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Numerical investigation of the Castle of Zena energy needs and a feasibility study for the implementation of electric and gas driven heat pump

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ABSTRACT

In this work a numerical investigation of the energy needs of the Italian historical building Castle of Zena (XXIII century) and a feasibility study for the retrofit of its HVAC plant is presented.

About the building envelope behaviour two types of numerical analyses have been performed. First of all, free floating conditions (no temperature control) have been considered, in order to evaluate the building envelope performance through the adaptive comfort approach. During almost the 50% of the summer season the internal temperature is above the upper limit of the comfort range, therefore a cooling plant is needed. Secondly, an ideal temperature control has been considered, in order to calculate the annual energy needs for space heating (around 164 kWh/m^2/year) and cooling (around 5 kWh/m^2/year).

Regarding the HVAC retrofit, due to the historical constraints, it has been decided to use a fan coil emission system linked to a heat pump appliance. Four combination have been analysed, combining two type of heat pump (compression and absorption) with two type of heat source (air and water). Neglecting the control, emission, storage and distribution sub-system energy needs, there are two systems with the lowest primary energy consumption: the EHP-WS and the GAHP-WS (around 130 kWh/m^2/year), followed by the GAHP-AS (around 147 kWh/m^2/year) and the EHP-AS (around 180 kWh/m^2/year). From the economic point of view the EHP-WS has the shortest pay-back time, 7 years, also thanks to the use of the existing well. However, excluding the water source, only the GAHP is economically feasible. Lastly, a significant reduction of greenhouse gas emission (CO_2) could be obtained replacing the EHP-AS with the GAHP-AS (−26%), the EHP-WS (−28%) or the GAHP-WS (−34%).

1. Introduction

Many Italian buildings have a historical value. In order to reduce the national building energy consumption, a refurbishment of this sort of buildings is needed, as well as an effective use of appropriate HVAC technologies today available. Nowadays, designers often choose the plant and equipment according to their previous experience and information from technical data sheet, without performing a prior detailed analyses to verify their performance in a whole annual cycle and under dynamic conditions. This article highlights the importance of numerical preliminary analysis to identify the best plant system, in terms of energy consumption, economic benefits and environmental impact.

The work presented in this paper has two main purposes: first of all, the identification of a simple design procedure to increase the overall energy performance in historical buildings; secondly, this procedure has been applied to a case study and results have been presented.

As far as the design process is concerned, it is based on the detailed numerical simulation of the building-plant system. Some technologies of heat and cold generation are compared in terms of primary energy consumption, economic and environmental benefits. In the recent past, this procedure has been used in the framework of the S.O.C.R.A.T.E.S. project [1]: its primary object of study is the Castle of Zena (Italy, Piacenza) and its surroundings, but it is also aimed at the definition of general purpose models and methodologies that lead to the functional recovery of buildings with high historical and architectural value.

The actual Castle building has been used as a case study in the work described in this paper, being analysed through numerical simulations using the TRNsys 16 calculus suite [2]. The modelling

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COP	electric heat pump coefficient of performance [*adim.*]
EER	electric heat pump energy efficiency ratio [*adim.*]
GUE	absorption heat pump gas utilisation efficiency [*adim.*]
NPV	net present value [€]
PV	present discounted value [€]
Q	thermal power [kW]
$T_{air,SP}$	air temperature set-point [°C]
T_c	comfort temperature for an indoor environment [°C]
T_{DM}	daily mean of the external temperature [°C]
T_{RM80}	running mean of the external temperature [°C]
Subscripts	
f	fuel
el	electric energy
PE	primary energy

process is made of three main steps: we have divided the building into thermal zones, in which rooms with similar use destination are grouped; then internal and external boundary conditions have been defined. This has led to two main results: first, we have determined the thermal loads for both heating and cooling plants. Since the summer energy need obtained was low, we have used the adaptive comfort approach [3–6] to verify the need for a dedicated plant. The final step has been the simulation of four heat pump systems: two using electric heat pumps (EHP) and two using an absorption heat pump (GAHP). For both the type of heat pump in one case the external air has been considered as energy source (AS) and the other a water source (WS).

We have calculated the primary energy consumption for the four technologies, then an economic and environmental assessments have been carried out.

2. Case study

The Castle of Zena is a square building with an internal courtyard, a missing side, and is surrounded by a wall corresponding to the old moat. The original building seems to have been built in the XIII century, then has been modified and transformed during its life, until the last restoration works that took place in the Seventies (Fig. 1).

The Castle consists of a basement floor (370 m^2), two main floors (700 m^2 each), and an attic (700 m^2, 225 of which are not fit for habitation). The overall net surface is around 2470 m^2.

Among all the purposes of the S.O.C.R.A.T.E.S. project [1], one is the redefinition of the building functions. More in detail, it still has a residential function, together with hospitality and events (i.e. yoga and meditation classes): in the project there are four rooms, six meeting rooms, seven bedrooms with bathrooms, and a wine and food area.

Fig. 1. Picture of the Zena Castle.

In order to achieve a better thermal efficiency of the envelope, some improvements have been introduced: the old windows have been changed with more insulating double-glazing systems, and the floor between the first floor and the attic has been insulated too, only where the temperature of the room facing on its upper side is not controlled.

The next section deals with the investigation of the envelope energy performance through numerical simulations.

3. Building envelope numerical model

The first step of this work has been the evaluation of the Castle energy needs for heating and cooling, which has been performed through numerical simulations. For this purpose, the following data were required:

- drawings of the building under investigation (plans, sections and constructive details if any);
- hourly based climate data for the external environment (temperature, relative humidity, solar irradiation, etc.);
- energy requirements estimation related to the destination use of each room.

The assessment of the overall energy needs has been achieved simulating the behaviour of the building using a capacitive model defined in TRNsys 16 [2] software environment (TRaNsient SYstem Simulation). The latter consists of two main software: Simulation Studio (the calculation engine designed for the resolution of complex energy problems), and TRNbuild (the graphical user interface used for modelling building structures). The high level of complexity of these tools has allowed to perform an accurate analysis of the building under consideration, taking into account all those variables that would have been neglected using a simplified procedure [7].

In this section, all parameters and hypotheses assumed in the model definition are discussed, followed by the presentation of results.

3.1. Thermal zones and envelope definition

The first phase of the modelling process has been the subdivision of the building into thermal zones: rooms with the same usage have been grouped into the same zone of the model. Going more in detail, the whole building has been divided in eleven zones: five of them are equipped with heating and cooling plants, with fan-coil terminals; in all other zones internal temperature is not controlled. Even if this last group of zones does not have any energy need, they have been considered into the numerical model because they represent the boundary conditions for the rest of the enclosed environments.

As far as the first group of zones is concerned, it is composed by a part of the basement floor (CA_{20}), part of the levels above the ground (PA_{18}, PA_{20} and PA_{23}), and part of the attic (MA_{20}). The identification code of each zone is reported in Table 1, together with a brief description and the overall surface area.

Once those thermal zones of the Castle have been identified, we have defined every element of the envelope and of the internal partitions between adjacent zones, both in terms of geometry and thermophysical properties.

Dealing with walls, external and internal structures are made of solid bricks coated with plaster; the roof has a wooden structure, covered with tiles; the main stratigraphy of internal horizontal partitions consists of a brick vault, covered with a load