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# Energy simulation and optimization of a double ventilation chimney in a historical building in L'Aquila (Italy)

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**Abstract**

The paper presents the operation mode of a ventilation chimney placed in a historical building through the use of *Design Builder*, a modeling and dynamical simulation software. The aim is to verify the improvement of the comfort level and energy efficiency of the simulated environments through the usage of the duct as a passive ventilation system. The method adopted to intervene in a complex system, such as that represented by historic buildings, is to enhance the preexisting architectural values through their conversion into devices able to improve the performance of the building in terms of $CO_2$ and energy consumption reduction. The case study is Palazzo Bruni-Riga, a valuable building located in the historic center of L'Aquila. The building has a double ventilation duct, probably also used as a light-pipe, in correspondence of two windowless rooms of similar dimensions. The dynamical simulations presented concern the analysis of the passive ventilation duct and its effects on the thermo-hygrometric well-being of the modeled rooms. The goal of this paper and this research in general, is that the wise use of such devices installed in times when there were no air conditioning systems, allows you to better use the ventilation chimneys, and have the maximum thermal indoor comfort, with the minimum effort and use of mechanical systems. Through the simulations it was possible to verify that through the use of the ventilation chimney, it is possible to have the indoor comfort conditions, by checking the Fanger indices for the data obtained from the simulations carried out.



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## 1. Introduction

The interventions aimed at optimizing the energy performance of buildings use active and passive control strategies as regards the amount of thermal energy that the product exchanges with the environment. Ventilation chimneys (active and/or passive) and light chimneys can be technological solutions integrated into the building system and can contribute significantly to improving the building's energy performance.

If the restoration-technology relationship, we can still notice a considerable delay under various profiles, including the regulatory one, but a few years ago a process of disciplinary "refoundation" was triggered in order to bring it back within the restoration fundamental criteria: minimum intervention, reversibility and compatibility [1]. In this regard, the concept of 'improvement' as opposed to that of 'adaptation' [2], already elaborated in the field of structural consolidation, can be applied in a similar way to the technological and energy theme with excellent results in favor of cultural heritage and their preservation, but without forgetting the 'integrated conservation'. The basic problem will always be that of the better integration of new technologies with pre-existences and the optimization of their functioning, so as not to distort them and end up losing their historicity.

In relation to these considerations, a field of application of extreme interest are the buildings of significant historical-artistic value: the interest in this category of buildings is also due to the considerable diffusion in Italy.

In this scenario, an ideal case study is represented by the Palazzo Bruni-Riga: the building in fact presents the historical pre-existence (about 1960) of a double ventilation duct, used both as an air intake and as a light socket for two blind environments. This work intends to enhance the pre-existence, studying the optimization of its operation mode through *Design Builder* simulations. In this way is possible to establish for which boundary conditions (period of year, indoor/outdoor temperatures, etc.) the operation of the duct as a passive ventilation chimney can be exploited with an advantage of the internal comfort conditions of the adjacent rooms.

Lighting and ventilating the rooms in an appropriate manner has a direct effect on internal comfort and therefore on the psychophysical wellbeing of the users. A possible strategy for controlling the interior comfort of an environment is the adoption of solar or ventilation chimneys [3, 4].

The light chimneys exploit existing cavities or are inserted in new ducts to transfer the light radiation from the outside to inside through capturing systems placed in the South or in the zenith position, the aid of simple equipment such as reflective coating systems or tubular photoconductors for light transmission, and clear diffusion systems in polycarbonate or glass embedded in the ceiling. In addition to the direct effects on the daylight factor, the design of light flues is a tool that affects the natural heating and cooling strategies of blind environments thanks to the contribution of thermal energy due to solar radiation. The position and dimensioning of the light fireplace are the tools available to the designer to optimize interior comfort [5].

The natural ventilation devices, however, have always been used in the historical architecture for air conditioning environments, especially in hot climates. It is possible to include among the most famous examples of this natural cooling method the Iranian wind towers and the Norman Arab architectures in Sicily culminated in the construction of the "Palazzo della Zisa" in Palermo [6, 7]. As in the case of the control of the light factor, the controlled ventilation of the environments contributes to the achievement of adequate conditions of thermo-hygrometric comfort, as well as helping in preservation of the historic building from destructive phenomena of condensation.

The activation of natural ventilation phenomena using the stack ventilation chimney, can be pursued through more or less invasive interventions, depending on the morphological characteristics of the building. Often, in fact, you can encounter buildings already equipped with cavities with sections large enough to be used as ventilation chimneys with small activation measures, in other cases the vertical connection systems are suitable for the preparation of new devices. In order for the chimney effect to occur, it is necessary that the cavity develops in height sufficient to guarantee an adequate temperature gradient inside the ventilation duct. In fact, the chimney effect exploits the difference in temperature between indoor and outdoor air that will be put into circulation in the device naturally by means of the air outlets positioned at the ends: the hot air will naturally rise and will be let out from the upper openings [8–10].

The use of passive systems produces positive effects not only on consumption fuels, but also on emissions of $CO_2$. Ref. It has been proven that the use of natural ventilation systems, even alongside mechanical ventilation (especially in tropical climates, where it is not possible to achieve adequate thermos-hygrometric parameters with only natural ventilation), produces a saving in electric energy about 20–30 % and $CO_2$ emissions also decrease up to 30 % compared to the use of mechanical systems only [11]. Many studies have looked at solar chimneys through mathematical simulations and experimental investigations: this choice of passive ventilation depends on design parameters and the thermal performances for different geometrical configurations. Research has shown that air speeds in chimneys are influenced by the width of the channel and the angle of inclination of the chimney. Saifi et al. [12] developed an experimental and numerical study for a tilted solar chimney (30° and 45°) whilst Chung et al. [13] studied the performance of a solar chimney in hot and humid climates in order to improve the thermal performance of a terrace house in Malaysia: nine configurations of chimney dimensions were tested and validated using CFD in *Design Builder* software in order to find the best solution for the case study analyzed. Another CFD studied was developed by Baxevanou and Fidaros for a two-story building with a solar chimney: three modifications of the basic 2D geometry were examined in order to exploit the functionality design of a solar chimney that operated better in the morning and afternoon, the worst time being noon in June [14]. Yan et al. [15] compared theoretical research, numerical simulations and experimental results showing how factors like heat collection height and width, solar radiation intensity, the inlet and outlet area ratio of chimney and air inlet velocity, etc. affect solar chimney ventilation. Sohail [16] design a 25-storey high rise residential building relying primarily on natural ventilation with *Design Builder* software.

Despite the large amount of literature on analytical studies of ventilation chimneys operation, widely validated by CFD analysis and optimized in geometry, there is a lack of research into the integration of these systems in historical buildings, which represents a large part of the Italian built heritage.

Unfortunately, the potential of wind as a renewable, alternative energy source to oil for the production of electricity in Italy is rather limited, [17]. Italy's geomorphological characteristics determine widespread wind with a prevailing breeze regime; wind with relatively low average speeds (1–2 m/s), variable frequency, and alternating directions during the day. However, these characteristics, although unfavorable for the production of electricity, are particularly suitable for use in natural ventilation systems for the renewal of air in confined spaces and passive cooling of buildings [9]. This use, if exploited, would result in far higher savings in terms of electrical energy than could be obtained directly from wind power generation.

## 2. Case study: Palazzo Bruni-Riga

The proposed case study presents an example of a pre-existing solar chimney whose function is to be tested by analyzing its behavior as a ventilation chimney, reserving the possibility to carry out further studies on the upgrading of this device through appropriate precautions.

The building is located in the historic center of L'Aquila (Italy), on the corner between Via Cavour and Via delle Aquile and is under monumental protection: it is located in the heart of the historic core of the city, in front of the Civic Tower and the Municipality Building. The building, probably built in the fourteenth century during the first phase of construction of the new city, although with dimensions and features quite different from the current ones, was part of what at that time was presented as the true administrative district of L'Aquila.

The historical section in Fig. 1(a) dates back to the 16$^{th}$ century: from the plan it is possible to understand what was the arrangement of the streets and buildings around the bell tower (Fig. 1(a), building n.164) [18, 19].


(a) (b)

Fig. 1. (a) plan of Piazza Palazzo [18]; (b) axonometric plan of Piazza Palazzo engraved by Jean Bleau (1663). In red the aggregate where Palazzo Bruni-Riga is located [17].

Internally, the staircase built in masonry with rampant vaults and with very precious marble coverings serves the different apartments. In many of these, it was possible to find the presence of brick vaults of the nineteenth century, which are largely decorated with paintings and stuccos. The cornice is in stone and in the roof there is a bush-hammered stone parapet interspersed with higher elements that recall the Gothic battlements. The interiors have barrel vaults on the ground floor and vaults and cross vaults on the other levels, some of which are frescoed. In addition, there are valuable floors in particular in the entrance hall, consisting of white stone and marble steps.

The building, after the earthquake of 6th April 2009 that hit the Abruzzo region, was awarded an E "habitability result, corresponding to the worst degree of damage (unusable building) detected by the Civil Protection following the post-earthquake inspections. This is a building consisting of four-storey masonry portions, including a basement made of stone vaults. The load-bearing structure of the building is mainly composed of irregular stone masonry. During the analysis of the building the presence of some renovation works of a pre-existing earthquake are listed below:

- Reinforced concrete ledge;
- Emptying and consolidation of the vaults at the last level;
- Reconstruction of the lamellar roof;
- Reproduction of plaster fillings on the upper part of the facades.

The reconstruction of the roof before the earthquake of 6 April, has also involved the reconstruction of the lighting and ventilation chimney which has assumed a different size and configuration compared to the current state.

Fig. 2. Palazzo Bruni-Riga after the earthquake: angled facade on Via Cavour and Via delle Aquile. On the right the basement of bell tower.

Following the seismic event of 6 April 2009, the building has undergone collapses such as the breaking of some of the stone decorations, parts of the façade and cornices, bulges at the base of the walls. A very serious crack pattern with collapses of the internal vaults can be found on the first level. In the interiors, there are collapses of the stairway and of the overhanging roofing parts, partial collapses of walls and partitions that have led to important disruptions of the vaults. Due to the dangerousness of the instabilities detected at the base of the walls on the road, the first interventions were prepared and carried out urgently the shoring with wooden beams of the two facades, the removal of the rubble in front and the gutters protruding from the eaves, beyond unsafe elements. For all the interiors the shoring of all the vaults, starting from the basement, were foreseen.

### 2.1. The simulated duct

On the second floor of the building there is a housing unit with residential destination in which two blind toilets are located. The precaution adopted in the past to give air and light to these two rooms was to create a large cavaedium with a translucent roof in order to illuminate the rooms and, at the same time, allow air circulation.


(a) (b)

Fig. 3. (a) building plant: in grey the rooms analyzed; in blue the position of the duct; (b) duct picture from inside (reconstruction phase, 2018).

Two openings are visible inside the bathrooms separated by the partition, which convey in a single large cavaedium that crosses the real estate unit upstairs and reaches the roof. On the roof there is a large “chimney pot” with a wooden structure and a plexiglass cover for the passage of light. On the sides of the “chimney pot” there are also two ventilation grids positioned on two opposite walls.

(a) (b) (c)

Fig. 4. The lighting and ventilation chimney: (a) chimney on the roof in 1969; (b) chimney on the roof before 2009 until now; (c) inside duct picture.

## 3. Dynamical simulations

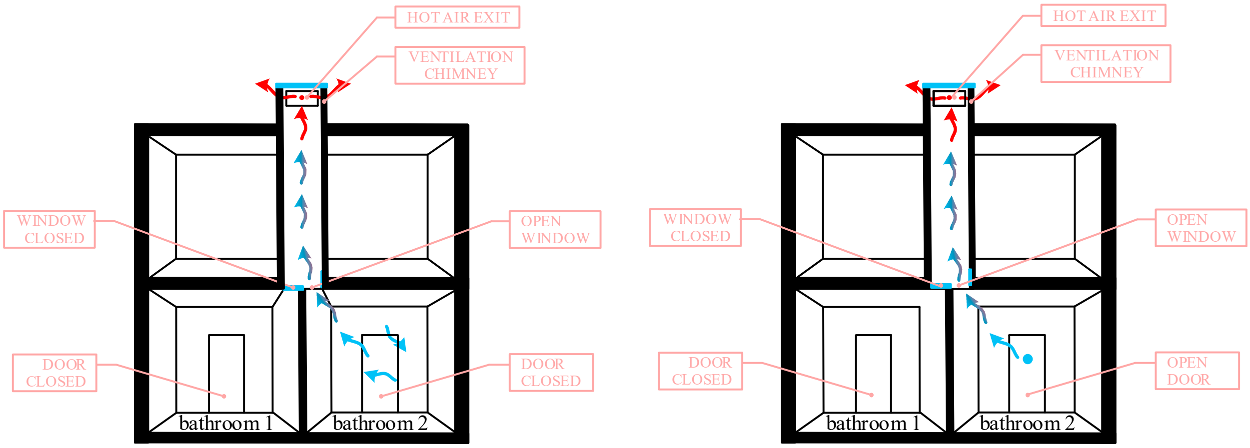
The dynamical simulations have been carried out with *Design Builder* software considering the duct as a ventilation chimney [19]. There are two hypotheses of operation mode of the chimney in relation to the opening or closure of the only other opening of which the room is equipped: the door (see Table 1).

Table 1. Scheme of the simulations carried out.

| | Bathroom 1 | | Bathroom 2 | |
|---|---|---|---|---|
| | Window | Door | Window | Door |
| Simulation 1 | Close | Close | Open | Close |
| Simulation 2 | Close | Close | Open | Open |

As shown in Table 1, the simulations have been performed considering one of the two rooms (Bathroom 1) with the door and the duct opening (window) always closed. Whilst, for the second room (Bathroom 2) two hypotheses have been made: the first with the window open and the door closed, and the second one also opening both the window and the door. In this way, it has been possible to evaluate the benefit of the ventilation chimney activation as a comparison between the simulation results of for the two environments analyzed, in relation to the comfort conditions.

The two simulations are schematized below:

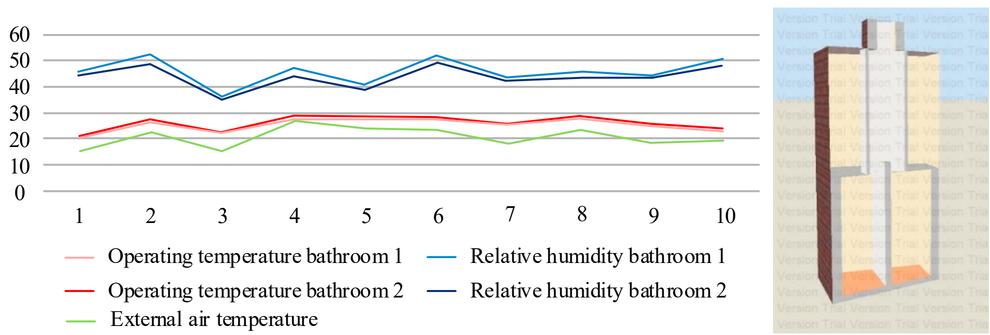



(a) (b)

Fig. 5. Schematic sections: (a) simulation 1 hypothesis; (b) simulation 2 hypothesis.

The dynamical simulations have been carried out for both rooms calculating the operating temperature and relative humidity from 1 July to 31 August (the hottest summer months). The graphs below show the temperature and humidity curves with the two baths for the two hypotheses considered:

- Simulation 1 (Bathroom 1: blind; Bathroom 2: door closed). From the analysis of the curves it is noted that in Bathroom 1, with closed window duct closed, the operating temperature assumes values lower than those of Bathroom 2, compared to a higher relative humidity;
- Simulation 2 (Bathroom 1: blind; Bathroom 2: door opened). One can notice a trend of the curves different from the previous simulation. The temperature values in Bathroom 2 are decidedly higher as well as the relative humidity values.




(a) (b)

Fig. 6. Simulation 1: (a) operating temperature and relative humidity curves for bathroom 1 and 2 and external air temperature curve; (b) 3D model with *Design Builder*.

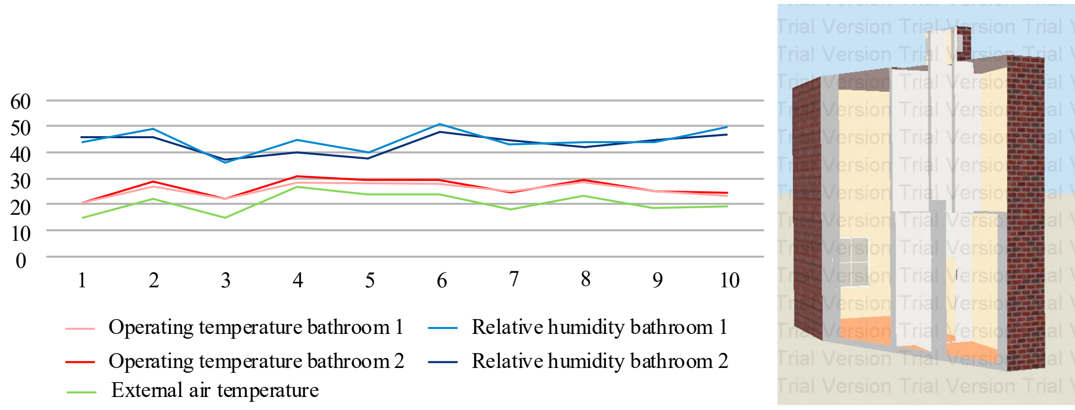
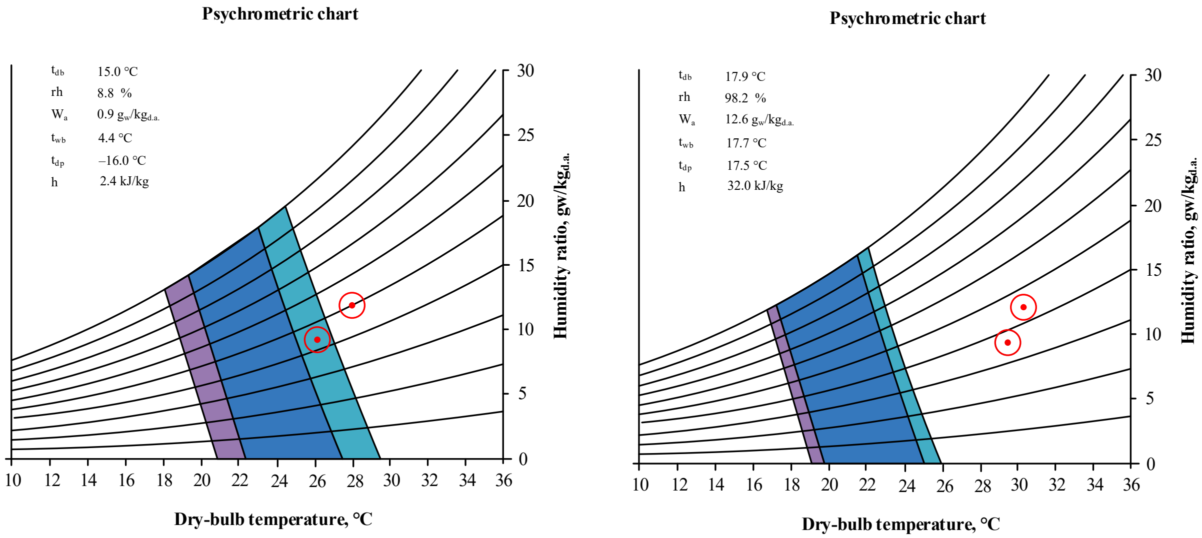



Fig. 7. Simulation 2: (a) operating temperature and relative humidity curves for bathroom 1 and 2 and external air temperature curve; (b) 3D model with *Design Builder.*

Inserting the results of the simulations in the psychrometric comfort card (the average values of operating temperature, relative humidity and the parameters 1.2 met, speed of 0.1m/s and 0.5 Clo.) it is possible to notice how Bathroom 2, in the first hypothesis, benefits of the natural ventilation, fitting into the comfort zone, as opposed to what happens in Bathroom 1. On the contrary, the comfort conditions are not reached in Bathroom 2 when the door is opened.

| | #1 | #2 |
|---|---|---|
| Compliance | X | √ |
| PMV | 0.99 | 0.38 |
| PPD | 26 % | 8 % |
| Sensation | Slightly Warm | Neutral |
| SET | 28.5 °C | 26.2 °C |

| | #1 | #2 |
|---|---|---|
| Compliance | X | X |
| PMV | 1.64 | 1.32 |
| PPD | 59 % | 41 % |
| Sensation | Warm | Slightly Warm |
| SET | 30.4 °C | 29.1 °C |




(a) (b)

Fig. 8. Psychrometric chart: (a) Simulation 1; (b) Simulation 2. In bordeux bathroom 1 with its comfort zone in violet, and in red bathroom 2 with its comfort zone in light blue (CBE Thermal Comfort Tool).

## 4. Conclusions

What emerges from the simulations is a benefit in terms of comfort produced by the activation of passive ventilation through the pre-existing duct [20]. It should be noted that, in this condition, the activation of passive ventilation occurs only in the hypothesis of keeping the room door closed. In fact, opening the door causes an increase in the operating temperature in the room, decreasing the temperature difference between the air in the room and the air present on the top of the duct and therefore canceling the activation of the stack ventilation effect.

From the studies carried out it is clear that in order to activate the operation of the ventilation chimney in any condition of use of the environments analyzed, it is necessary to make technical adjustments that allow to maintain a temperature difference between the base of the chimney and its top, sufficient to trigger the natural ventilation. These measures will be the object of the development of this research and will be orientated to the use of the duct jointly as a ventilation chimney and as a light-pipe.

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