ENERGY PERFORMANCE ASSESSMENT OF A HIGH SUSTAINABILITY BUILDING USING WHOLE BUILDING SIMULATION AND IN SITU MEASUREMENTS

C. Cornaro[1,2], R. Latorre[1], F. Bucci[1], M. Pierro[1]

1. Department of Enterprise Engineering, University of Rome Tor Vergata, Via del Politecnico, 1 – 00133 Rome, Italy; e-mail: cornaro@uniroma2.it, ribe3@hotmail.it, frabucci@gmail.com, marco.pierro@gmail.com.
2. Center for Hybrid and Organic Solar Energy (CHOSE), University of Rome Tor Vergata, Via del Politecnico, 1 – 00133 Rome, Italy.

Abstract

The purpose of this study was to investigate the energy performance of a building that is part of a newly built residential development located in the city of Rome, Italy. The district, named *Rinascimento 3rd*, is of great energetic value and consists of 20 buildings fabricated with high thermal performance materials to reduce energy dispersions both in winter and summer. The whole residential settlement is also served by an innovative centralized energy production system that consists of a trigeneration (combined heating cooling and power) unit fed with biomass (vegetable oil), a heat exchange plant with geothermal heat pumps with 190 vertical pipes and a thermal generator fed with vegetable oil, as well. Dynamic simulation using a whole building simulation (WBS) tool and in situ measurements were used to investigate the energy performance of one of the 20 buildings. The approach consists in a careful survey of the building characteristics in order to build the model and in a short term monitoring campaign in one of the building apartments to calibrate the model. Simulations were then used to evaluate the energy demand of the building. The findings confirmed the high energetic standards of the construction.

Keywords: dynamic simulation, energy efficiency in buildings, monitoring, IDA ICE

1 INTRODUCTION

Recently the European Council confirmed the objective of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990 [1]. The construction sector has a primary role in the CO_2 reduction in Europe since buildings use around 40% of total energy consumption and generate almost 36% of greenhouse gases in Europe. Allouhi et al. [2] presented recent data on the world energy consumption in both residential and commercial buildings together with an overview of measures and policies adopted by different countries, for the reduction of energy consumption in buildings.

Although there is a great need of high efficiency building design solutions, buildings often do not perform as well as predicted [3]. The continuous improvement of building technologies highlighted the importance of Post-Occupancy Evaluation (POE), in order to bridge the gap between designers, building managers, and occupants after handover [4]. The use of advanced simulation software tools together with microclimatic measurements represents one of the best approach to POE.

Currently several simulation software are available for the evaluation of energy performance of buildings. These systems can be classified as static, semi-dynamic and dynamic [5]. Stationary and semi-dynamic approaches are simplified methods that consider a limited number of factors. They are more related to the evaluation of energy performance in standard conditions of use and usually input data are provided by standard references from national databases. On the contrary, dynamic simulation softwares are able to evaluate accurately all factors but they need detailed input data for climatic conditions and building properties. Moreover accurate calibration of the simulation model is a key factor to represent the real case as accurately as possible to be a reliable means to suggest optimization solutions.

This work presents the energy performance assessment of a high performance building complex designed and built by Mezzaroma company in Rome suburb, Italy. The main objective of the analysis is to produce a reliable and accurate simulation model of the building envelope to evaluate the energy demand and verify the design solution adopted.

Figure 1. Location of the building complex within the City of Rome

Figure 2. Layout of *Rinascimento 3rd*

Moreover the obtained tool will be used to evaluate post-occupancy optimization solutions for dynamically assisted building energy management.

2 BUILDING COMPLEX

The evaluated building complex is situated in the North-East Rome suburb, 41°57'23.55''N and 12°33'00.03''E (fig. 1), precisely on the west border of Parco Talenti, and its features in relation of high population density makes it a great example of environmental sustainability.

The whole project provides for residential development of 600.000 m^3, integrated with services, business, sports complex, and wide areas of public park, on an area of 650.000 m^2, and building complex is composed by 20 buildings, for a total of 930 flats (Figure 2).

The method which characterized this initiative is based on the analysis of the environmental background, by monitoring and microclimate and weather mapping: prevailing ventilation (direction and intensity), solar radiation, temperature, relative humidity, and biophysical analysis of this area, e.g. vegetation trim, earth morphology, above all paying specific attention to geothermic features of the ground that has been used as main renewable source.

The planning choices which characterized this project were aimed, in addition to the respect of the environment also to the fulfillment of a local identity.

The chosen strategy concerns especially the selection of typical materials of roman areas, selected on the basis of their ability of energetic control, the creation of wide outer areas, which guarantee the complete usability of local mild climate and can be used as a thermal buffer between open areas and the buildings, and the use of sustainable plants, which produce emissions reduction of CO_2 estimable in about 70% compared to buildings of the same area and supplied by traditional plant systems.

In the specific case of building project, first of all every executive detail of the part composing the building envelope was chosen (cladding, floors, covers, fixtures, etc.) improving thermal capacity and reducing heat dispersions, with specific attention to thermal bridges. Furthermore, also acoustic comfort was taken into consideration, improving several parts of the building.

2.1. Plants

The following aspects were taken into account during the plant design phase:

-compliance with the rules;

-size of the intervention;

-availability of a wide free area;

-the use of alternative renewable energy sources to photovoltaic owing to no optimal orientation of buildings because of respecting urban parameters;

- high standard of environmental comfort;

In figure 3 a general arrangement of the plants is shown. The system consists of a trigeneration (combined cooling, heating and power) plant for the production of electricity supplied by renewable energy source (biomass, e.g. oil), which is able producing hot water as byproduct (waste) of primary process of electricity production and chilled water integrating thanks to an absorber and a cooling tower; a heat exchange plant, composed by a set of 190 geothermal probes situated at 150 meter of depth and by 4 high performance heat pumps, which is able producing hot and chilled water; an oil fired system for the production of hot water in the

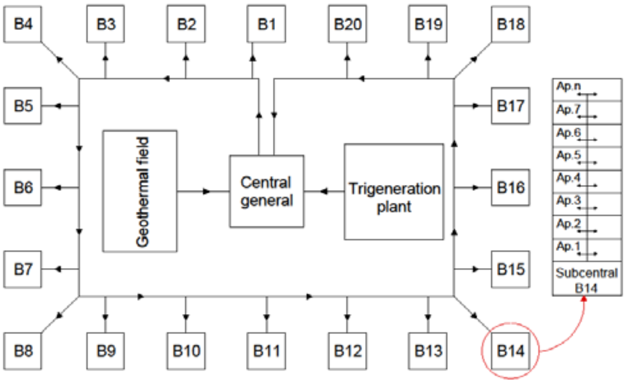

Figure 3. Conceptual arrangement of the plant

case of trigeneration failure and to guarantee the observance of resolution 48 of the Municipality of Rome. Eventually, in case of failure or maintenance of the primary plant, a backup usual plant, composed by refrigeration air source units supplied by electricity network for the production of chilled water and gas fired heating systems for the production of hot water, comes into operation.

Every subsystem contributes, according to advanced control software, supplying a single primary circuit which, in turn, feeds substations placed in the basement of every building.

The building complex requires an overall annual supply of primary energy (air-conditioning in winter and summer, hot water, electricity for lightning and power) equal to 10.443 MWh; this integrated system is designed to support also peak demand, and primary energy provided is due to renewable source for about 63% (6.579 MWh).

The integrated system of *Rinascimenro 3rd* will be able, in standard use, reducing CO_2 emissions of about 5.000 tons every year compared to a conventional system.

3. CASE STUDY: C4 BUILDING

To accomplish *Rinascimento 3rd* buildings energy performance study, the C4 building was chosen as reference (fig.4, fig.2 red encircled).

This building is composed by 8 floors and 47 apartments. Air-conditioned total volume is 12321 m^3, surrounded by a building envelope which total surface is 5633 m^2, with 0.46 surface over volume ratio. C4 building was chosen mainly due to its orientation, and for logistical reasons.

Indeed this building was recently built and then scarcely populated; therefore the company could easily provide a free apartment for monitoring activity.

Figure 4. Picture of C4 building

Apartment 30 was chosen with a surface of 50 m^2, located at the 4^{th} floor, facing the south-east-side. This case presents the worst conditions in summer and also a greater exposure to weathering due to the high floor.

In the apartments radiant floor heating and cooling with low temperature fluids is used. Fluid low operating temperature (tightly connected to the envelope thermal “capacity”) allows system overall cost saving and long term management cost reduction. For summer conditions, the plant is integrated by electric dehumidifier and air-conditioning system. The apartments are also provided with controlled mechanical ventilation, which performs automatic and controlled air exchange at a rate of 0.5/h. Fresh air is collected from outside and a heat recovery system, providing air pre heating, reduces energy losses.

Furthermore, the apartments are equipped with an electrical home automation system which improves environments internal management. A set of probes is installed in every room, which detects temperature and humidity and sends these data to a control system, which in turn automatically adjusts fluid flow in the radiant floor circuits and action of dehumidifier and air-conditioning system (in summer), according to values set by the user.

4. METHODOLOGY

Dynamic simulation using a whole building simulation (WBS) tool and in situ measurements are used to investigate the energy performance of the C4 building and to evaluate the operation of the plants system. The method has been developed in two consecutive phases: energy performance assessment and thermal plants functioning evaluation. In the first phase the approach consists in a careful survey of the building characteristics to be able to build a model as similar as possible to the real construction. A short term monitoring campaign is then carried on in the chosen apartment and temperature data are used to calibrate the model. The main objective of the calibration in this phase is a reliable characterization of the building envelope and short term campaign can be considered suitable for the purpose [6]. For this reason high rate data are used and the influence of plants is reduced to a minimum. Simulations are then used to evaluate the energy demand of the building using ideal heater and cooler as thermal devices. The second phase consists in the implementation of real plants into the building model and in the evaluation of their performance considering standard occupant behaviour. Calibration of the plants is carried out using data from long term monitoring during plants operation. The obtained tool will be used to evaluated optimization solutions of envelope and plant functioning paying attention to occupancy and comfort conditions. In the following sections the first phase of the method is described.

5. MONITORING CAMPAIGN

The monitoring campaign was conducted from November 11 to November 27 2014 using a thermo-hygrometer for air temperature and relative humidity both inside and outside the apartment. All sensors were connected to a data logger CR1000 by Campbell Sci.; this device allowed data download even from remote, their visualization in real time and their subsequent elaboration through data management software.

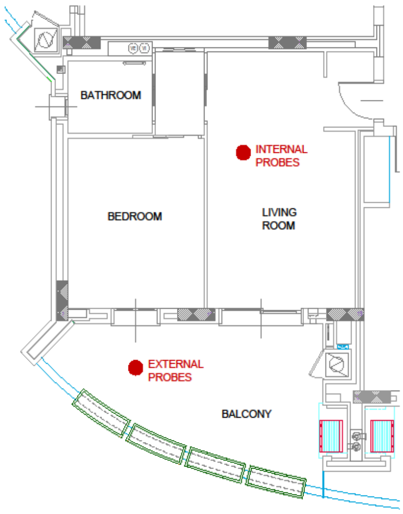

Figure 5. Position of the probes in the apartment

Figure 6. Picture of indoor monitoring system

A plan view of the apartment with the location of the sensors is showed in Figure 5. Figure 6 shows the arrangement of the monitoring system in the living room of apartment 30.

The collected outdoor data were used to build the climatic file used in the dynamic simulation program in order to get a more reliable climatic picture than that deduced by reference climate files provided by the software.

In order to characterize the building envelope, data were collected with plants shut-off. Since controlled mechanical ventilation plant in the building is centralized and in operation for the whole year, air placing and extraction hoses were manually plugged.

Figure 7 shows outdoor temperature and solar radiation patterns for the days of test. The weather in that period was quite mild with temperature that reached 20°C and sunny weather especially in the first days of measurement activity.

Figure 8 shows temperature and relative humidity patterns inside of the analyzed environment. Relative humidity trend appears regular, since it varies on a quite wide interval, while temperature appears more fluctuating

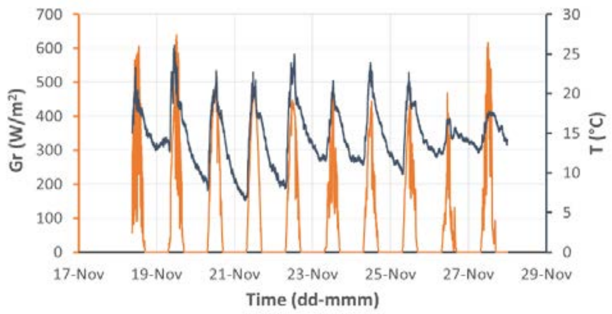

Figure 7. Global horizontal irradiance (Gr) and outdoor temperature recorded during the campaign

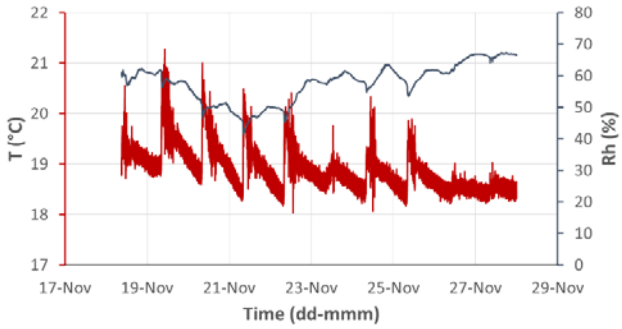

Fig. 8. Indoor temperature and relative humidity recorded during the test

since it varies on a more limited range of about 3 °C. This is mainly due to the high thermal inertia and insulation provided by the building envelope.

Furthermore, in the first 3 days of operation temperature trend shows some peaks. This could be due to the fact that they are sunny days and the probe placed in line with a glass wall could have been affected by direct solar irradiance causing overheating and recorded temperatures higher than those real.

6. MODEL CONSTRUCTION

The model was created with the dynamic building simulation software IDA Indoor Climate and Energy 4.5. The thermal simulation software tool is based on a general system simulation platform with a modular approach. The multi-domain physical systems are described in the IDA through symbolic equations using the Neutral Model Format (NMF) simulation language. In Figure 9 a 3D view of the C4 building provided by the simulation tool is showed.

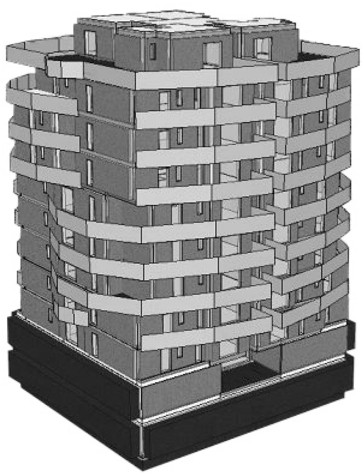

Figure 9. 3D view of the C4 building simulation model

First of all, building orientation was included in the construction of the model and trials were made by shadow animation in order to control if surrounding buildings or urban planning elements would produce shading effects. Only two adjacent buildings produced shading and they therefore were included as volumes.

Table 1 and 2 list materials and thermal properties of vertical and horizontal partitions of the building inserted as input data in the program.

Stratigraphy was accurately reported from technical specifications of C4 building, by which all component materials and their technical features were deduced.

Windows consists of double glazing with low emissivity glass, separated by an argon gas layer and whose aluminum frames thermal features, deducted by data sheet provided by construction company, were furthermore included.

Thermal bridges declared by designer were included in addition to those concerning doors and windows. A thermal zone for each apartment of the C4 building was built, except in the monitored apartment, which was patterned in a more detailed way using 3 thermal zones, one for each room. The final model, therefore, was composed by 66 thermal zones.

Table 1. Materials and properties of the vertical partitions of the building

Vertical partitions	Materials	Thickness (cm)	Thermal cond. (W/mK)	Density (Kg/m3)	Specific heat (J/KgK)
Perimeter wall with plaster finish	plaster	1.5	0.9	1800	840
	perforated brick	12	0.292	930	840
	polyurethane foam spray	8	0.035	37	1300
	air	6	0.26	1.3	1000
	perforated brick	12	0.292	930	840
	plaster	1.5	0.9	1800	840
Perimeter wall with curtain finish	curtain	12	0.432	1200	840
	polyurethane foam spray	8	0.035	37	1300
	air	11	0.26	1.3	1000
	perforated brick	12	0.292	930	840
	plaster	1.5	0.9	1800	840
Perimeter wall in the basement	concrete	12	1.3	2500	880
Partition between landing and apartment	plaster	1.5	0.9	1800	840
	perforated brick	8	0.08	1000	840
	polyurethane foam spray	9	0.035	37	1300
	perforated brick	8	0.08	1000	840
	plaster	1.5	0.9	1800	840
Internal partition	plaster	1.5	0.9	1800	840
	perforated brick	8	0.292	930	840
	plaster	1.5	0.9	1800	840

Table 2. Materials and properties of the horizontal partitions of the building

Horizontal partitions	Materials	Thickness (cm)	Thermal cond. (W/mK)	Density (Kg/m3)	Specific heat (J/KgK)
Partition between basement and ground	concrete	35	1.3	2500	880
Partition between hall and garage	floor	1.5	1.163	2300	840
	concrete	5	1.3	2500	880
	polyurethane foam	3	0.04	25	1450
	foacem	20	0.085	400	500
	concrete	35	1.3	2500	880
Partition between apartment and apartment	floor	1.5	1.163	2300	840
	concrete	5.5	1.3	2500	880
	polyurethane foam	3	0.04	25	1450
	foacem	10	0.085	400	500
	concrete	29	1.3	2500	880
	plaster	1.5	0.9	1800	840
Partition in case of retraction upper wall	floor	2	1.163	2300	840
	politerm	8	0.085	320	1400
	extruded polystyrene	6	0.04	35	1700
	concrete	30	1.3	2500	880
	plaster	1.5	0.9	1800	840
Partition in case of retraction lower wall	floor	1.5	1.163	2300	840
	concrete	5.5	1.3	2500	880
	polyurethane foam	3	0.04	25	1450
	foacem	10	0.085	400	500
	concrete	22	1.3	2500	880
	polyurethane foam	4	0.04	25	1450
	concrete	4	1.3	2500	880
	plaster	1.5	0.9	1800	840
Roof	floor	1.5	1.163	2300	840
	politerm	8	0.085	320	1400
	extruded polystyrene	6	0.04	35	1700
	foacem	8	0.085	400	500
	concrete	30	1.3	2500	880
	plaster	1.5	0.9	1800	840

7. MODEL CALIBRATION

Model calibration was made comparing temperatures experimentally detected inside the apartment and those calculated by the simulation program.

Climatic file for Ciampino area, near Rome, provided by the software climatic database was opportunely modified inserting data in part measured in the balcony of apartment 30 and in part collected by the ESTER outdoor facility of the University of Rome Tor Vergata [7] for the period of test. Indeed direct and diffuse solar irradiance were provided by ESTER facility while outdoor temperature and relative humidity measured at the apartment were used. A first comparison of the temperature trends showed simulated temperature values lower than the measured ones. This difference was ascribed to a too approximate modeling of air vents located in the kitchen. A survey allowed detecting the right structure of these vents, and making more realistic hypothesis in the model. Nevertheless this first comparison pointed out that temperature trend simulated by the program followed the measured temperature trend, then confirming the model reliability.

Besides the correct modeling of air vents in the kitchen also air infiltration was estimated according to the building quality, whose result after some trials was 0.18 l/sec*m^2.

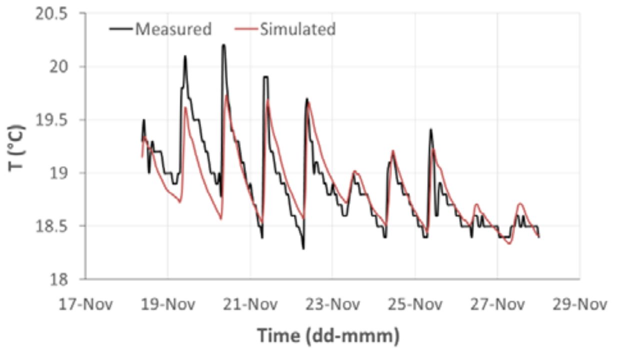

Figure 10. Comparison between measured and simulated temperature trends

Figure 10 shows the measured and simulated temperature trends obtained after the above mentioned modifications. The obtained result is very good indeed the two temperature trends, are almost perfectly superimposed.

Only peak measured temperatures in the first days are higher than the simulation due to the influence of the direct solar irradiance on the internal temperature probe.

In order to evaluate error margin between measured and simulated temperature values the common used index named root mean square error (RMSE) was adopted. RMSE was found to be equal to 0.23 °C over the test period. RMSE was also normalized by the average of temperature measurements obtaining a value of 1.2%. A more accurate percentage error was evaluated normalizing RMSE also by the maximum temperature difference of the measurements in the period considered obtaining a value of 12%. These numbers confirm the reliability of the model realized for C4 building.

8. BUILDING ENERGY PERFORMANCE

Building energy requirements assessment was evaluated inserting ideal plants in the model. The obtained results could also be compared to consumption data collected by the company for the solar year 2013-2014 in two buildings located in the same district and therefore built using the same construction criteria.

Even though the two buildings are oriented in a different way with respect to the case study their consumptions average provides an order of magnitude about consumption levels expected for C4 building.

In order to obtain a realistic comparison, a climatic file related to year 2013-2014 provided by ESTER facility was inserted in the program.

Ideal heater or ideal cooler are ideal plants which give arbitrarily efficiency values and maximum power, and furthermore kind of fuel needed.

Table 3 shows operating hours and temperature limits considered in the apartments, in summer and winter for the modeling.

Table 3. ideal plants schedule and inside temperature

	Period of operation	Schedule	T (°C)
Winter	1 Nov-15 Apr	5:00-11:00 17:00-23:00	20
Summer	1 Jun-30 Sept	18:00-22:00	26

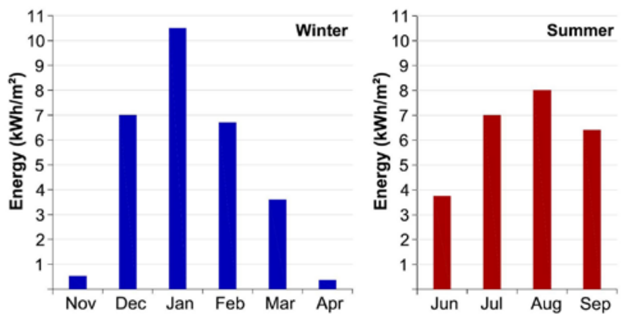

Figure 11. Energy performance of C4 building for winter and summer

Temperature and operating hours in heating season are fixed by legislation, while for cooling season an approximate evaluation was made, since legislation doesn't impose restrictions and they only depend on the occupants behavior.

Occupants and equipment provision were neglected, since occupation rate of the building was very low.

For lightning, according to the legislation, a contribution of 416 W was considered. The operating hours, different between summer and winter were:

- summer: from 19:00 to 23:00
- winter: from 5:00 to 11:00 and from 17:00 to 22:00

Two simulation files were generated, one for winter case, and another for summer case.

Figure 11 show energy performance for the two cases.

Table 4 compares overall results (overall consumptions in the whole operating period, in winter and summer) provided by the model with real data calculated by thermal energy meter readings. The values in the table are calculated per surface unit.

In winter case, when plants are operating from November 1st to April 15th, the program calculated an overall energy requirement less than that needed in the same year. However, the consumptions calculated by the program are referred to the analyzed apartment, south-facing-side, and since it is situated at the fourth floor it has a good exposure to solar radiation, while consumptions provided by the company are referred to the average of all apartments. According to these considerations, therefore, the agreement with the simulation results can be considered acceptable.

Table 4. Comparison between real and simulated energy consumption

	Real consumption (kWh/m^2)	Calculated consumption (kWh/m^2)
Winter	38	28
Summer	9	24

In summer case, on the other hand, the program provides energy requirements that are higher than energy meter readings.

Since the apartment is on the south-facing-side, in winter heating load reduces energy consumption, while in summer increases cooling requirement. There is also a further consideration to be done: the values recorded by thermal energy meter are referred to effective consumption detected in the building, which in August is probably reduced due to scarce occupancy caused by summer holidays. Indeed eliminating August from the calculated values the overall summer consumption decreased to 14 kWh/m^2, much closer to the real value. The remaining surplus is probably due to the exposure of the apartment considered, as already mentioned.

Furthermore, the use of cooling system strongly depends on occupant behavior and its determination is not easy. However this is just a first comparison with energy consumption data obtained from other buildings of the district and a more reliable comparison should be done when consumption data from the C4 building will be available.

Modeling results shows an overall annual consumption of 52 kWh/m^2 of the tested apartment of C4 building. This value is approximately half of what is obtained for a standard building in the city of Rome (mainly built between the 60' and 70').

9. CONCLUSIONS

Energy performance assessment was carried out on a high sustainable building of the *Rinascimento 3rd* district using WBS and in situ measurements. The used approach allowed to build a reliable model, calibrated using indoor temperature trends. This is confirmed by NRMSE index which provided a percentage of 1.2% normalizing the RMSE by average temperature and of 12% normalizing by maximum temperature difference.

Energy analysis pointed out a deviation of consumptions provided by the program compared to measured values obtained for another building of the same characteristics; however it was possible to explain in part these differences considering the orientation of the apartment analyzed. Further verifications should be carried out when consumption data will be available for the C4 building.

Future developments will regard the implementation of the second phase of the methodology that will consist in the addition of real plants system in to the model and in the validation of plants.

Furthermore, this model will be adopted for possible further optimization of the building envelope, e.g. retrofit hypothesis with similar energy performance materials but with lower costs. Also optimization of the plants operation based on building occupancy will be carried on to complete the analysis.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Barbara Mezzaroma, CEO of Mezzaroma company, and Eng. Pasquale Latorre design coordinator for Mezzaroma at the time of *Rinascimento 3rd* construction for making possible this study providing all the necessary information and permissions. Thank you also to Eng. Fabrizio Guidi for helping in the English draft.

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