Determining the Energy Benefits from Passive Solar Design Integration through the Sensitivity Analysis of Different Case Studies

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Abstract

The increasing energy demand of our buildings is putting stress on the building systems and energy grids in terms of need for efficiency improvements. The maximization of the overall performance requires a multidisciplinary approach towards seeking innovative solutions to help reduce the building loads. In terms of efficient energy planning, the building design phase has often been often disregarded or looked at from a single point of view. In this case, research places its attention either on the performance of the opaque or transparent envelope to define optimization criteria. A comprehensive analysis of the impact of different passive solutions on the energy demand of buildings with different uses is the core of the present paper. The main goal is to define design guidelines for the integration of simple to complex passive configurations into the building design to help reduce the heating demand by better exploiting solar radiation. The paper gathers data from 384 simulations, on different test buildings, with the permutation of various design parameters, including window-to-wall ratio, wall heat transfer coefficient and heat capacity. Simulations were run in two different locations, typical of southern and northern Italian climate conditions, for both residential and office use. After the best solutions according to the heating or total energy performance over a nominal year were highlighted, the guidelines were applied to a case study. The aim is to determine a methodology to properly integrate passive solutions on the basis of energy performance. This performance, indeed, constitutes a trade-off of the potential of passive systems to understand when it can be profitable to integrate these. The building analyzed, a cohousing project still in the design phase, showed that 10 to 16 % of the total energy demand can be saved. The energy saving is reached by simply integrating and declining the passive configuration suggested with marginal modifications to the initial design.

1. Introduction

The impact of the residential sector share on global energy consumption is known to be relevant. Therefore, practice has increasingly paid attention to energy conservation and efficiency strategies, use of efficient building plants and, recently, integration of renewable energy systems (RES). Among the latter, photovoltaic and solar thermal technologies have spread all over the market as the most user-friendly RES to integrate into buildings (O'Shaughnessy et al., 2018), but proper sizing and management of these systems is crucial to avoid wasting the energy produced (Cillari et al., 2021a and 2021b). From the perspective of nearly-zero-energy buildings (Albayyaa et al., 2019), the rational use of available sources must be further increased. Solar energy being one of the most suitable for exploitation in the building sector, the design of the building envelope must take into account the impact of an integrated passive solar system (Bajcinovci & Jerliu, 2016). to maximize the potential benefits,. Even if passively exploiting green and renewable energy, such as solar radiation, can be regarded to as a relevant advantage in the application of these solutions, their integration, especially in modern buildings, has been limited to a few, broad projects, due to the prediction of the final performance being hard to estimate. The prediction of passive solar potential on a suburban scale may help the performance of neighborhood design and find the optimal starting configuration (Nault et al., 2017). The energy behavior of the passive solar design, however, is influenced by many different factors, either intrinsic or extrinsic to the design, from latitude and orientation to specific solution details, such as cavity depth (Cillari et al.,

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2021a and 2021b). Various optimization techniques and objective functions can be used to improve the behavior of solar passive design due to its multi-disciplinary nature, as it can positively affect heating, cooling, lighting and ventilation demand (Stevanović, 2013).

Based on the operational characteristic of each solution, such as adaptability, overheating sensitivity and estimated cost, a schematic view of different suggested solutions has been already proposed (Cillari et al., 2020). The present work deals with the modeling of the integration of different passive solar solutions and evaluation of the related energy results achievable. The purpose is to define a methodological approach for the integration of such solutions based on the trade-off regarding their energy performance. To deal with different affecting parameters, a permutation of the most impactful factors was implemented, as described in Methodology, Section 2. Section 3 presents the results and discussion of both general investigation and case study. Finally, conclusions are drawn in Section 4.

2. Methodology

Passive strategies are usually divided, according to the relative position of the solar collector, the thermal mass and the indoor environment, into direct gain systems, indirect systems, and isolated gain systems (Givoni, 1991). In the first category, we have wide windows systems, shading systems and solar paintings, while indirect gain systems include the most complex configurations, such as roof pond, massive and Trombe walls. The last class consists of sunspaces and Barra-Costantini systems. In order to develop a comprehensive analysis of passive solar design, four different solutions were analysed, namely *direct gain systems*, *Trombe walls*, *direct sunspaces* and *nanopainting*, which can affect cooling savings. The present investigation is based on a sensitivity analysis of these passive configurations through an extensive dynamic energy simulation with the software EnergyPlus™. Simulations are based on two different climate conditions and building destinations: residential and office buildings in location 1, Palermo, and location 2, Bolzano. The two climatic contexts are defined by an average annual solar irradiation of 1673 kWh/m² and 1218 kWh/m² respectively, with an average air temperature of 18.8 °C and 13.7 °C. Maximum, minimum and average monthly temperature and average monthly global horizontal solar radiation are shown for the two locations in Fig. 1. The three orientations were investigated. Lightweight and heavyweight structures were considered for the simulation, with average heat capacity per unit area values using 30-cm-thick concrete and wooden structures as a reference.

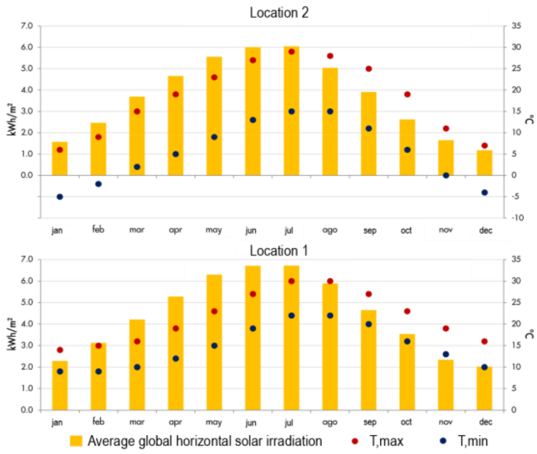

Fig. 1 – Temperature and radiation for location 1 and 2

The direct gain systems simulation consists of the increase of the reference window-to-wall ratio (WWR), according to Table 1, as with glass U-values. The Trombe wall was simulated as a detached thermal zone, with different constructions for the heat capacity and the WWR of the outer glass collector values of Table 1. Within the air cavity of the zone, for the modeling of the Trombe Wall, the ISO 15099 correlation, as validated by (Ellis, 2003), was adopted. For the summer period, the following equation was used to model the thermal chimney behavior of the opened air cavity:

$$Q = C_d A_o \sqrt{[2*(T_{fo}-T_r)/(T_r)*gL]}/(1+A_{rt})^2 \quad (1)$$

$$A_{rt} = A_o/A_i \quad (2)$$

where C_d is the discharge coefficient, A_o and A_i are the cross-sectional areas of air channel outlet and inlet, respectively, T_{fo} is the outlet air temperature,

T_r is the room air temperature and L is the total length of the thermal chimney. The sunspace was simulated as a detached sunspace, thus in a different thermal zone, with a local airflow network. Walls and roof are completely glazed; the floor construction is the same of the main building. Finally, nanopainting characteristics were included in the outer plaster layer of the wall, according to reflexivity and emissivity parameters of Table 1. For each passive solution analysed, the simulation included all the permutation of the two values of each parameter. To manage the results, an alphanumeric code was adopted based on the acronyms in brackets showed in Table 1. The simulated building, with average heat transmittance coefficients given in Table 2, has a surface-to-volume ratio of 0.715 over 77.44 m^2.

The sensitivity analysis of the parameters listed with relative ranges of variation in Table 1 provides results based on the mutual effects of common design factors already investigated in previous research separately, such as orientation (Morrissey et al., 2011), glass U-value (Nielsen et al., 2001) and thermal mass (Albayyaa et al., 2019).

As the objective is to gain potential energy savings during the heating season, the simulation is set accordingly. The blinds activate in winter to reduce night losses, and in the summer period, when the solar radiation on the windows rises over 250 W/m^2. Natural ventilation was added in summer, reproducing full opening of the windows in daytime during building occupation. The aim and novelty of the analysis is to provide not an optimization method, but a preliminary optimized set of parameters for specific solutions. Through the application to a case study, the scope is to determine an energy-related trade-off for the possible application of such passive solutions providing designers with a starting set of design parameters to investigate the benefits of integrating passive solutions in their projects. A multi-objective approach, including comfort indexes to modify system set points according to an adaptive approach, will be explored in future work.

Table 1 – Acronyms of the alphanumeric code

Category	Acronyms	Characteristics/Value
Building reference	B1	
Building destination	R	Residential
	O	Office
Location	L1	Palermo
	L2	Bolzano
Passive solution	DG	Direct gains
	TW	Trombe wall
	SS	Sunspace
	NP	Nanopainting
Orientation	E	East
	W	West
	S	South
Window to Wall Ratio (WWR)	*first parameter*	0.2 – 0.6
Glass U-value [W/m^{2}K]	*second parameter*	0.8 - 2.3/1.0*
Heat capacity per unit area [kJ/m^{2}K]	*third parameter (TS1-TS2)*	160-800
Reflectivity	*fourth parameter*	0.1 – 0.9
Emissivity	*fifth parameter*	0.1 – 0.9

**limit in North Italy*

Table 2 – Heat transfer coefficients of building constructions

Construction	U-value [W/(m^{2}K)]
Roof	2.2
Floor	2
Wall	1.26

3. Discussion of the Results

3.1 Passive Solar Design Guidelines

On the basis of Table 1, four reference cases can be detected, based on location and building use: Table 3 shows the related energy demand.

Table 3 – Energy demand of the reference cases

CODE ID	Heating demand [kWh]	Cooling demand [kWh]	Total demand [kWh]
B1_R_L1	961	1671	2632
B1_O_L1	977	1896	2873
B1_R_L2	4494	391	4885
B1_O_L2	2854	436	3290

It can be noticed that a slight difference occurs in terms of destination for L1, larger in L2. In this section, the best results of each specific simulated solution from the sensitivity analysis in terms of heating and global energy saving are introduced. **Direct gain** systems show the highest performance in residential applications and close to the highest in offices. From Fig. 2 it is clear how south can be seen as the best orientation option, with more thermal mass needed in the northern areas. **Trombe wall** systems perform slightly better than direct gains in offices, with a still-high share of energy saving in residential buildings. Fig. 3 highlights how south-bound systems are still the best choice, with heavyweight structures generally preferred, to limit nighttime losses and prevent excessive heat transfer from the air cavity. **Sunspace** best configurations still include south, with one west-bound configuration, as in the previous cases. In this scenario, the heavyweight system is preferred due to the high amount of solar radiation to dispose of. As described by Fig. 4, they perform better in residential applications, thanks to the delay guaranteed by the thermal mass. **Nanopainting**, in Fig. 5 shows very low shares for heating performance, while they mainly impact on the cooling load.

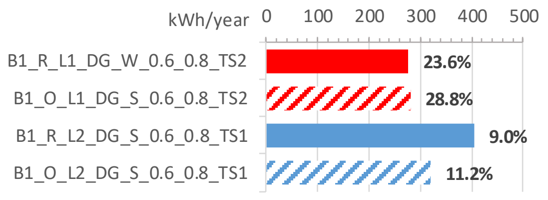

Fig. 2 – Best direct gain configurations

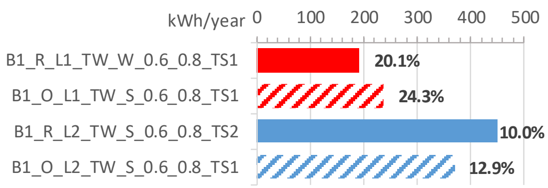

Fig. 3 – Best Trombe wall configurations

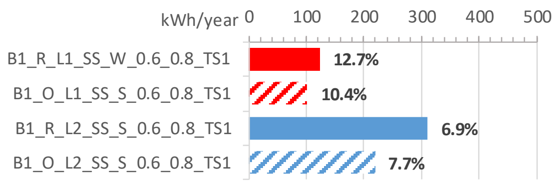

Fig. 4 – Best sunspaces configurations

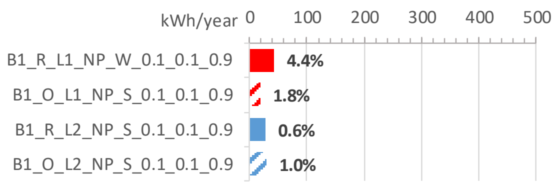

Fig. 5 – Best nanopainting configurations

South orientation proved to be the best solution, as described in Fig. 6, with west in second place, performing better than east in order to get heat late in the afternoon when people are back home. Almost all the configurations prefer 0.6 and 0.8 as WWR and glass U-value. It is worth noting that direct gain systems are the suggested solution for Palermo, while Trombe walls should be preferred in Bolzano.

Finally, Table 4 shows the best configuration for the four base case scenarios in terms of heating performance, while Table 5 shows the code of the passive solar design configurations that perform better in terms of total energy saving.

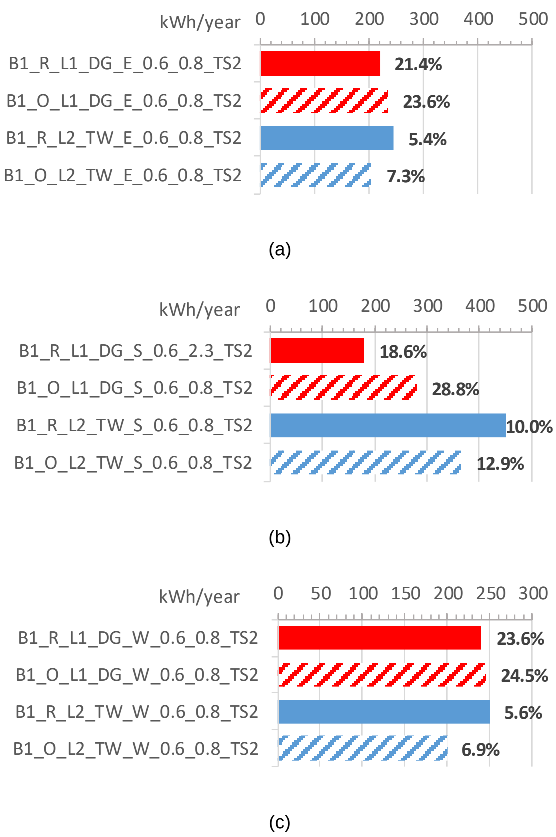

Fig. 6 – Best east (a), south (b) and west (c) bound configurations

Table 4 – Best configuration for heating energy savings

CODE ID	Heating [%]	Cooling [%]	Total [%]
B1_R_L1_DG_W_0.6_0.8_TS2	-23.6	+120.3	+67.8
B1_O_L1_DG_S_0.6_0.8_TS2	-28.8	+64.3	+32.6
B1_R_L2_TW_S_0.6_0.8_TS2	-10	+33.2	-6.6
B1_O_L2_TW_S_0.6_0.8_TS2	-12.9	+20.6	-8.5

Table 5 – Best configuration for total energy savings

CODE ID	Heating [%]	Cooling [%]	Total [%]
B1_R_L1_NP_W_0.1_0.9_0.9	+1.8	-2.5	-0.9
B1_O_L1_TW_S_0.2_0.8_TS2	-11.3	+3.3	-1.7
B1_R_L2_TW_S_0.6_0.8_TS2	-10	+33.2	-6.6
B1_O_L2_TW_S_0.6_0.8_TS2	-12.9	+20.6	-8.5

In Palermo, L1, the high solar irradiation leads to an increase of the cooling loads, which, as a result, generates an increment in the total energy loads. In Table 5, total energy savings are achieved as long as they are low. This is mainly due to the simulation set, as it focuses on the heating performance, with no optimized shading system for the summer period. However, for Bolzano (L2), the best heating configurations correspond to the best in total energy savings, between 6-8 %. The solution is Trombe Wall, with a high WWR and a low heat transfer coefficient. Direct gain configurations are the best passive heating systems for Palermo (L1), but can even double the cooling demand. In terms of total performance, nanopainting and Trombe walls slightly reduce the total demand even in a hot climate with a short heating season. As in previous cases, south-bound solutions are the most useful ones, with west limited to the residential case in location 1.

3.2 Optimization of the Case Study

The analysis of the case study allows a generalization of the approach to the previous solutions. The test case demonstrates the benchmark of the potential savings achievable through passive systems. The trade-off between passive and active solutions depends on the energy benefit the building can obtain, which is related to the climatic conditions, the kind and use of buildings, and the behavior of the occupants. The case analyzed is a co-housing project located in central Italy. Fig. 7 provides a schematic view. The building is a part of a masterplan for the development of 16 blocks. Developed on 4 floors, 180 m² each, the building hosts a co-working space and standardized flats for families. Each flat consists of a wide living space, a private terrace, one bathroom and two bedrooms, for a total of 78 m². The approach to the case study started from the application of the configuration suggested by the analysis previously described. Starting from the simulation of the base case, reference loads were identified, with an overall demand of 30.11 MWh per year. Fig. 8 shows the results of the cumulative application of suggested solutions in terms of energy savings. The case study took place in the center of Italy, Pisa, defined by L3: the climatic conditions, 14.8 °C average air temperature and 1500 kWh/m² of annual solar irradiation, fall between the two locations previously analyzed. The solution applied, taken from L1 results, will then be linearized according to both series of results. Firstly, direct gains on the west façade were integrated: the increase of the WWR led to 7.8 % heating energy saving. However, the cooling load increased to 16.5 %, causing the total demand to rise around 6 %. Looking at the orientation solutions in Fig. 8, east appears to be the second-most efficient for residential application. Direct gain systems are thus simulated on the east façade, with a close heating performance and a slightly lower cooling increase compared to west orientation. In the third step, the increase in the WWR was split between the two façades to better exploit solar radiation early in the morning and late in the afternoon - basically when passive heating is needed by the house occupants. To reduce the cost of the intervention, the increase in the WWR is compensated for by moving out the windows from the north-facing façade.

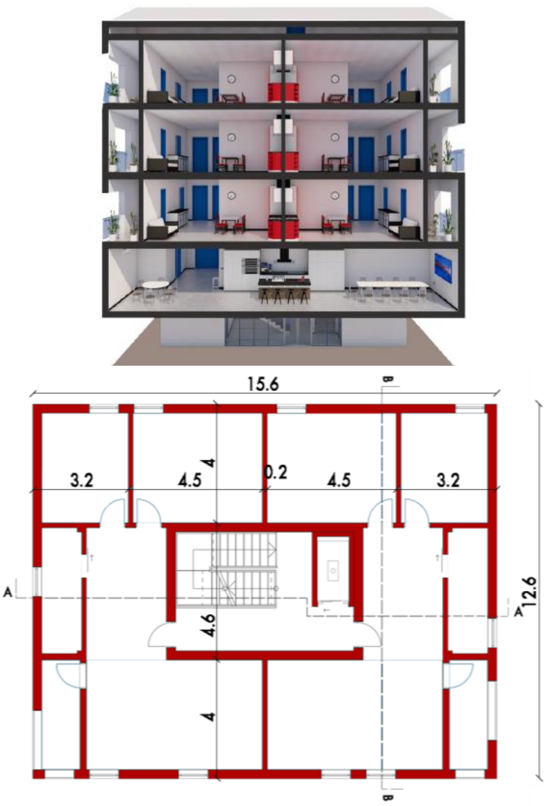

Fig. 7 – Schematic section of the building

This results in a higher heating performance, with an increase of the total demand, due to the cooling demand, being almost imperceptible. To reduce the cooling load, the best configurations in terms of total energy, in Table 5, were applied in step 4, starting with nanopainting. The cooling load is drastically reduced, 8 % compared to the base case, and finally energy saving is achieved in a total basis, even if the improvement in the heating performance is halved. Step 5 includes the optimization of summer shading, to further reduce the cooling load, -23.6 %. Finally, in step 6, sunspaces were implemented. This configuration was included due to the specific design of the building, whose terraces can be easily closed. Sunspace management system is optimized to get passive heating in winter, and assure natural ventilation through opening in summer. Shading system is implemented too. The result is a 14.3 % reduction in heating energy demand, 18.4 % in cooling and a total energy saving of 16.7 %.

Fig. 9 shows the changes in the building design. By moving additional windows from the north façade, the cost of the intervention is low, while the modular rhythm of the façades is preserved.

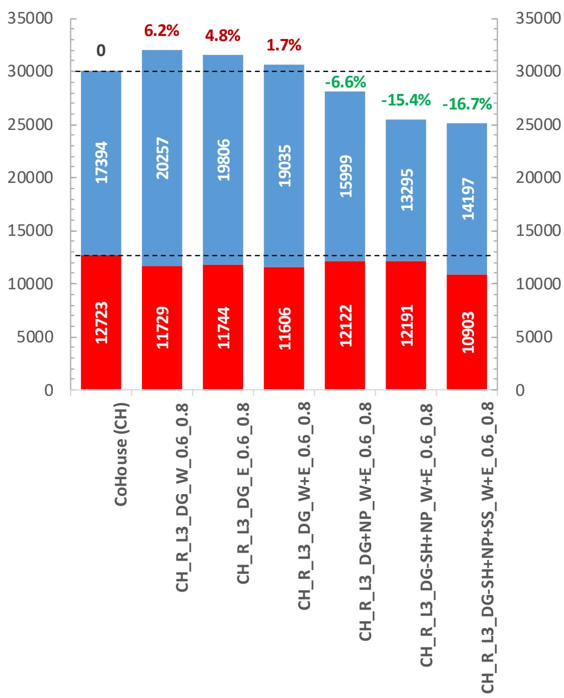

Fig. 8 – Heating, cooling and total energy saving of the case study design steps

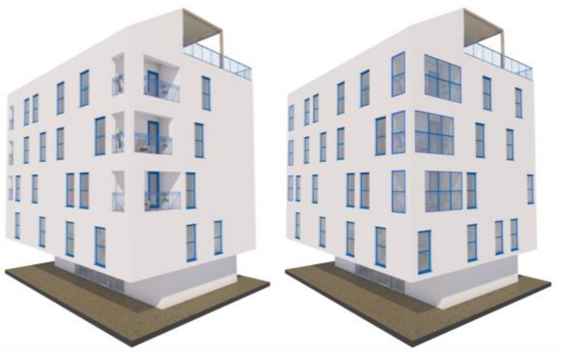

Fig. 9 – Starting (left) and final (right) project design

While nanopainting has no influence on the overall architectural design, the integration of sunspaces in the terrace does have a minimal impact, limited to the winter time. The test case confirms the limits of complex passive configurations in terms of energy benefits and management, to balance passive heating with cooling request. The integration of wide direct systems or sunspaces led to relative savings in the heating demand, but their counter effect on the cooling load unbalanced their effect on the overall consumption. More simple solutions, such as shading systems and nanopainting, on the other hand, proved to perform equally. The use of nanopainting, with its impact on the cooling demand, and the integration of a properly set shading system brings a reduction of the overall demand, allowing for a higher degree management of the passive heating load. Being easier to integrate, in technical and economic terms, their trade-off makes them more appealing for building application.

4. Conclusion

Passive solar design strategies are a tool for reducing building energy demand by exploiting solar energy. High heating energy savings can be passively achieved by simply optimizing the building design through the integration of passive solar solutions. The focus on the energy performance of the different passive configurations analyzed allowed the most proficient solutions in terms of both passive heating and energy saving for office and residential buildings in two different climates to be determined. The sensitivity analysis was based on both extrinsic and intrinsic factors, such as building use, location, WWR and glass U-value. The present work aims to address the lack of guidelines or suggested solutions and a methodology for a rational application of such configurations in different kinds of buildings. The purpose is to define an analysis to determine the possible energy-related trade-off for simple to complex passive configurations. A general methodology for the application and integration of the configuration during the design step of a new building was proposed through the analysis of a case study. The analysis moves from the solutions suggested by the general investigation to the integration of elements due to the specific building design:

- marginal savings can be achieved by simply applying the suggested solution for passive heating (direct gains, -7 % of the heating demand)
- the integration of the suggested solution in terms of total energy saving reduces the cooling load (nanopainting, -7 % of the demand)
- the optimization of the shading system helps to prevent the overheating risk in summer (optimized shading system, -15 % of the demand)
- finally, building specific solutions boost the performance (sunspaces, -14 % of the heating demand, -16 % of the total demand).

The results are achieved by minimizing two relevant factors for the promotion of passive solar design integration: impact on the building design, and thus architectural interferences, and the cost of interventions. A relevant element for a widespread application of passive solar design, which this paper attempts to address, is the development of design guidelines. The results of the present analysis can be generally applied as preliminary suggested parameters for the integration of passive systems in the Italian climate, by properly scaling values according to local climate conditions. To generalize the application of these guidelines, the trade-off of the application of passive solutions must be addressed. As seen by the test case, simple kinds of passive measures, such as nanopainting and shading, have a comparable performance on the demand of the building: with easier integration and lower cost, their trade-off suggests a wider application when compared with complex solutions. Further analysis must be carried out to take into account the effect of climate-related parameters, such as solar radiation, and local economy factors on the trade-off of these systems. Cost analysis and comfort models should be integrated into the sensitivity analysis.

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Nomenclature

Symbols

A	cross-sectional area (m^2)
Ar	aspect ratio of the cavity
C	discharge coefficient
g	gravity acceleration (m/s^2)
L	length of the chimney (m)
Q	air flow rate (m^3/s)
T	temperature (K)

Subscripts/Superscripts

d	discharge
fo	outlet air
i	inlet
o	outlet
r	room air
rt	ratio

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