Experimental evaluation of different natural cold sinks integrated into a concrete façade

Authors: MCarmen Guerrero Delgadoa, Jose Sánchez Ramosb, Luisa F. Cabezac, Servando Álvarez Domíngueza

a Grupo de Termotecnia, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos S/N, 41092, Seville, Spain
b Máquinas y Motores Térmicos, Escuela Superior de Ingeniería, Av. Universidad de Cádiz, 10, 11519, Puerto Real, Spain
c GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida

*Corresponding author. mail address: mgdelgado@us.es (MCarmen Guerrero Delgado)

Abstract

The new demands, the climate change and challenges set by society intend to generate major reductions in the heating and cooling demands of buildings. However, conventional measures to improve the performance of the building envelope can easily reduce the heating demand and, in many cases, worsen the cooling behaviour of the building. Therefore, we need innovative solutions that provide high heating performance and use natural heat sinks to cool the building's thermal mass when in cooling mode. This work describes and tests a solution consisting of a façade built as a precast concrete element with high thermal inertia. This solution integrates different natural cooling techniques as a natural sink. For that, it has different modes of operation when in cooling mode, which allow it to adapt to the needs of the building and the natural resources available to guarantee high performance. To evaluate the impact of the three operating modes of the proposed solution, an experimental prototype has been built and tested over two summers. This experimentation, combined with an inverse thermal characterisation model, has made it possible to estimate the real impact of three passive cooling measures (nocturnal storage of cold in the thermal mass of the façade element, nocturnal ventilation of the building itself through the façade element and pre-cooling of the air before entering the chamber by using the evaporative system). All these measures are presented as different possible modes of operation of the described solution, with hardly any extra cost on the base solution, but with a considerable energy impact.

Keywords: climate change mitigation technology; natural cold sinks, night cooling, evaporative cooling
Nomenclature

<table>
<thead>
<tr>
<th>Variable/Acronym/Abbreviation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABS</td>
<td>Thermal activated building system</td>
<td>-</td>
</tr>
<tr>
<td>EPBD</td>
<td>Energy Performance of Buildings Directive</td>
<td>-</td>
</tr>
<tr>
<td>NZEB</td>
<td>Nearly Zero Energy Buildings</td>
<td>-</td>
</tr>
<tr>
<td>PCM</td>
<td>Phase Change Materials</td>
<td>-</td>
</tr>
<tr>
<td>( T_{IA-FREE}(d) )</td>
<td>Average of indoor air temperature in free-running mode</td>
<td>°C</td>
</tr>
<tr>
<td>( T_{OA}(d) )</td>
<td>Average of outdoor dry-bulb air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>ISOUTH(d)</td>
<td>Sum of radiation incident in a vertical south façade</td>
<td>Wh</td>
</tr>
<tr>
<td>IG</td>
<td>Internal gains effect</td>
<td>°C</td>
</tr>
<tr>
<td>DD</td>
<td>Degree day</td>
<td>[°C·day]</td>
</tr>
<tr>
<td>( T_{IA-MEAS}(d) )</td>
<td>Average of indoor air temperature measured</td>
<td>°C</td>
</tr>
<tr>
<td>( \tau )</td>
<td>The main time constant of the thermal system</td>
<td>day</td>
</tr>
</tbody>
</table>

1 Introduction

1.1 Context

High energy consumption in the construction sector and climate change are the main problems encountered in the built environment in Europe [1]. Cities have become one of the cornerstones due to their increasing demand for electricity. In this problem, buildings stand out, being responsible for 40% of energy consumption in the European Union and 36% of greenhouse gas emissions [2]. In addition, facing the objective of combating climate change, the Urban Heat Island (UHI) phenomenon is presented, which is an increasingly important global problem [3]. This problem, together with the overheating to which urban centres are subjected, have caused a rapid increase in the demand for cooling in buildings. [1,4]. All these causes that currently, the cooling of buildings represents a considerable fraction of total energy consumption in the world [5]. Due to new regulations derived from the need to reduce energy consumption in buildings [6,7] and the increasing awareness of energy saving in society, there is an increase in the number of studies aimed at producing an increase in energy efficiency. Reducing the energy demand for air conditioning in buildings is achieved through various measures, such as using an appropriate insulation system, eliminating thermal bridges, through the use of highly energy-efficient windows and the correct design of the openings and proper orientation of the buildings. However, improving the thermal quality of the conventional elements of the envelope leads to a considerable reduction in the demand for heating and the near elimination of this demand in some climatic areas [8,9], but, in most cases, it means an increase in the demand for cooling. As a result, many buildings have year-round cooling demands [10] and, to avoid an unacceptable increase of the indoor temperature (overheating) [11,12], thermal gains must be eliminated from the indoor of the building. Balcomb et al. [13] quantified the effect of stored solar gains on the building's thermal mass, and how the interior temperature could be increased by up to 10°C as a result of them. For this reason, it is necessary to study innovative constructive solutions that guarantee performance at least equal to that of conventional solutions in heating regimen and improve the performance of these in refrigeration regimen.

1.2 Constructive solutions

Reduction of energy consumption motivated by the appearance of innovative elements, "thermally activated building systems" (TABS) are presented as an alternative of great current interest [14]. Studies about TABS highlight the high energy performance. Also, they are classified...
in function of work fluid to activate thermal mass: water or air [15–17]. The higher specific heat in water than in air makes the former particularly promising, as it can carry large amounts of heat at a reasonably low flow rate. The use of water as an activation fluid is widely studied in recent studies [18], but obtaining cold water is a problem to solve, since it would be necessary to use natural techniques that produce said cold water without conditioning consumption [19]. Within the TABS classification of air, the "ventilated opaque façades" are a possible constructive solution. Said element is characterized by a precast concrete construction activated by cold air by means of its circulation through an air chamber. This cold air is easily obtainable with studied and consolidated natural techniques such as evaporative cooling. The benefits of active façades have been widely studied [20–22], finding that, depending on their design and climate location, they generate reductions in overall energy consumption of buildings. The advantage of this opaque façade is that it has higher thermal inertia than glazed façades, and better cooling performance because it reduces the high solar gains of the glazing. Also, low electrical consumption can be easily countered by low-cost renewable electrical systems [23].

The integration of phase change materials (PCM) using the inertia of the building appears in this line of generating thermal storage systems. For some years now, research on the topic of the integration of PCM materials into façade elements has grown exponentially [24]. As shown by works such as De Gracia et al. [25] or Pomianowski et al. [26], the storage capacity (kWh/m²) of these systems is very high, but there are low conductivity problems that are gradually being solved, and adding these materials allows to increase the thermal mass of the building without the need for huge quantities of conventional materials. However, at present, there is a problem linked to the high cost of these materials [27].

Focusing the analysis on solutions for ventilated façades, authors such as De Gracia et al. [28–30], utilizing simulation and experimentation, discuss the thermal performance of this type of solution in heating and cooling modes. In these works, it can be seen that the solar heating of the façades depends on the good design and operation of the system. In this context, De Gracia et al. [31] tested experimentally the thermal performance of a ventilated double skin façade (DSF) with phase change material (PCM) in its air channel, during the heating season in the Mediterranean climate. The experimental results conclude that the use of the ventilated façade with PCM improves significantly the thermal behaviour of the whole building (working as a heat supplier in free floating tests and reducing significantly the electrical consumption of the HVAC systems). However, these improvements might be increased if thermal control is used, as the author comments in the study [32]. From the experimental winter campaign, important net electrical energy savings were registered. On the other hand, no net energy savings were achieved during summer due to excessive use of mechanical ventilation. Moreover, the high hysteresis of the PCM limits strongly the potential of the system in supplying cooling during the severe summer period [33]. The set of experiments demonstrated that the cold storage system is almost useless unless the PCM has been fully solidified during the night period [34]. Natural cooling is very limited to the availability of natural cold sinks. Therefore, the challenge consists of integrating cold sinks into a façade.

Many works propose to use the airflow effectively through the air chamber of opaque façades as a natural heat sink, accomplishing it by using fresh air [35]. This fresh air usually appears at night. Different authors [36,37] demonstrated the possibilities of a Trombe wall for heating, cooling and even hot water production. The work of Stazi et al. [38] experimentally delves into the need for a good control of this type of solutions. The authors proved that optimal operation of a Trombe wall solution is possible by measuring surface temperatures, air temperatures, and climatic conditions. Corgnati et al. [35] provided results of the impact of free air cooling strategies and thermal mass activation on a concrete element. The results show that large reductions in peak cooling loads are achievable. However, fresh night air in hot months may not be enough to achieve good performance over a high number of hours [20], especially in hot climates. Therefore, this works
proposes to add water as a second natural sink. The water will evaporate inside the chamber to
cool the air at night, so the night effect can be enhanced to wet bulb temperature levels.
Evaporative cooling has gained in popularity in recent years for its simplicity, low cost and use
of renewable resources [39]. Its high cooling efficiency makes it an attractive alternative to
conventional systems in warm, dry climates. Evaporative water loss is a drawback, however,
against a backdrop of the constant universal growth of water consumption [40].

1.3 Energy impact assessment

Energy impact assessment of this type of innovative solution is usually measured in terms of the
variation of the indoor temperature of the room on which it is installed, i.e. improvement of
comfort. This methodology has been implemented both in experimental studies on prototypes
[41–43] and in real buildings [44,45]. It is common to use comfort indicators to assess the impact
of improvement measures in the air-conditioning system [46,47]. Valentina et al. [48] proposed a
daily calculation of the comfort improvement of an innovative window system. Sara et al. [49]
worked with experimental data to generate inverse characterisation models for the study of
variations in indoor temperature between rooms of dwellings and linked this result to the occupants' well-being. This makes indoor temperature an interesting indicator for evaluating the
occupants' comfort and social well-being [50–52]. Wang et al. [53] evaluated the impact of a
thermal storage wall by comparing the measured data and those obtained via simulation using
comfort indicators. However, the use of simulation tools [54] or detailed simulation procedures
[55] require their calibration using experimental data and the difficulty of replacing the default
values of this simulation with measured parameters, such as transfer coefficients inside the air
chamber [56]. These alternatives work in controlled environments like test cells but become
unfeasible for real buildings. These alternatives work in controlled environments like test cells or
laboratory prototypes but their application in real buildings can be complex.
The evaluation of the energy impact requires having an identical prototype but without the
coupled innovative construction solution, which allows comparing both under the same climatic
conditions and therefore determining the improvement in comfort obtained after the
implementation of the solution. In the case of not having a comparison prototype, there is a need
to develop a model, using experimental data, to characterise the initial energy situation and from
which to evaluate the impact on the days of operation of the planned strategies. This is what is
known as a baseline and is integrated into the most widely used protocols for measuring and
verifying savings, such as that of EVO [57]. Also, as the most referenced proposal in the literature
[58,59], the use of the baseline allows the calculation of the energy impact between a reference
situation and the measured changes over this reference situation. That is why the definition,
measurement and characterization (baseline, inverse thermal model) of the reference situation
become the most important point. This important motivation is, in turn, the motivation for this
work, since residential buildings in the Mediterranean area have no consumption of air
conditioning by lack of conditioning equipment, or for not having available funds for its operation
[60]. It is in these cases that this work's proposal resolves the need to evaluate the energy impact
of the installation of an innovative façade solution for the reduction of discomfort with the use of
the thermal mass of the building. This problem, as justified by Pellegrino et al. [61], is a necessity
in developing countries. In these cases, since they do not have an air conditioning system, the aim
is to improve the comfort conditions inside the houses, that is, the response variable would be
temperature instead of consumption. Therefore, in this work, a baseline on indoor temperature
will be used to characterise the reference situation of the building and to be able to use it to
estimate the improvement in comfort derived from energy saving measures.
The potential of water-based systems to mitigate heat stress has been explored in depth by authors
analysing temperature patterns in cities surrounded by bodies of water. Urban wetlands contribute
to 'urban cool islands' where temperatures may be 1 °C to 2 °C lower than in other areas [62]. In
addition to natural bodies of water in cities, a number of evaporative elements such as ponds and
fountains have been used for cooling as well as decorative purposes [63]. A review of the literature reveals that to date research has targeted cold air production [64–66]. Bishoyi 2017 et al. [64] and Camargo et al. [65] study direct evaporative cooling in a hot and humid climate. Also, these authors proposed that this solution can be used in developed countries due to the low cost of operation and ease of maintenance. Even developed by the local industry. In another hand, Elgendy et al. [66] experimentally analyse the integration of direct and indirect evaporative systems in a desiccant solution. One of the conclusions of this work is that the current level of technological research guarantees its possibility to be integrated into façade elements with the minimum maintenance cost. In this work, a direct evaporative system is going to be integrated inside the air chamber of a ventilated façade as it is considered a sufficiently proven technology that takes advantage of a natural cooling technique that is the evaporation of water. The goal is to increase night-time cooling potential.

1.4 Aims

This work aims to experiment with a scale prototype of an innovative façade solution that integrates two environmental heat sinks: cold air at night and an evaporative system. Both techniques will allow the cooling of a massive façade element or even the structure of the prototype built during the night. Later, this stored cold will be released during the day, which will generate an improvement in indoor comfort that we want to evaluate by comparing it with the reference situation of non-operation of this innovative element. Therefore, the secondary aim is to create a baseline on indoor temperature to characterise the reference situation of the building, and to be able to use it to estimate the improvement in comfort derived from energy saving measures.

The paper demonstrates the possibilities night cooling offers for cooling opaque double envelopes, and how the coupling of an evaporative system exponentially increases the cooling potential, both in quantity and in the number of possible operating hours. To this end, this product will act as a sink for the heat generated in the building employing several mechanisms: movement of the air inside by means of a ventilated air chamber, the thermal mass that can be activated by this air, and pre-cooling of the outside air using micronization of water if necessary.

2 Experimental prototype

2.1 Adaptative façade

The experimental façade element presented in this article consists of two opaque sheets and an air chamber (see figure 1). The construction material of the façade element and of the test cell itself is high density concrete (2200 kg/m³). Also, the value of specific heat is 1000 J/kg·K and thermal conductivity is 1.15 W/m·K. This is because the aim is to demonstrate the cold storage capacity of this material if optimal activation is achieved using a façade element, which can be prefabricated, and the use of environmental heat sinks (cool night air and evaporative cooling).

The façade element is an example of climatic-adaptative building envelope. So, it presents two configurations: one for the summer and another for the winter. In winter mode, the chamber remains completely closed (airtight), so that the insulation installed in the external element guarantees a low transmission coefficient value. In summer regime, the chamber is made to operate as a traditional ventilated façade, except that it will only operate when the external conditions are suitable enough for the cooling of the massive internal element. Therefore, test cell allows three different strategies in the summer regime: use of the thermal mass of façade element (mode 1) by air circulation inside the chamber but not inside the cell; night ventilation inside the test cell (mode 2); and use of an evaporative system to maximize mode 1 (mode 3). These modes are described in section 2.3.
Figure 1 shows the details of the element, as well as some peculiarities of its operation. The positioning of the evaporative system inside the chamber can also be seen. This evaporative system sprays drops of less than 30 microns’ size in order to evaporate in the fluid stream that runs through the chamber.

2.2 Overview of the experimental set-up: test cell

The experimental set-up consists of a concrete test house or cell, located in the facilities of a cement factory near the city of Seville, Spain, (37°21'35"N, 5°51'50"W) at approximately 40 m altitude. The average monthly temperature varies from 11 °C in January to 28 °C in July, the average minimum in January is 5.7 °C and the average maximum in July is 36.0 °C. Among the Spanish climates, this town is classified as having an extreme summer and a moderate winter.

The indoor dimensions of the house are 2.9 m wide, 2.40 m deep and 2.40 m high. The walls of the north, east and west façades have two layers: the exterior is made of concrete with a density of 2500 kg/m³ and 12 cm thick; the interior layer is made of polystyrene with a thickness of 8 cm. The door is on the north façade and is insulated internally by a layer of polystyrene of the same thickness as the walls. The roof is made of concrete with an internal insulation layer of expanded polystyrene of 5 cm thickness.

The façade element (see figure 2) that is being studied is in the south façade. The layers of the façade, from inside to outside, are a concrete wall of 2500 kg/m³ density and 16 cm thickness, interior air chamber of 5 cm thickness, a layer of polystyrene of 8 cm thickness and a concrete layer of 12 cm thickness. Only in winter mode, it is possible to add a glazed sheet with simple glass (see figure 2, left). This glass would create a new air chamber as a Trombe or solar wall. However, this alternative has not been studied in this work, and during the winter the facade will not have this glass (see figure 2, right, real photography of experimental prototype).
Air circulation in the ventilated chamber is carried out by 6 Sunon 2123HBL fans with a maximum flow of 147 m³/h each and located in the upper zone so that the air flows through the inner chamber in an upward direction.

For the building's air-conditioning, there is a Split-type heat pump with a cooling power of 900-3000 W and heating power of 900-3600 W.

Sensors to measure the temperature were placed at the points indicated in Table 1 to evaluate the performance of the proposed façade element.

**Table 1. Overview of measured variables**

<table>
<thead>
<tr>
<th>Variable to be recorded</th>
<th>Type of sensors</th>
<th>Measurement points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal temperature</td>
<td>Type T thermocouples</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>RTD PT100</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>NTC Thermistor</td>
<td>7</td>
</tr>
<tr>
<td>Interior surface temperature (See figure 3)</td>
<td>Type T thermocouples</td>
<td>12 (4 on the south wall, 4 on the ceiling and one sensor on the remaining surfaces)</td>
</tr>
<tr>
<td>Interior and outside air chamber temperature</td>
<td>Type T thermocouples</td>
<td>8 (4 in each chamber)</td>
</tr>
<tr>
<td>The external surface temperature of the concrete layer (see Figure 3)</td>
<td>Type T thermocouples</td>
<td>4</td>
</tr>
</tbody>
</table>

The thermocouples are connected to a National Instruments Compaq DAQ data acquisition system with an accuracy of 0.8 °C. The four-wire PT100 RTDs are connected to a Delta Ohm HD 32.7 data logger which achieves an accuracy of ±0.01 °C ±1 digit. The NTC thermistors are located inside a Testo 174 T data logger with an accuracy of ±0.5 °C.

The seven indoor air temperature measurement points were distributed as shown in Figure 3(b) in order to record possible temperature differences in the volume of indoor air and to allow to calculate a representative average.

In the special element (see Figure 3(a)), 4 temperature sensors (type T thermocouples) were placed in the interior chamber of the element, 4 in the exterior chamber of the element as shown in Figure 3(a).
The surface temperatures of the indoor enclosures were taken with type T thermocouples. 4 sensors were placed on the south wall and the ceiling, and only one on the others. The difference in the number of temperature sensors on each of the surfaces is due to the thermal gradients on each of them. These thermal gradients were detected using thermographies carried out on each of the surfaces. The thermal gradients were found to be noticeable on the south wall and the ceiling. The reason for this is that the south wall borders an air chamber that can present an important thermal gradient, either by stratification of the air when it does not circulate, or by temperature variation in the direction of air movement when it does. In the case of the ceiling, it has a slight slope that makes it not homogeneous. On the other hand, the other walls are uniform and therefore do not present important thermal gradients.

Because the temperature sensors on the outer surface and the air temperature sensors in the chamber would be exposed to solar radiation, they were protected. The surface sensors were covered with a thin layer of concrete-like coloured cement so that the radiating properties of this protective layer would be as close as possible to those of the concrete. The air temperature sensors in the outer chamber were placed inside a small aluminium tube that was protected with a layer of reflective insulation (low emissivity) and a small fan was placed at one end to achieve a forced airflow. With this, the heat transfer between the air and the temperature sensor by convection is much higher than the heat transfer by radiation. Also, the internal surface temperature of the aluminium tube will be close to that of the air, so that the effect of solar radiation on the temperature sensor is negligible.

Calibration of thermocouples has been done using Fluke Calibration 9173. This instrument has been recommended by the manufacturer. “Calibration oven” Fluke 9173 has the precision and stability needs required for the data recorded in this work. This calibration was performed before placing theses sensors in the experiment.

Outdoor condition data were recorded on a Weather Station WatchDog 2000, installed on top of the house as shown in Figure 2. The data recorded were: air temperature, relative humidity, wind speed and direction, precipitation, global radiation on the horizontal surface and global radiation on the southern surface.

The measurement of air flows and speeds in the ventilated chamber was done punctually, that is, a continuous recording of this variable was not done, among other reasons, because this air flows always have almost the same value, given that they are driven by fans that work in almost the same conditions. Two portable anemometers were used for this measurement, one turbine and one hot-wire.

2.3 Operation strategies

The façade studied presents an adaptative operation:
In winter, the air chamber remains completely closed (airtight), which makes it a conventional façade element with good thermal performance.

In summer, the air is circulated on the façade if the outdoor air temperature is more than 2°C lower than the indoor air temperature. Control is important because it defines when the fans start up. A non-optimized control generates excessive starts or, on the contrary, not taking advantage of the available natural cooling. It has been chosen to establish control at air temperatures as it is the easiest and most direct measurement for its possible replicability in real buildings. This issue will be analysed in section 4.2.

During the night, openings are made in the lower part of the south façade in such a way that air circulation is established when the fans are working. The operation of the fans is controlled by a control system that is commanded by the temperatures measured. This air can circulate only through the air chamber of the façade element (mode 1 and 3) or enter into the test cell (mode 2).

Operation strategies in summer regime are three:

Mode 1: During the night, the air is circulated (from outdoor to outdoor) through the chamber, cooling the inner sheet and simultaneously counteracting the cooling demand. The excess energy accumulates in the inner sheet. During the day, the accumulated energy is inevitably released towards the interior and the exterior sides. To reduce the energy released to the exterior during the day, the fans are stopped. This Mode 1 is outlined in Figure 4.

Mode 2: Even if at the exit of the air chamber, the air temperature is still lower than the temperature of the indoor air (from outdoor to indoor but passing through the air chamber). This air is drawn into the living space to cool the roof (Mode 2). Mode 2 shares the operation of Mode 1 but, also, if the air is still cold at the end of the air chamber, the air chamber extractors are switched off and the door extractors are switched on (opposite façade, see Figure 5). This causes the air to enter the cell from the chamber. A deflector at the inlet leads the air to the roof, as it is the element most exposed to solar gains during the summer and the only one not insulated on the inside.
Door extractors let to propel 20 air change per hour (ACH) of the prototype air volume. There are 8 axial extractors (electrical power 140 W and nominal flow rate 40 m³/h) in the door and the control system is only on-off by means of a relay.

Mode 3: Both operating modes (modes 1 and 2) can be enhanced by activating the evaporative system installed on the façade (Mode 3). This Mode 3 can be activated as long as the wet-bulb temperature is at least two degrees below the dry air temperature. Figure 6 shows the details of the implementation of the evaporative system next to the air access dampers to the element chamber. There are 6 micronizers and constant water flow of 11 l/h. The electrical power of high pressure pump is 400 W. The diameter that qualifies nozzles for given rated working conditions is VMD or mean volumetric diameter, defined as the volume-median droplet diameter (the diameter for which half the total water content is contained in droplets larger and half in droplets smaller than the median volume). VMD of these micronizers is 15 microns. The feed tank is chemically treated to avoid bacteria or algae growth problems. The growth of bacteria or fungi is a weak point of evaporative systems [67–69] that can be mitigated with good maintenance.
3 Impact evaluation methodology

3.1 Procedure

To evaluate the effect of the innovative solution on the experimental prototype, the procedure described in the following scheme is followed:

The methodology (see Figure 7) has the following steps:

1. Reverse characterisation of the reference situation of the prototype, i.e. the thermal behaviour of the test cell without the operation of the innovative solution. The product is the baseline that will allow a comparison of the measured values with the estimation obtained by this mathematical model. This comparison allows for obtaining the real impact of the operation of the innovative element. The inverse model is necessary to evaluate the effect on the thermos-energetic performance of strategies separately. The most used way in the literature is to build a reference cell without strategies for performing differential (comparative analysis). To remedy this lack, a thermal model was implemented. It is a possible solution but it does not have the same accuracy as differential analysis. However, the use of the inverse model has greater replicability since it can be used in real buildings.

2. Once the experimentation and characterisation of the reference situation are completed (identification of the model's coefficients), the summer mode is set up (operation of the innovative solution) and an experimental phase is carried out. The energy model of reference situation is the baseline for estimating the impact of the strategies.

3. The energy behaviour of the prototype is estimated from the characterisation model of the reference situation and under the same boundary conditions measured in the innovative solution. Based on this estimate and the energy behaviour measured in point 2, the energy improvement produced is evaluated.

In the area of thermal evaluation of experimental prototypes present in the literature, the new applications with the test cells of the PASSYS project [70] stand out. In another trend, and more innovative than the PASSYS works, we can find the research by Luisa F. Cabeza [71–73]. These publications are linked to the current work because they test innovative solutions by comparing them with a reference prototype without the innovative solution, which is not available in the current work—as it is in real buildings. The conclusion of these experimental works is that in order to evaluate the impact of measurement, it is usual to build a reference prototype that allows comparison of the measured study solution with the results measured on that reference cell. However, this is not possible in real buildings. That is why, in this work, it is proposed to
obtain a baseline that allows the estimation of the response of the system under reference conditions. This estimate will be compared with the values measured in the improved situation. The difference between both values will be due to the effect of the improvements. Therefore, there must be complete experimentation of the reference situation without any improvement measures, an experimental model of that situation must be obtained, and the model must be executed under the same conditions as the experimentation ones on the improved situation to assess the real impact of that improvement. However, at present, the most widespread option in the literature for the assessment of the impact of an innovative solution is the use of detailed simulation models [74,75], calibrated, simply corrected or compared with the experimental data.

In the case of this work, we have chosen to adopt the methodology that underpins most of the protocols for measuring and verifying savings. This methodology proposes obtaining a baseline of the variable measured before the intervention and comparing the estimate made by that baseline with the values measured after the intervention. In this line, the publications of the EVO and ASHRAE organisations stand out above the rest, with the former being the leader in disclosure. EVO presents its guidelines in the IPMVP protocol [57], from which the definition of the savings calculation is adopted. ASHRAE, in its standard [76] describes some general lines for the measurement and verification of energy savings in buildings. Both references, together with some that are quite descriptive of the applicability of these techniques [46,77,78], are the basis of the definition of savings adopted in this work, but while developing a path that gives greater weight to the physical component compared to the mathematical one. The following section summarises the foundations of the model and its mathematical formulation.

It is important to note that the control time step is 2 minutes. That is, every 2 values of the commented sensors are recorded (see section 2.2.), for every 5 minutes to evaluate the different control decisions. Furthermore, daily base time is used for the baseline. It allows for evaluating the impact. The baseline allows for climatic and temporal normalization (see section 3.2).

Finally, the main limitations of the methodology are:
- Proposed baseline uses a representative indoor air temperature. So, it requires to define reference conditions and definition of this representative temperature.
- The inverse model proposed is related to the physical behaviour of the prototype. So, it assumes that it is possible to extrapolate it for other climatic conditions. Validation of the model demonstrates the validity of this hypothesis.
- Also, the behaviour of thermal systems is not linear in relation to the scale. This is an important limitation to take into account the replicability in real buildings.

### 3.2 Inverse model

As mentioned in Figure 7, the aim is to analyse the impact of the operation of the 3 operation modes in the summertime. However, we do not have a cell reference. This cell would be the same as the prototype built, but the innovative solution would not be operated on it. If there was one, the measured value in the reference cell and the one in the cell operated with the element could be compared to estimate the impact. Since this is not the case, a temperature baseline has been generated to estimate the average daily temperature that would have been inside the cell if none of the passive cooling strategies had been operated. This baseline will be defined from inverse characterisation, using the data measured on the test cell in the winter configuration.

The basis of the model described below is preceded by the application of the transfer functions in the field of construction [79,80]. Several reasons justify the need for transfer function models [81,82]: the relationship is almost instantaneous and established a priori and the input variable influences the output variable, but not vice versa. These models are used in all fields of science to evaluate dynamic responses. If inputs are controllable variables, these models simulate and evaluate alternative policies. If not, they offer the possibility of studying how certain "scenarios", defined by the possible evolution of the excitation variable, affect the response variable.
It is important to remember the main objective of this model. Through the monitoring (in a short period time) of the test cell, the thermal parameters of the model must be identified in order to characterise the evolution of the indoor air temperature. Julian et al. [58] share the objective in their work and propose the use of a daily time base. However, Elena et al. [46] share this modelling philosophy, apply it on an hourly time basis and obtain good results in verifying savings linked to adaptive comfort.

It should be noted that the measurements are a time base of less than one minute. Analysis of the experiments, as shown in the results section, is done on the measurement basis. However, impact assessment is done on a daily basis. This decision is common when characterization models are used to assess the impact under real operating conditions. The literature review carried out shows that most studies work on a monthly or annual basis. In this work, the daily basis is chosen, as later justified. Besides, advantages of daily basis use have been analysed in recently several works and in the past a lot [83–86]. Especially, when it is working with real measurements in real buildings. This time base has been chosen because being an experiment in free evolution for a day is a sufficiently homogeneous time base and, in addition, it is a time base of enormous applicability for real buildings because it reduces monitoring requirements [87,88].

From the review of the existing literature, focusing on relevant publications that provide solutions to the characterisation of indoor air temperature in buildings in free evolution [89–92], it can be concluded that the physical dependencies of this variable are the outdoor air temperature, the incident radiation, the internal gains of the building and its inertia. However, this assumption is confirmed with experimental data in section 5. Therefore, assuming the same dependencies adopted in the literature and applying the transfer function basis, the resulting model for the inverse thermal characterisation of the daily evolution indoor temperature (see equation 1) is:

\[ T_{\text{IA-FREE}}(d) = a_0 T_{OA}(d) + a_1 T_{OA}(d-1) + b_0 \text{ISOUTH}(d) + b_1 \text{ISOUTH}(d-1) + d_1 T_{\text{IA-FREE}}(d-1) + IG \]  

Where the variables refer to day \( d \):

- \( T_{\text{IA-FREE}}(d) \) [°C] is the average indoor temperature in free-running
- \( T_{OA}(d) \) [°C] is the average outside temperature
- \( \text{ISOUTH} \) [Wh] integral of the southern radiation incident during day \( d \)
- \( IG \) [°C] is the effect of internal gains, mainly. There is a computer with data acquisition and relay driver modules inside the prototype. So, air volume of the prototype is around 16 m³. Also, the daily average of energy consumption of the computer is 3 kWh (power average 150 W). So, internal gains are not negligible.

Coefficients \( a_0, a_1, b_0 \) and \( b_1 \) multiply the excitations. These coefficients are linked to the permanent response of the system associated with each excitation. In turn, coefficient \( d_1 \) (see eq. 2) is related to the inertia of the system through its time constants [79], since they create the dependence of the target variable at the current instant with its value in past instants.

\[ d_1 = e^{-\frac{\tau}{\text{day}}} \]  

Where \( \tau \) [day] is the main time constant of the prototype on daily basis time. Also, as all the surfaces of the prototype have a high level of interior insulation except the southern element of the façade and roof, this time constant refers to this element.

In this case, a period time of one day has been taken. Likewise, the use of an hourly basis, as most building energy simulation tools do, would have meant an increase in the complexity of the model and the need to take into account the variation in the coefficients proposed by the temporary modification of the climatic excitations. The latter is linked above all to the variation of the solar gains as a function of the sun-earth position and the need for the direct and diffuse decomposition of this radiation.

These circumstances would reduce the application of the proposed methodology when the prototype tested is built in a real building, under real operating conditions. The uncertainty of these real conditions, for example in residential buildings, would suppose an hourly uncertainty
that is difficult to overcome. On the other hand, uncertainty associated of daily basis is mitigated because there will be a relationship between the days before (reference period) and after the intervention in the building. However, the energy impact of a saving measure is linked to the difference in interior temperature between the temperature measured, when this measure has been implemented in the building and the interior temperature that would have been in the building situation before of intervention. This link between consumption and temperature difference is what is known as “Indirect Method or Room Air Weighting Factor Method” [93,94]. It is a method widely used in simulation tools and in research papers. It requires the estimation of the interior temperature that would be if the equipment did not work and compare it with the setpoint temperature to obtain that temperature difference. Adopting this method allows estimating the impact of the measurements without the need to measure the different heat flows involved in the balance of the space. Since the difference between the reference situation (baseline temperature) and the measured situation (indoor temperature measured) is due to the effect of the natural cooling measurement. Indirect Method is the one that supports the need to estimate the impact of the techniques studied in this article by calculating the accumulated difference in temperatures in the indoor air. For example, the most recent comfort studies [46,95,96] also rely on the existence of this method to only measure the temperature of the indoor air in the impact studies. Also, the characterization and evaluation of the variation of the interior temperature would also respond to the impact in buildings with limited or no use of conditioning systems, that is, in conditions of energy poverty. Furthermore, the daily timebase allows categorising days, which is interesting in the framework of the current work. This is because the operation of the innovative element will be during the night, so a comparison between days with/without operating the solution, or comparing the performance differences between the operation of Mode 1, 2 or 3 (see Figure 4, 5 and 6) can be made on a daily basis. Also, it has considered as a reference situation a free running scenario in which none of the additional modes operates (section 3.1). So, the aim of this study is to assess the impact of each of the modes as an additional behaviour of the facade. The differences between the measured values of indoor temperature and those estimated by the application of baseline are due to the effect of the facade operation; since the effect of the facade in passive mode is implicit in the estimation of the baseline. So, degree day is the variable used to estimate the impact of the techniques studied. Eq. 2 shows the definition:

$$DD = \sum (\overline{\text{TI}_{\text{A-FREE}}(d)} - \overline{\text{TI}_{\text{A-MEASURED}}(d)})$$

Eq. 2

Where DD [ºCꞏday] is the indoor temperature difference during period d between the estimation of baseline $\overline{\text{TI}_{\text{A-FREE}}(d)}$ (reference conditions) and $\overline{\text{TI}_{\text{A-MEASURED}}(d)}$ the daily average indoor temperature measured. This indoor temperature difference is linked to energy consumption [93,94]. Also, the estimation of baseline in reference conditions (freerunning) should be higher than indoor temperature measured when natural cooling techniques would be used.

Finally, the baseline (see eq. 1) is applicable to real buildings using indoor air temperature data under non-operating conditions of the conditioning system. In tertiary buildings, this data can come from stoppages such as weekends or holidays. In residential buildings they can be obtained in those months when there are no cooling / heating needs, for example, in the Mediterranean climate, it usually happens in the transition months between winter and summer. Likewise, it is necessary to decide the representative indoor temperature of the building. These types of decisions are common in savings evaluation and verification protocols [97].
4 Results

4.1 Winter configuration – reference situation

This section presents the most important results of the cell experiments in the winter configuration, or, what is the same, in the conventional operation of the prototype with the air chamber sealed and without forced circulation over it. In this period, the southern façade is simply a wall with a non-ventilated air chamber inside it that functions just like a conventional wall. The aim is to establish the behaviour of the building without the action of the active façade, in such a way that a model can be established to determine the response of the building under any climatic condition.

In section 3, the use of a daily model has been justified. This model is the baseline proposed and the use of it lets to estimate the impact of natural cooling strategies. For that, it is necessary to compare the estimation of indoor temperature by baseline model and indoor temperature measured. The difference between these two variables is the effect of cooling savings [78]. Then, a relevant point of the work is the identification of the interior temperature model. This model should be valid for summer and winter, since the aim is to characterize the thermal response of space to climatic excitations. Section 4.1 shows the process to obtain the model coefficients in the reference situation considered.

This winter period will be separated in two: the first one, from December to February, which will be used for identifying the coefficients of the baseline model; and the second one from March to May, which will be used for validating the model. Note how this validation is done in the spring period, where the solar effect on the test cell is quite different from the first period. This will allow us to certify the validity of the baseline and the need for a physical basis for it.

Figure 8 shows the values of outdoor temperature, and global radiation incident in the horizontal and vertical south plane, together with the value of the indoor air temperature.

The measurements in Figure 8 show how the climatic conditions are variable, with minimums below 5 °C and maximums reaching 25 °C air temperature. A fortnight in December has been chosen for the graph, but, as mentioned above, the reference period for identifying the model is from 1 December to 30 March.
Figure 8 further shows how incident radiation is significant at these latitudes, even in cold periods. For this reason, Figure 9 shows the temperature of the inner surfaces of the cell and compares the average daily temperature inside with the average daily temperature outside.

Figure 9. Winter configuration - climatic excitations during reference period: effect of solar and internal gains

The analysis of Figure 9 shows that the average indoor temperature has a similar trend to the outdoor temperature, with a certain delay and a variable difference of 3 to almost 10 °C. This difference is due to the overheating generated by the heat gains. If Figures 8 and 9 are observed at the same time, it can be seen how 8 and 9 December are days of low radiation and a progressive increase in outdoor temperatures. These two facts together generate a close-up of the two temperatures plotted in Figure 9. This minimum closeness is linked to the effect of internal gains, since solar gains on December 8 and 9 are low.

As mentioned, once the model coefficients that minimise the error of the model estimation against the measured data of the period (December-March) are obtained, this model is executed in the period April-May with the winter mode for its validation. Figure 10 shows the values measured during the validation period. This graph shows how the incident radiation is significantly higher than the values measured in the first period (see Figure 8), and how the temperature of the roof surface is 2 to 3 °C higher than the indoor air temperature. This increases the solar capture of this constructive element and justifies the need to cool the element during the summer. Also, there are a series of days with a low value of radiation (see figure 10). Daily different between indoor air and outdoor air is due to the effect of internal gains.
Now, Figure 11 shows the comparison between the indoor temperature measured and estimated by the daily baseline model, together with the average daily temperature of the outdoor air and the integral of the incident radiation on the southern vertical surface (second y-axis).
Model coefficients and statistical indicators of the adjustment are shown in Table 2:

<table>
<thead>
<tr>
<th>Value of model coefficients</th>
<th>b₁</th>
<th>b₀</th>
<th>a₁</th>
<th>a₀</th>
<th>d</th>
<th>IG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.3009</td>
<td>0.3662</td>
<td>0.3410</td>
<td>2.1440</td>
</tr>
<tr>
<td>Variables of the model (see eq. 1)</td>
<td>ISOUTH(d-1)</td>
<td>ISOUTH(d)</td>
<td>T_{OA}(d-1)</td>
<td>T_{OA}(d)</td>
<td>T_{IA,FREE}(d-1)</td>
<td></td>
</tr>
<tr>
<td>Coefficient of correlation (Pearson)</td>
<td>0.4130</td>
<td>0.1629</td>
<td>0.5946</td>
<td>0.6995</td>
<td>0.8836</td>
<td></td>
</tr>
<tr>
<td>p-value</td>
<td>0.0234</td>
<td>0.3400</td>
<td>0.0371</td>
<td>0.0693</td>
<td>0.053</td>
<td></td>
</tr>
</tbody>
</table>

There are three basic elements to consider when analyzing a correlation: sign, magnitude, and significance. Values of coefficient (see table 2) are positive. The most representative variables are ISOUTH (d-1), T_{OA}(d), T_{OA}(d-1) and T_{IA,FREE}(d-1). All of them are linked to the data measured the previous day (d-1), except the outdoor air temperature. These results are reasonable, since the prototype does not have solar collection elements, and has high insulation inside. These variables have significance in the model.

In this line, the statistical results (see table 2) associated with radiation ISOUTH (d) are indicative that this variable could have been eliminated. It was decided not to do it to maintain the logic of the model. However, the deviation associated with this coefficient shows that its value can fluctuate around 0. P-value (see table 2) associated to this variable shows that the significance of this variable in the model is null.

In another hand, the existing internal gains IG suppose an increase in temperature of the prototype. This increase is possible to estimate using the steady state of eq. 1. Also, daily formulation (eq.1) re-written in steady state allows obtaining the effect of solar gains. Then, eq.3 shows the effect of internal gains $\Delta T_{IG}$ [°C].

$$\Delta T_{IG} = \frac{T_{IG}}{1-d_1} = 3.25 \text{ [°C]}$$

This value of 3.25 °C (see eq. 2) is expected according to the experimental results shown in figure 10. In another hand, Eq.4 shows solar gains parameter $\Delta T_{SG}$ [°C/W·h]. This parameter is linked with the solar area and indoor response of solar gains.

$$\Delta T_{SG} = \frac{b_0 + b_1}{1-d_1} = 0.00015 \text{ [°C/W·h]}$$

$\Delta T_{SG}$ takes a positive and small value. This is due to the absence of transparent or semitransparent elements that allows radiation to enter in the indoor space. Therefore, the negative value of $b_0$ is not usual, same as windowless space. According to ASHRAE Handbook [98], air weighting room factors can take positive or negative values. Variation of indoor air temperature due to radiation of day d is very low. So, negative value of $b_0$ is a mathematical result and the statistical results show this variable could be eliminated. Values of $b_0$ and $b_1$ require four significant decimal places, and the temperature sensors, together with the uncertainty associated with the rest of measurements, do not have the required precision.

Furthermore, thermal inertia is linked to the value of $d_1$ (see eq. 2). In this case, value of $\tau$ is 22.3 hours. This value is characteristic of high thermal mass element [99].

And finally, the comparison between the estimated and measured value during the whole reference period in winter mode appear in Figure 12. In this Figure 11, the values used for the validation of the model (April and May measurements) are in green; and the values of the period
of obtaining the model (December-February) appear in red. These coefficients (see table 2) have been obtained using a least squares adjustment process using the Matlab IDEM tool [100].

Figure 12. Inverse model vs measured data.

To analyse the results of figure 12, it is used the regression coefficient ($R^2$) and normalized mean bias error (NMBE). The normalized mean bias error (NMBE) indicates if the estimated value of the model is higher or lower than the experimental value. So to judge the quality of the model, the correlation coefficient $R^2$ has been used, which takes a value higher than 0.99 for the identification points (red in Figure 12); and higher than 0.97 for the validation points (green in Figure 12). The average NMBE is less than 4 %, and the maximum error is 12 %. In conclusion, this model makes good estimates and can be considered valid for estimating the impact of the measures under study.

Model of table 2 is the daily baseline. It is the chosen method for the evaluation of the impact. It would be used to estimate the thermal behaviour of the prototype in other weather conditions. The estimation of indoor air is compared with the measured indoor air temperature to get the influence of the different strategies. It should be noted that there is no conditioning system in the prototype since the final objective of the project in which this solution is developed is to achieve passive buildings. Validation of the model has been done using data from April and May (spring, see figure 12), but the identification of the model has been done using data from winter (December to March). Likewise, the concept of baseline for the hypothesis that the model can be extrapolated to other climatic data of a different range than those used to obtain the coefficients. Figure 8 and 10 show differences between climatic data of winter and spring. Then, this is the main hypothesis of the proposed methodology. This hypothesis is common in inverse characterization models. This objective of passive buildings is to be achieved by integrating natural sink into the envelope of the same.

### 4.2 Summer configuration: mode 1 - inertial activation

As shown in section 2.3 (see Figure 4), the objective of this measure is to make air pass through the chamber when this air is cold enough to cool the thermal mass of the construction element. In this mode, openings are made in the lower part of the south façade in such a way that air circulation is established when the fans are working. The operation of the fans is controlled by a control system that is commanded by the temperatures measured. Figure 13 shows two weeks of standard operation. The experimentation in this way begins on June 6 and lasts until July 14 of 2018.
By analysing Figure 13, it can be seen how the average temperature of the air chamber (linear network) drops sharply when the fans are switched on at night (Fan ON). However, the temperature of the inner surface of the element (green line) will rise for several hours. During the rest of the day, the temperature of the element's inner surface, is on average, 3 degrees below the air temperature; and almost 5 degrees below all other surfaces. These surfaces (roof and other vertical enclosures) are at a higher temperature due to the effects of outside temperature and solar gains.

Also, it is important to highlight the problem of successive starts and stops of the fan. Fans turn on when the difference between outdoor air temperature and indoor air temperature is higher than 2 °C. These variables have been selected for the ease of its measurement. Besides, this control provides the most stable operation of fans and the best use of the natural cooling potential. However, this result is possible improvement of the solution in case it is going to be implemented in real buildings. Since fans with industrial sizes would generate consumption peaks at very damaging starts.

In turn, Figure 14 shows the daily results of the incident radiation integral (red line), average outdoor air temperature (green line), average measured indoor air temperature (blue line) and average air temperature estimated using the baseline (black line).

The difference between the measured indoor temperature and the estimated indoor temperature in Figure 14 is due to the effect of the night cooling of the innovative element. Note how the indoor temperatures coincide with the period before June 6, when the solution is put into operation.
Adding the difference between the baseline value and the average temperature gives a total of 45-degree day DD during the period 6 June to 14 July (38 days). These degrees can be directly linked to energy saving.

### 4.3 Summer configuration: mode 2 - night ventilation

Mode 2 refers to the prototype roof's night cooling measurement. This measurement combines the effect of the previous one, but it also introduces air inside the living space to cool the thermal mass of the roof. See Figure 5 for how the incoming air is guided into the roof and how the exhaust is positioned at the top of the door to promote a direct flow to the outlet.

This mode is tested during September. During August, the cell has been in the winter configuration, i.e. without operating any of the summer modes. From the night of September 2 to 7, Mode 1 is operated, with only ventilation in the chamber. And from the 9th to the end of September, the air is also passed through the interior of the living space. On the 8th, the cell is allowed to develop freely without operating any of the modes. All of these experiments have been done during 2019.

Figure 15 shows the daily results of the 12 days of experimentation. It can be seen that a cumulative reduction of 48 DD has been achieved with Mode 2. On the other hand, half of the operating days of Mode 1 obtain a cumulative reduction of 5.5 DD. The accumulated value of Mode 2 over 12 days is almost equal to the value obtained during the 38 days of the experiment in the previous section (see 5.3).

### 4.4 Summer configuration: mode 3 – evaporative cooling

Finally, in Mode 3, the evaporative system is operated to enhance Mode 1. This air could have been introduced into the living space, boosting the Mode 2 as well. However, this mode of operation was discarded because of the humidity problems that could occur inside the cell.

The experiments in this mode are carried out in the summer of the following year (2019) since the experimental results of Mode 1 and 2 were validated during the first year (2018) in the summer configuration. This is done by repeating a sequence of experiments in free-running during June (Winter configuration); then, testing in Mode 1 (Summer configuration); and finally, running the evaporative Mode 3 (Summer configuration).

In experiment Mode 3, the façade is operating with the evaporative system. The temperature of the indoor surface decreases even further in comparison with the other experiments. The temperature of the air chamber is lower than the outside one when the fans work because of evaporative cooling. Figure 16 shows the temperature difference between the air inside the living space and the outdoor temperature.
space and the temperature of the inner surface of the south side where the innovative solution is located.

![Graph showing temperature differences](image1)

**Figure 16. Daily mean temperature difference between indoor air and inner surface of the innovative facade.**

The objective of Mode 3, as well as Mode 1, is the cooling of the thermal mass of the innovative element by circulating the air through the air chamber. This means that the inner surface of the wall to the south would be the cold spot with which to cool the inner air. See Figure 16 for how this surface is cooler in the reference situation since it is not radiated during the day and has the insulation on the outer sheet. When the air is circulated at night, the difference increases by one degree (Mode 1), and when this air is cooled previously by using evaporative cooling (Mode 3), the difference increases by an average of more than 3 °C. This difference is linked to the discharge of the accumulated cold in the innovative element inside the building.

Figure 17 shows the real impact of both modes. The baseline obtained in section 5.1 has been used for this purpose. This baseline (red line in Figure 17) should coincide with the indoor temperature measurements during the reference period (1 June to 17 June).

![Graph showing temperature differences](image2)

**Figure 17. Daily mean temperature difference between indoor air and inner surface of the innovative facade.**

The impact of evaporative cooling is significantly greater than that of night-time cooling alone, as shown in Figure 17. This impact can be obtained as the difference between the baseline (red line in Figure 17) and the two modes under study. The cumulative difference over the 21 days of operation in Mode 1 is 33.2 DD of indoor temperature reduction (an average value of 1.6 DD per day). In Mode 3, the cumulative difference rises to 53 DD during the 15-day experiment (an average value of 3.5 DD per day).

The commercial evaporative system used only has an on-off control. This control was connected to a relay to establish a start signal based on the dry temperature of the outside air and the time.
Once switched on, the flow rate driven by the micronizers was constant and equal to 11 litres/hour. The average evaporation efficiency was 95% because the system was oversized, so the humidity at the outlet was close to 100%. For this reason, it was decided not to mix modes 2 and 3, that is, to introduce humid air into the interior of the cabin where the electronic systems of the experiment were located. Also, it was also a low interest situation in real buildings. Finally, average water consumption is 630 litres per week. This value was measured using counter located at the pump supply point. Ideally, the water used should be non-potable, either from the recovery of gray water or rainwater. Due to it is necessary to minimize ecological impact.

5 Conclusions

In the work, different natural cold sinks have been integrated into a building element. This façade solution has been experimentally evaluated. Design and operation of this solution allow the integration of two environmental heat sinks: night cooling air and water evaporation. To this end, an experimental prototype has been built and tested over two summers. This experimentation, combined with an inverse characterisation model, has made it possible to estimate the real impact of three passive cooling measures. All these measures are presented as different possible modes of operation of the described solution, with hardly any extra cost on the base solution, but with a considerable energy impact. Measure 1 consists of night-time storage of cold in the thermal mass of the façade element. Measure 2 is a combination of measure 1 plus the night ventilation of the building itself through this façade element. And finally, measure 3 is measure 1 plus the pre-cooling of air before entering the chamber by the use of the evaporative system.

The evaluation of the impact of this solution has been done in a free running mode, that is, evaluating the evolution of the indoor temperature in the building. This evaluation method is common for passive solutions (buildings without HVAC systems).

The main conclusions of the work carried out are:

- The methodology proposed to evaluate the impact of the element's different modes of operation provides reliable and rigorous results. The identified baseline has been validated with data from different years, providing acceptable estimates with errors of less than 0.5 °C.
- Night ventilation through the element (Mode 2) is a very interesting solution because, in addition to cooling the building by sweeping the ventilation, it efficiently activates the thermal mass of the element itself.
- Mode 1 circulates air through the chamber when it is cold enough to cool the thermal mass of the building element, but since the availability of this heat sink is intermittent, this mode of operation is not of particular interest.
- As mentioned above, the use of the night-time potential of cold air varies depending on the time of year, so the use of the evaporative system provides an effective solution to maximise the impact (Mode 3). The results prove that the associated savings can be more than triple. This would justify the investment in the micronization and water consumption system. However, it is important to take into account the low performance of evaporative cooling in hot and humid climates. Also, evaporative systems require careful maintenance to avoid the growth of fungi and bacteria.

Furthermore, although the element studied has not been evaluated in heating mode, it will have good performance since the thickness of the insulation is high and the air chamber is small and remains hermetically sealed during the cold months. Moreover, if a third exterior glazed element were added to serve as a sun trap, it could be an element with excellent performance in heating mode. This element would have to be mobile in order to be removed in summer mode.

Finally, the solution proposed is easy to integrate into new buildings and conceptually could lead to new products for rehabilitation.
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7 Author Contribution Statement

- MCarmen Guerrero Delgado: Research, Software, Writing, Original draft preparation, Visualisation, experimental facility
- José Sánchez Ramos: Software, Validation, Data Curation, research, Conceptualisation
- Luisa F. Cabeza: experimental facility, analysis, Writing – Review & Editing
- Servando Álvarez Domínguez: conceptualisation, methodology, analysis, supervision, formal

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