mathematical description regarding a great number of variables able to represent the user-building-environment interactions. International Standards provide simplified methods, which should be realistic, sufficiently sensitive and robust but also reliable, verifiable, transparent and reproducible. Recent studies demonstrate the accuracy of these methods in building energy performance simulation [21] and the suitability in the development of control systems [22].

Equivalent Resistance-Capacitance (RC) schemes are broadly used to represent thermal systems. This method of representation derives from the lumped capacitance solution of the transient heat transfer equations. A lumped model is based upon the assumption that the temperature of an element (or a part of it) is spatially uniform during a transient heat transfer. This approach is a good candidate to represent the overall thermal behavior of a building [23], [24].

According to the lumped capacitance solution the heat balance equation acquires a second order differential layout and is capable to describe the evolving temperature of a thermal node T(t) [K] due to the storing Φ_{in} [W] and extraction Φ_{out} [W] of the heat power from the thermal mass of the system:

$$C\frac{dT}{dt} = \Phi_{in} - \Phi_{out} \quad (1)$$

Each multi-layered opaque and transparent component is so represented as a 3R2C thermal node. Assuming to have n modules to describe a generic building, the i-th 3R2C module is connected to a thermal network T_i and heat flows.

By connecting each module with the others through the internal temperature node it is possible to determine the following balance equation:

$$C_{air}\frac{dT_i}{dt} = \sum\left[H_{o,i}\left(T_{s,i_i} - T_i\right)\right] + \Phi \quad (2)$$

RC models are often embedded in control system with the aim of predicting the building energy demand and optimizing the operating plants [25] and coupled with model-based design tools. In particular a Model Predictive Control (MPC) was specifically designed and developed for the real time control and management of the energy consumptions and thermal comfort, based on the RC model of the building. The MPC is a collection of algorithms that manipulate a set of variables to optimize the future behavior of a process. In this case the aim of the MPC is the optimization of indoor thermal comfort minimizing the energy consumption.

3. Case study

The on-site test is aimed at testing both the hardware and the software architectures of the developed diagnosis system by assessing the functionality of the monitoring system, the data management and transmission and the effectiveness of the diagnosis tool. Thus, the system has been applied with different degrees of detail to three publics buildings placed in the province of Mantua: a recently built multi-story building used as offices and nursing home, a multifunctional historic building where the municipal library is established and a multifunctional building. The experimentation across multiple sites has allowed the applicability of the system in different contexts to be verified and the diagnosis process to be optimized. The information required for the energy audit [26] were collected with on-site survey with particular attention to: energy performance of the envelope, types and heating system efficiencies, use profiles of the spaces.

The first step of the test consists of the identification of homogeneous thermal zones. The hardware components were installed within the building in selected places in order to detect the most representative energy and environmental variables. In particular a dedicated weather station is mounted outside the building for to detect the external variables and smart meters are installed on the heating/cooling system for detecting the energy consumption of each thermal zone. Both energy and environmental data are recorded, encoded and transmitted through the concentrator unit to the black box. The data are processed by the diagnosis tool and information about the energy behavior of the building are provided. Finally the data are used to predict and optimize the energy consumption of the building.

In the paper, the results of the experimentation carried out in the multi-story building are presented. The data refer to monthly historical consumption for heating mode retrieved from energy bills. The building is characterized by the presence of a plurality of uses such as nursing home for elderly, primary care clinics, clinics for specialist visits and offices for municipal social services. These uses occupy different portion of the building and are characterized by specific thermo-physic data and hourly use profiles that have required the choice and subsequent modelling of the most representative environments.

In Table II the main thermo-physical and geometric information of the considered thermal zone are shown. The geometric quantities were determined on the basis of information found during on-site inspections and design drawings. The thermo-physical quantities (thermal transmittance of opaque and transparent elements) were taken from project reports.

Table II. Thermal zone characteristics.

Elements	Exposition	Boundary	Area [m^2]	U value [W/m^2K]
Wall	SE	External	9.73	0.44
Wall	SW	Internal	21.28	1.32
Wall	NW	Internal	12.11	1.32
Wall	NE	Internal	21.28	1.32
Ceiling	-	Internal	24.85	0.65
Floor	-	Ground	24.85	0.62
Window	SE	External	1.68	3.40

4. Results

The software component for the energy diagnosis was tested considering the monthly historical consumption for heating mode of the considered thermal zone detected in the period January 2009 - February 2015. The DES was built by calculating the global heat transfer coefficient, H [W/s], as a function of the heat losses of the building zone by transmission and ventilation on the basis of the information about the geometrical and thermo-physical characteristics of the envelope elements and considering a standard air flow rate equal to 0.5 [h^{-1}]. The ARPA weather station placed at about 7 km from the building site provides the monthly average climate data. In Table III the average seasonal values of the data and the performance indices for the energy diagnosis process are shown.

Table III. Thermal zone characteristics.

Period	Range		Tavg	Qavg	m	q	ρ	Outlier
2014-2015	15/10	15/04	7.87	127.19	-10.64	210.94	0.98	X
2013-2014	15/10	15/04	8.55	133.24	-8.68	207.45	0.94	X
2012-2013	15/10	15/04	6.20	138.79	-9.35	196.77	0.94	X
2011-2012	15/10	15/04	5.72	142.37	-9.91	199.10	0.98	X
2010-2011	15/10	15/04	4.89	148.79	-10.63	200.74	0.87	V
2009-2010	15/10	15/04	5.29	142.70	-7.92	184.60	0.85	X

The yearly trend of the historical consumption highlights a coherent energy behavior of the building related to both the design data and the external temperature (Fig. 2, Fig. 3, Fig. 4).

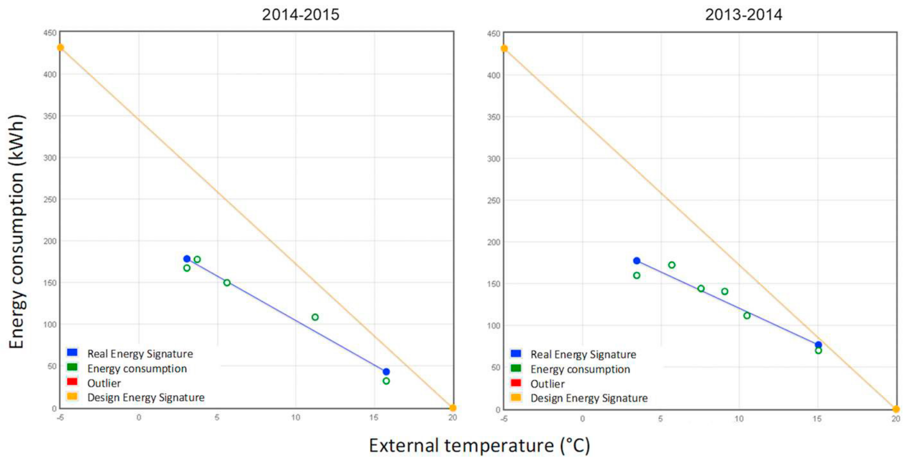

Fig. 2. ES of the monthly consumption between 2013 and 2015.

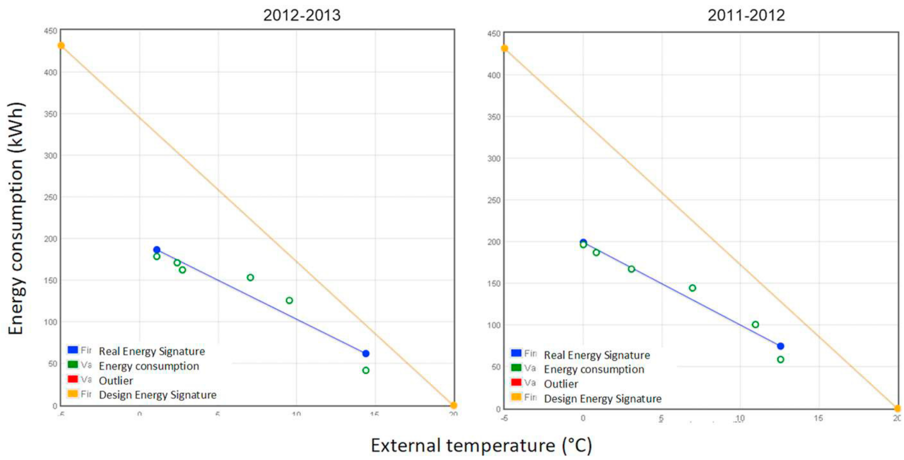

Fig. 3. ES of the monthly consumption between 2011 and 2013.

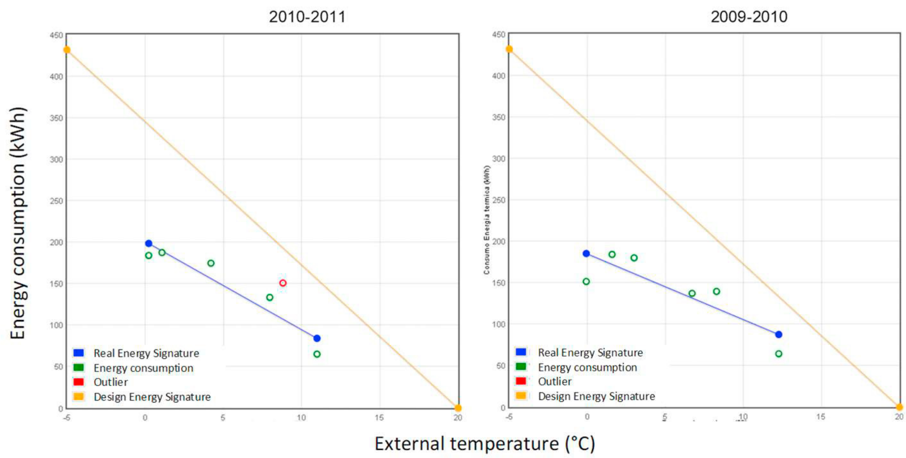

Fig. 4. ES of the monthly consumption between 2009 and 2011.

The benchmarking phase allowed to analyze in detail the energy behavior of the building-plant system on the basis of the specific indices. The comparison of the considered parameters with the benchmarks highlight a correct energy behavior of the building relative to: slope of the regression lines, heating limit external temperature both related to the proper building envelope design, and linearity of the data. Faults emerge for the other indices. In particular, the coefficient of determination R^2 shows as there may be anomalies in the energy behavior. The causes have been identified in the lack of specific set-points temperature as a function both of the different uses and the temperature profiles. The identified refurbishment solution provides the installation of a new control system allowing an optimize management of the temperature hourly profiles as a function of the use and the activities in the considered thermal zone. The diagnosis detected one outlier referred to the excessive consumption of a specific month during the heating season 2010-2011 related to the external temperature. Since this is an isolated case it may be traced to a temporary malfunction of the plant, then solved.

The operation of the control logics was tested by simulating the thermo-energetic behavior of the considered thermal zone initializing the 3R2C model with the data detected by the on-site survey and the monitoring phase. The effectiveness of the MPC was compared with a baseline scenario based on steady-state control logics. The aim of control is to minimize the energy consumption of the thermal zone complying minimum requirements for thermo-hygrometric comfort. The standard EN ISO 7730 provides the thermal comfort classes as a function of the PMV (Predictive Mean Vote) and PPD (Predicted Percentage of Dissatisfied) values and the operative temperature. In particular, the class B (corresponding to PPD < 10% and -0.5 < PMV < 0.5) was assumed as threshold value which corresponds to an indoor air temperature in heating period of 22 ± 2 °C. The baseline control was implemented starting from the Analytical Comfort Zone Method principles suggested by ASHRAE, which allows to define an actuation solution to bring the conditions within the considered range. The comparison shows how the MPC allows to obtain good results from the thermo-hygrometric point of view compared to the baseline control, reducing both the periodical fluctuations of the PMV index within the range ± 0.1 and the energy consumption.

4. Conclusions

The article describes the development, testing and optimization phases of an integrated tools for the energy diagnosis of buildings aimed at the identification of anomalous energy behavior, possible causes and optimal management of the energy flows as a function of the thermal comfort requirements. The process required the design of the hardware (sensors, transmission infrastructure and data processing) and software components (diagnosis and control methodologies), the testing and optimization through the application in real conditions.

From the diagnosis point of view, in the stricter sense, the use of the ES as an indicator of the energy behavior of building presents a number of significant advantages, consisting of: more complete analysis than the methods related to only monitoring of consumption, analytical assessment, expenditure of resources. The method allows to detect anomalies and above normal consumption and to identify the possible causes. Starting from the punctual indices provided by the method of analysis a benchmarking phase was defined allowing the correlation of the assumed values by each indicator with possible anomalies and corrective solutions. Finally, the definition of a control system allowed to define control logics for the optimization of the energy consumption of building to reach the desired levels of thermal comfort.

The testing in real buildings shows the applicability and the flexibility of the system in different working conditions. At this time the overall system is tested using existing data (monthly historical consumption for heating mode retrieved from energy bills). The test on the single components, hardware and software, highlighted the effectiveness of each elements. The complete application of the system to a real case allows the steady real-time energy diagnosis of the building. Future developments provide the application of the system in other context testing the functionality of the diagnosis software with other plant and the interaction of the method with the final users.

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