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Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study

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ABSTRACT

The paper presents a method involving on-site measurements and dynamic simulation to evaluate refurbishment solutions of an extended and complex building of great artistic and historical value, *Villa Mondragone*, located in the *Colli Albani* area and property of the University of Rome *Tor Vergata*. The approach has been successfully applied to a historic building of great construction complexity that was built during centuries, superimposing different construction technologies and styles. Masonry characteristics of ancient buildings are often hard to find and in situ measurements of thermal parameters (*U*-values) are time consuming, especially for large estates with structures of various superimposed ages as the case of *Villa Mondragone*. The paper demonstrates how a specific calibration of the dynamic model using only indoor temperature measurements can overcome this problem. The model was used to evaluate the energy performance of the actual use of the *Villa* and two possible cases of intervention. An improvement of approximately 40% in the energy demand has been evaluated adopting refurbishment solutions without impact on the historical value of the building. The model could be used also in the future to evaluate various refurbishment solutions not only regarding the envelope but also the plant and its use.

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.

The refurbishment of the existing building stock is the greatest challenge, also more significant than the construction of new and nearly zero energy buildings.

The new Energy Efficiency Directive 2012/27/EU [3] gave great attention to public buildings, indeed, from January 2014, a share of 3% of buildings owned and/or occupied by public institutions should be refurbished yearly.

Europe building heritage consists of a great part of historical buildings and recently European Community funded two European projects on sustainability and energy efficiency of cultural heritage [4,5] stressing the importance of looking at historic buildings as a value from an economical, energy and environmental point of view.

Furthermore also from the research point of view, growing numbers of papers in the literature deal with the retrofit of historic buildings as pointed out by the recent special issue published by Energy and Buildings [6].

In Italy, energy retrofit is not mandatory for historical buildings, this because historic heritage is considered a priority with respect to energy performance [7].

However, considering that many historic buildings are property of public institutions such as for example Universities and Museums, public sector will have to cope with this issue preserving cultural integrity and improving energy efficiency. Taking into account these two important features entails less flexibility in the proposal of energy efficiency measures.

Many works can be found in the literature regarding the evaluation of energy efficiency in buildings undergone refurbishment and most of these works are focused on residential buildings and/

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or offices. Ma et al. [8] provided an overview of the state of the art and methodology applied to building refurbishment. Most of the studies evidenced that improvement of thermal insulation and renovation of HVAC can improve the energy performance of buildings, however if also the economic and ecological aspects are considered it is difficult to identify the best refurbishment solution. For this reason multi-criteria approaches have been introduced such as Asadi et al. [9] that presented a multi-objective optimization model using genetic algorithm and artificial neural networks and also recently Penna et al. [10] that analyzed a set of reference buildings with the purpose of investigating the influence of the reference buildings' characteristics on the definition of optimal retrofit solutions considering economic, energy and comfort performance.

More recently systematic approaches were also proposed for historic buildings. Ascione et al. [11,12] presented a multi-criteria approach for the energy refurbishment of historic buildings, with particular attention to the historical value of buildings. De Berardinis et al. [13], proposed a methodology to design the refurbishment of historic buildings and centers, by using a "case by case" approach to identify the method of intervention in each context. Bellia et al. [14] presented a case study of refurbishment of *Palazzo Fuga* in Naples. A systematic approach for energy refurbishment of historic buildings was recently proposed by Franco et al. [15] applying it to the *Albergo dei poveri* in Genoa. With reference to the use of renewable energies López and Frontini analyzed the problem of integration of solar energy in historic buildings, [16].

Although systematic approaches are desirable it has to be considered that it is difficult to have a general approach for historic buildings and a case by case study is preferred. It is also desirable that a set of examples, methods and procedures could be available to architects and engineers to help them in the resolution of specific problems.

Currently several simulation software are available for the evaluation of energy performance of buildings. These tools can be classified as static, semi-dynamic and dynamic. 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. In particular, results from static tools are simplified because they do not consider the periodic trend of temperature and do not take into consideration thermal inertia of the structures. Semi dynamic systems can do this but however they require simplified inputs for climatic data and building description. 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. Despite their complexity these tools are more suitable to be used for the modeling of historic buildings due to their flexibility and can produce more accurate results. A recent study [17] evidenced how modeling of historic buildings using dynamic simulation produces better results in terms of energy performance evaluation with respect to other methods. For these reasons whole building simulation has been considered the best tool to approach historic buildings refurbishment.

The use of such tools in conjunction with on-site ambient measurements to obtain accurate calibration of the simulation model is the key factor to take advantage of the complex features of the software in order to represent the real case as accurately as possible to be a reliable means to suggest retrofit solutions. In particular, for historic buildings, such calibration procedure can be time consuming especially when building materials are not precisely known and structures of different ages are superimposed. So the application of dynamic simulation to historic buildings requires also accurate study of the building construction history that should become an essential part of the investigation. Few works have been found in the literature that study refurbishment solutions through the use of dynamic simulation and indoor climate measurements; Ascione at al., for example, [11,12] used Energy Plus to model historic buildings located in Benevento, Italy, however they calibrated the model using the real energy request of the buildings. In this case some of the input data were directly measured on-site. Todorovic et al. [18] proposed a holistic and sustainable approach to the refurbishment of the Aviation Museum in Belgrade using Building Energy Simulation (BES) and renewable energy implementation. These cases are referred to buildings of quite regular shapes and with structures that are not made of materials of different ages. A more complex building, Albergo dei Poveri in Genoa, was recently studied but using the semi-dynamic approach [15].

The objective of this work was to apply a method involving on-site ambient measurements and a commercial whole building simulation tool, IDA ICE 4.5, commonly used to evaluate contemporary buildings, to build a reliable model of a complex historic building, *Villa Mondragone*. The model was required to evaluate refurbishment solutions for energy preservation. Especially for complex ancient structures, masonry characteristics are hard to define and in situ measurements of thermal parameters are time consuming, due to building extension and complexity of masonry of various superimposed ages. In the case studied a methodology involving indoor climate measurements and dynamic simulation was adopted using model calibration to define thermal properties of the building. Cardinale et al. [19] used a similar approach to evaluate the energy performance of vernacular buildings in Italy, however they also need laboratory and in situ measurements of material properties. The accurate knowledge of the construction history was also fundamental and it is here reported. A monitoring activity of 1 month was performed and the collected indoor temperature measurements were used to calibrate the model by comparing the experimental data with the results obtained by the model. The calibrated model was then applied to evaluate the energy performance of the building applying a particular non invasive high efficiency plaster to reduce energy consumption.

2. Villa Mondragone: history and description

Villa Mondragone is a grandiose building estate of approximately 80.000 m^3 in volume and an overall plant of more than 8000 m^2 allocated on four levels (one basement and three levels above ground) built at an altitude of 416 m over the sea level. The mansion is located on the *Colli Laziali* or *Colli Albani*, a very ancient volcanic system south east of Rome, and it is part of the Monte Porzio Catone municipality (41° 48' 33" N Lat., 12° 41' 48" E Long.). Aerial views of the construction are shown in Fig. 1. Its initial construction was started almost four centuries and a half ago, considering only the modern part of the mansion otherwise its building history can be dated from the first century a. D. Building stratification is therefore its main peculiarity.

During Renaissance, in the middle of XVI century, under Paolo III papacy, the *Colli Albani* territory was mainly reconsidered as a residential area, as already experienced by the Romans many centuries earlier. In few decades twelve mansions (named *Casini*) were built in the area further uphill of Frascati (one of the main town in *Colli Albani*) providing a dense weave of avenues to connect each other [20]. In 1573 cardinal Marco Sitico Altemps, nephew of Pope Pio IV, designated Martino Longhi Il Vecchio to build a new mansion. Very often these modern properties were built over the remnants of ancient Romans buildings; this was also the case for *Villa Mondragone*. Indeed it was built on the roman ancient building remnants attributed to Condiano e Massimo of the