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Assessing energy savings in cooling demand of buildings using passive cooling systems based on ventilation

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Abstract

The objective of this article is to develop and test a simplified method to compute the savings in building cooling demand by use of passive cooling systems based on ventilation (direct night ventilation, air-soil heat exchangers, controlled thermal phase-shifting, evaporative cooling, as well as possible combinations thereof). The systems are characterized in terms of a climatic cooling potential, independently of any building, which is then compared to the cooling load of a particular building. The method is tested against an extensive numerical simulation campaign, combining diverse passive cooling systems and sizes with diverse constructive and operational modes for an administrative building situated in Geneva. The key point of the simplified method is to choose an appropriate time resolution, for taking into account the building thermal inertia. Although best results are obtained with a daily resolution, good results are also obtained with monthly data, where an overestimation of the passive cooling fraction remains less than 20% in half of the cases. This opens way for using the method for first assessing the potential of these passive cooling techniques on a large spatiotemporal scale, for which integrated building and system simulation becomes prohibitive.

Keywords: passive cooling; climatic cooling potential; useful cooling potential; effective savings

1. Introduction

1.1 State of the art

In most parts of Europe, electricity demand for air-conditioning of buildings is in rapid increase [1,2], and will be further boosted by the global warming issue [3,4]. Mitigation of this demand requires as well adequate architectural and constructive measures (reduction of the solar and internal gains, access to the thermal mass), as development of passive cooling techniques. Such techniques make use of naturally available heat sinks, which are usually closely related to local meteorological variables. The viability of such systems/techniques has been proved in several works, either by the use of simulation tools or in situ measurements [5]. State of the art can be divided in studies of effectiveness, implementation, modelling and prediction of the cooling demand reduction in buildings by the use of the referred passive cooling techniques.

Within this study we will focus on passive cooling systems which are linked to ventilation, namely direct ventilation, evaporative cooling, buried pipes and phase-shifter. The simplest of the mentioned techniques and certainly the most widely used is direct ventilation. Direct ventilation techniques use the ambient cool air to reduce the building´s inner temperature, therefore the building´s structure is used as a heat sink, allowing the inside air temperature to be reduced. Direct ventilation can be mechanically forced (by fans), natural (by openings and use of thermal gradients) or both natural and mechanic [6]. The use of direct ventilation to cool a building is often used during the night period and is referred as night cooling. The direct ventilation cooling effect on the reduction of cooling loads depends on three main parameters: the difference between indoor and outdoor temperatures (mostly during the night), the air flow rate, and the building´s thermal mass [7]. The effectiveness of night ventilation techniques on the reduction of the cooling loads of a building has been proven in several studies [8-11]. As a second technique, evaporative cooling is a process where the latent heat of vaporization of water is used. Evaporative cooling can be direct or indirect. Direct evaporative cooling is the process where cooled and humidified air is directly brought into the building. This process can have low efficiency in the case of humid climate, where air can be close to its saturation point. In order to improve the cooling efficiency the air is sometimes forced into a membrane that allows separation of the water vapor from the air. The indirect evaporative cooling is a similar process but using a heat exchanger (permeable wall) between the air flow and the cooled air, allowing the air inside a room to cool down without increasing its humidity, therefore decreasing the eventual condensation and the consequent release of heat into the room [12]. The evaporative cooling techniques have been largely studied and its efficiency has been shown both from technical and economical stand points [13-16]. It is expected that the indirect evaporative cooling systems will take up 20% of the air-conditioning market in buildings in the next 20 years in particular for the dry and hot climes [17]. The third technique, namely buried pipes or earth to air heat exchangers, act like a damper for the outside temperatures, so that at times of the day when temperatures are high the outlet air is at a lower temperature. There are several modelling and validation studies of buried pipes systems [18-22], as well as on its economic viability and effectiveness on the reduction of buildings cooling loads [23-25]. Finally, thermal input signal delay or phase shifting is a phenomena first discovered in a study concerning a buried pipes system [26]. The thermal phase-shifting device is a storage device were the storage material is homogeneously distributed within a ventilating duct in order to increase the heat-transfer surface of inlet air, and to decrease the penetration distance to thermal mass. In this way a homogeneous airflow and a good convective exchange are provided, permitting to delay the day/night temperature´s oscillation almost without dampening, and allowing the night cooling peak to be available in the middle of the day [27].

All of preceding systems are linked to the ventilation system of the building (possibly with some thermal storage) so as to activate the available cooling resource and distribute it within the building. As will be mentioned further down, several analytical and numerical models allow computing the achievable cooling temperature of these systems in a particular climatic situation, in function of specific design properties. However, determination of the effective cooling potential for a particular building usually needs further integrated dynamic building simulation, with ventilation from the available cooling source [8,28].

Despite the extensive literature and numerous validation models on the referred techniques, a model relating the output temperatures from a given passive cooling system and the cooling demand savings in a building has not yet been developed in a way independent of building thermal simulation. Ideally such a model would enable the computation of the cooling demand savings in buildings by the use of the aforementioned passive systems in a simplified and accessible way without the need for detailed knowledge on thermal simulation software and of the building properties. In this regard, Artmann et al [6] proposed a new integrated index named "climatic cooling potential" (CCP), defined as the summation of products between building and external air temperature-differences and time interval, that was computed for several locations across Europe. Their results pointed out that for the Northern Europe there is a very significant potential for passive cooling by night-time ventilation, and that even in some regions of Southern Europe the climatic cooling potential is still significant. Nonetheless, these authors didn't address the relation between potential and effective savings, not emphasizing that even high CCP may have low utility (if there is no cooling needs then even a high CCP represents zero savings). Furthermore, the CCP was computed regardless of any building properties, such as internal gains, cooling demand, thermal inertia and insulation. Finally, the CCP was computed for night cooling only, neglecting some eventual day time potential that may be useful.

Another study in that direction was developed by Belarbi et al [29]. These authors suggested two approaches in order to evaluate the passive cooling potential. The first one is independent of any building characteristics, and the second is based on thermal simulation of the building. Both methodologies provide helpful information on the viability of the passive cooling techniques, however, the first only characterizes the "effectiveness" of a certain passive cooling system relatively to different climatic zones. The second approach allows a more detailed view, nevertheless, it requires expertise and detailed knowledge on thermal simulation software and of the building properties. A more recent study by V.I. Hanby et al [30] used UK climate projections (UKCP09) to access the wet-bulb depression and the effects of climate change on the performance of evaporative cooling systems. They simulated a simplified single zone building model combined with an evaporative cooling plant. The results provided by simulations showed that the evaporative cooling plant was able to decrease the cooling demand, however this decrease was lower than the one provided by the meteorological evaporative potential. Nevertheless, it was concluded that the evaporative cooling systems are a viable solution for cooling buildings presently and in the context of a changing climate. Although, this study showed a comparison between the potential provided by the weather data and the simulated building, no relation between savings and potential was established. Additionally, the evaporative cooling potential was simulated only for the summer period (taken as April to September) and for the occupation hours (07:00 to 19:00), neglecting some eventual potential, mostly during night, which might be used to take advantage of the building´s thermal inertia decreasing the cooling loads on the day after.

A.T.Nguyen et al [31] presented a method to assess the thermal comfort using passive systems (natural ventilation and passive cooling). This method was applied for the hot humid climate of Vietnam, and it relies on the selection of an appropriate comfort zone on a building psychometric chart, the extraction of data from the chart and printing, and on the analysis and assessment of thermal comfort, heating and cooling potential of passive strategies. It is a helpful tool for a quick assessment of the availability of thermal comfort by way of passive systems. Regardless of the simplicity of the method and its applicability do different climates, the results only express the potential percentage of time within thermal comfort that can be achieved in a certain climate using some passive systems, not relating it with savings in energy demand. Furthermore, in the referred study the method was not validated against simulations or in situ measurements, which raises questions regarding its effectiveness.

1.2 Objectives

The main goal of this paper is to develop and test a performance indicator for passive cooling systems based on ventilation. This indicator, to be called climatic cooling potential, should be sufficiently robust to allow the estimation of the potential savings in cooling demand of buildings, without need for integrated building-system simulation. The fundamental outcome of such an indicator is, for ongoing work, to allow the characterization of the diverse cooling techniques on a large geographical area (some hundreds of km) and a large time horizon (some decades, including future climate change scenarios), for which overall building simulation becomes computationally unaffordable, due of the many possible architectural and operational configurations. In this sense, the objective of the climatic cooling potential is not to replace integrated building simulation, which will give finer results, but to allow for rough estimation of the potential of the aforementioned cooling techniques on a large geo-referenced spatial and temporal scale.

For this purpose, we will develop a method which allows: i) to characterize the diverse passive cooling techniques linked to ventilation in a coherent way, independently of any building, in terms of output temperature and associated airflow; ii) in a second step, to evaluate their effective contribution in terms of thermal energy savings for a particular building, as characterized by its cooling demand in absence of passive cooling. In this respect, one of the crucial points is to determine the temporal precision at which the cooling sources (and separately the building cooling demand) have to be characterized. For this sake, the simplified method developed hereafter will be validated against integrated building simulation, for the case of an administrative building located in Geneva, for an important set of passive cooling techniques, as well as a variety of constructive and operational configurations (solar protection, thermal mass and insulation, internal gains).

This paper is organized as follows. In Section 2 we present the studied cooling passive systems, as well as their physical properties and a brief reference to related analytical models. Section 3 is devoted to the description of the proposed method, which allows the computation of the climatic cooling potential and the associated cooling demand saving. For the sake of validation, in Section 4 the method will be compared to integrated building-system simulations. Section 5 shows a brief description on the behavior (provided by integrated simulation) of some of the passive systems, followed by the results and validation of the proposed method. Finally, the main conclusions of the present study are presented in section 6.

2. Passive cooling with ventilation

2.1 System description

As an alternative to direct ventilation, for which the available cooling temperature is given by the outdoor condition, we will consider two types of passive cooling systems based on thermal storage of the meteorological day/night oscillation that is carried by ventilation (figure 1). The first concerns air-soil heat exchangers, in which the air passes through an array of pipes buried under or next to the building, for the meteorological day/night oscillation to be dampened by charge/discharge in the soil. Previous work allowed for the analysis of several case studies, as well as for development of well validated numerical and analytical models [18, 19, 26, 27]. As the daily heat wave propagation around the pipes extends on approximately 15-20 cm, latter can be arranged in a compact geometry, with inter-axial distance of approximately 50 cm, immediately under the building, if necessary in multiple layers. Although such systems may in principle also be designed for dampening of the summer/winter oscillation, the associated size (approx. 2 m depth and 4 m inter-axial distance) generally turns out incompatible with the available soil, at least in urban context and for buildings of a certain size.

As a second storage technique, we will consider controlled thermal phase-shifting, a device in which the storage material is homogeneously distributed within the ventilating duct, in order to increase the heat-transfer surface and to decrease the penetration distance to the thermal mass. Providing a homogeneous airflow and a good convective exchange, it becomes possible to delay the day/night oscillation almost without dampening, for the night cooling peak to be available in the middle of the day. This technique, which arises from a theoretical work, recently gave rise to the development of a first series of lab prototypes [32].

As an optional downstream complement to preceding techniques (or to direct ventilation), we will finally consider direct evaporative cooling, for further decrease of the air temperature brought to the building by ventilation.

2.2 Models

Within this study, modeling of the thermal storage systems (buried pipes, thermal phase-shifting) is performed by way of previously developed and validated analytical models, for a constant airflow. In the case of buried pipes [27], a set of two coupled differential equations account for the convective heat exchange between air and pipe, as well as cylindrical heat diffusion in the soil around the pipe, with adiabatic boundary condition at inter-axial pipe-pipe distance. In the case of the phase-shifting device [32], the physical phenomenon under consideration takes place in a thermal storage similar to a packed-bed, with storage elements sufficiently small for their individual temperature to be regarded as homogeneous (no intra-element temperature gradient), leading to a simplified set of differential equations known as the Schuman model.

In both cases, the core of the model concerns the case of a sinusoidal temperature input:

$$T\Big|_{x=0} = \theta_0 \cos(\omega t) \qquad \text{(Eq. 1)}$$

Explicit resolution of the associated set of differential equations leads to following temperature output, which is characterized by amplitude-dampening and phase-shifting of the input signal:

$$T = \theta_0 \cdot \exp\left(-\frac{S\,h}{c_a \dot{m}_a}\right) \cdot \cos\left(\omega(t - \frac{x}{v_a}) - \frac{S\,k}{c_a \dot{m}_a}\right) \qquad \text{(Eq. 2)}$$

In preceding equations, $\dot{m}_a$ (kg/s) and v_a (m/s) are the airflow rate and velocity, and c_a (J/kg.K) the specific heat of air.

In the case of the buried pipes $S = 2\pi r_0 x$ is the pipe exchange surface, with r_0 (m) its radius and x (m) its length. The amplitude-dampening and phase-shifting coefficients h (W/K.m^2) and k (W/K.m^2) account for the serial link of (i) convective heat exchange between air and pipe; (ii) heat diffusion in the soil around the pipe. They are given by decomposition in real and imaginary part of:

$$\frac{h_0 h_s}{h_0 + h_s} = h + ik \qquad \text{(Eq 3a)}$$

Where:

$$h_s = \frac{\lambda_s}{\delta} \cdot (1+i) \cdot (-1) \cdot \frac{I_1\left((1+i)\frac{r_0}{\delta}\right) \cdot K_1\left((1+i)\frac{R_0}{\delta}\right) - K_1\left((1+i)\frac{r_0}{\delta}\right) \cdot I_1\left((1+i)\frac{R_0}{\delta}\right)}{I_0\left((1+i)\frac{r_0}{\delta}\right) \cdot K_1\left((1+i)\frac{R_0}{\delta}\right) + K_0\left((1+i)\frac{r_0}{\delta}\right) \cdot I_1\left((1+i)\frac{R_0}{\delta}\right)} \qquad \text{(Eq. 3b)}$$

$$\delta = \sqrt{\frac{2a_s}{\omega}} \qquad \text{(Eq. 3c)}$$

In preceding equations h_0 (W/K.m^2) is the air-pipe convective exchange coefficient, λ_s (W/K.m) and a_s (m^2/s) are the thermal conductivity and diffusivity of the soil, r_0 (m) is the pipe radius and R_0 (m) the total pipe and soil radius (half of the inter-axial distance between the pipes). I_n and $K_n$are modified Bessel functions of order n.

In the case of the phase-shifting device, *S* represents the total exchange surface of the particles over the system length *x*. In this case, the amplitude-dampening and phase-shifting coefficients *h* (W/K.m^2) and *k* (W/K.m^2) account for the serial link of (i) convective heat exchange between air and pipe; (ii) heat storage in the particles. They are given by:

$$h = \frac{h_0 k_s^2}{h_0^2 + k_s^2} \qquad \text{(Eq. 4a)}$$

$$k = \frac{h_0^2 k_s}{h_0^2 + k_s^2} \qquad \text{(Eq. 4b)}$$

$$k_s = \frac{\omega c_s \rho_s V_s}{S_s} \qquad \text{(Eq. 4c)}$$

In preceding equations h_0 (W/K.m^2) is the air-particle convective exchange coefficient, V_s (m^3), S_s (m^2), c_s (J/K.m^3) and ρ_s (kg/m^3) are the volume, exchange surface, specific heat and density of the storage particles.

For the case of hourly meteorological data over an entire year, Fourier analysis allows to decompose the input temperature into a complete sum of harmonics (from yearly up to hourly frequency), so that the hourly system output temperature can be recomposed by applying preceding models to each one of the harmonics.

Finally, as a complement to these storage techniques (or to direct ventilation from outdoor), evaporative cooling is modelled by:

$$T = T_{in} + \eta\left(T_{wet} - T_{in}\right) \qquad \text{(Eq. 5)}$$

In preceding equation T_{in} is the input temperature of the evaporative cooling device (given by outdoor, buried pipe or phase-shifting), T_{wet} is the associated wet-bulb temperature, and η the evaporative cooling efficiency.

In the following, the results of these models will be used: (i) for determination of the climatic cooling potential of these techniques, independently of any building (section 3); (ii) as an input to building simulation, for determination of the effective savings in cooling demand (section 4).

2.3 System configuration

In the case of buried pipes, we will here adopt a configuration which consists of 12 cm diameter pipes with 50 cm inter-axial distance, for a specific airflow of 100 m^3/h per pipe (2.5 m/s). According to the model, with such a configuration and a typical soil (1.9 W/K.m conductivity, 1.9 MJ/K.m^3 heat capacity) a 10 m pipe reduces the day/night input amplitude to 41%, whereas a 20 m pipe reduces it to 17% (exponential damping), with a phase-shift which remains lower than an hour (figure 2b).

In the case of the thermal phase-shifting device, we will here adopt a configuration which consists of 16 mm diameter PVC tubes that are filled with water, piled up perpendicular to the airflow, with 2 mm spacing between tubes. With a duct cross-section of 50 x 50 cm subject to a specific flow of 100 m^3/h (0.39 m/s average interstitial velocity between tubes), the system enables an 8 h phase-shift within 1.6 m length, respectively a 12 h phase-shift within 2.4 m (linear phase-shifting), for a residual amplitude higher than 80% (figure 2c). Note that his system not only differs from the buried pipes in terms of thermal behavior, but also in storage volume, which is almost 10 times inferior.

As can be seen in figure 2 b and c, the outlet of the thermal storage systems is at times warmer than the ambient air, in particular at night. It hence becomes interesting to combine the use of the aforementioned storage systems with direct ventilation, taking at each moment the cooler of the two sources (however, such a setup requires a second ventilation fan, since the thermal storage needs to be regenerated at night). We hence will consider following passive cooling systems/configurations, as schematically depicted in figure 1:

- Direct: direct ventilation from outdoor
- Pipe10m: 10 m buried pipes, resulting in 41% residual amplitude of day/night oscillation
- Pipe20m: 20 m buried pipes, resulting in 17% residual amplitude of day/night oscillation
- Shift8h: 8h thermal phase-shifting device
- Shift12h: 12h thermal phase-shifting device
- Pipe10m&Direct: combination of 10 m buried pipes with direct ventilation
- Pipe20m&Direct: combination of 20 m buried pipes with direct ventilation

- Shift8h&Direct: combination of 8 h phase-shifting with direct ventilation
- Shift12h&Direct: combination of 12 h phase-shifting with direct ventilation

We finally consider direct evaporative cooling as an optional complement to the preceding techniques (dashed box in figure 1), which will be simulated with a constant efficiency of 50% (humidification up to 50% of the potential, as given by the difference between dry and wet bulb temperatures). As a result, we end up with 18 possible passive cooling systems (9 combinations of thermal storage and direct ventilation, with or without evaporative cooling). For a representative set of these systems, figure 2 shows the simulated temperature dynamic over a hot summer week, as simulated with meteorological data of Geneva.

2.4 Ventilation rate, control and system size

Like for direct night ventilation, in which the airflow may be increased at night to bring fresh air into the building, we can consider the preceding systems with a larger airflow rate than the strict minimum air-change value, as long as the system output temperature is lower than the one of the building. So as to maintain the same system performance (same output temperature), such increased ventilation strategies obviously imply proportional sizing of the evaporative cooling unit as well as of the storage device (buried pipe, phase shifter). Such increased ventilation strategies also imply electric overconsumption, which is to be kept as low as possible. While we will limit our study to the thermal contribution of such systems, we stress that the problem of electricity should eventually be studied carefully.

3. Climatic cooling potential and energy savings in buildings

While, for a given climate, the passive cooling systems can be simulated and characterized independently of any building, their effect on the cooling demand of a particular building must in principle be determined by way of integrated dynamic building´s simulation (with ventilation temperature given by the associated passive cooling system). As an alternative, we here develop a simplified method for assessing these energy savings from the knowledge of: i) the characteristic of the passive cooling system, in terms of a climatic cooling potential (CCP) which relates to the temperature of the cooling source and the associated airflow; ii) the characteristic of the building, merely and alone in terms of its cooling demand (Q_{cool}) in absence of passive cooling. Comparison of both values on an appropriate time step leads to the useful cooling potential (UCP) of the passive cooling system for the specific building. The method, which is developed below, is schematically depicted on following flowchart (figure 3).

The first step, for a given passive cooling system and associated airflow, is to define its climatic hourly cooling potential (CCP), which expresses the cooling load that the system can bring to a building as compared with ventilation at standard reference flow rate from outdoor:

$$CCP = cm(T_{set} - T_{vnt}) - cm_{ref}(T_{set} - T_{ext})$$
$$m = \begin{cases} m_{vnt} & if \;\; T_{vnt} < T_{bld} \\ m_{ref} & if \;\; T_{vnt} \geq T_{bld} \end{cases} \quad \text{(Eq.6)}$$

In equation 6: CCP is the climatic cooling potential for a given hour, in kWh; c is the heat capacity of air in kWh/K.kg; m and m_{ref} are the rate of ventilation and the reference rate of ventilation in absence of passive cooling, respectively, both in kg/h; T_{set} is the building´s set point temperature in °C; T_{vnt} is the hourly average output temperature of a given passive cooling system in a given hour, in °C; T_{ext} is the hourly average outdoor temperature in a given hour, in °C; m_{vnt} is rate of ventilation for a given passive cooling system, in kg/h; T_{bld} is the building´s hourly average temperature in a given hour, in °C.

Note that the CCP is computed by using T_{set} (typically 26°C) instead of the effective building temperature, of which there is no prior knowledge (see discussion further down). It is in this sense that CCP represents a climatic index (dependent on the climate under consideration, the passive cooling system and the flow rate, as well as the comfort set point), independently of any building´s characteristics.

As discussed before, the enhanced flow rate m_{vnt} is reduced to the reference value m_{ref} when its temperature exceeds that of the set point. In this regard, the CCP can also be expressed by:

$$CCP = cm_{ref}(T_{ext} - T_{vnt}) + c(m_{vnt} - m_{ref})(T_{set} - T_{vnt})_{+} \quad \text{(Eq.7)}$$

In the latter expression, reduction of the airflow is taken into account by considering only the positive values of the second term. As compared to the reference case, the climatic cooling potential of the passive system hence divides in: i) a first term concerning the reference flow rate, which relates to the input – output temperature differential of the passive cooling system; ii) a second term concerning the additional flow rate, which relates to the set point – system temperature differential, and which is only active when the latter is positive. Note that for the particular case of direct night ventilation, where T_{vnt} equals T_{ext}, the first term reduces to zero, obviously indicating that in this case only increased flow rates can provide a cooling potential as compared to the reference case.

In a second step, for a particular building, the CCP is compared to the cooling load Q_{cool} in absence of passive cooling, which is needed for the building temperature not to rise above T_{set}. Since the CCP is a climatic index, it will at certain times be higher than the actual cooling load of the building (especially during winter season, but possibly also at certain periods of the summer, typically at night). We hence cut off the CCP to its corresponding value of Q_{cool}, over a selected integration time step (hourly, daily, weekly, monthly). Depending on the integration time step, we hence define the annual useful cooling potential (UCP) as follows:

$$UCP_{hourly} = \sum_{h=1}^{8760} MIN(CCP, Q_{cool})$$
$$UCP_{daily} = \sum_{d=1}^{365} MIN(\sum_{h=1}^{24} CCP, \sum_{h=1}^{24} Q_{cool}) \quad \text{(Eq.8)}$$
$$UCP_{weekly} = \sum_{w=1}^{52} MIN(\sum_{h=1}^{7\times24} CCP, \sum_{h=1}^{7\times24} Q_{cool})$$
$$UCP_{monthly} = \sum_{m=1}^{12} MIN(\sum_{h=1}^{30\times24} CCP, \sum_{h=1}^{30\times24} Q_{cool})$$

In equation 8, UCP stands for the annual useful cooling potential in kWh, and the subscripts h, d, w and m stand for hour, day, week and month, respectively. Qcool is the building´s hourly cooling demand at a given hour, in kWh. Note that in all four cases UCP is an annual value, which represents the global savings on cooling demand one might expect from a given passive cooling technique and associated airflow.

In principle, the suitable choice of the integration time step for comparing CCP and Qcool relates to the thermal inertia of the building. As a matter of fact, when there is no cooling demand from the building and a certain cooling potential is present, the latter can be stored into the building thermal mass for subsequent use, which is not taken into account by a too small integration time step. On the other hand, a too long time step might lead to overestimation of the passive cooling load that can effectively be absorbed by the building when there is no cooling need. Furthermore, storage of the passive cooling potential will result in lowering the building temperature, which tends to invalidate the use of T_{set} in the calculation of the CCP.

In practice, the choice of the integration time step for comparing CCP and Qcool will condition the resolution at which latter data should be available. In a particular case this might become a crucial point when trying to access such passive cooling techniques on a large spatiotemporal scale (some hundreds or thousands of km, some decades), where limitation of the data quantity becomes an important issue.

Figure 4 shows a schematic representation of the relation between CCP and UCP over a year, for different cooling demands and two different rates of ventilation (left and right). While CCP has its highest value in winter (left and right of time axes), when the $T_{set} – T_{vnt}$ differential is at its maximum, it does not correspond to any cooling demand and is therefore of no use. On the contrary, in summer, the cooling demand might exceed the available cooling potential, which cannot be entirely covered by the passive cooling system. This representation allows understanding the relation between cooling demand and airflow rate (and associated system size). While low flow rates allow 100% covering of low cooling demands only (Fig.4, left), their baseline contribution to higher cooling demands might still be of interest. In this respect it is worthwhile noticing that, with increasing cooling demand, the useful cooling potential UPC of the passive system tends to a maximum value, given by the total CCP over the cooling period. Differently, high flow rates (right part of figure 4) allow 100% of a wide range of cooling demands, obviously indicating system over sizing in the case of lower demands.

4. Integrated building simulation

In order to validate the proposed method, to characterize its robustness and its sensitivity to the integration time step, we will compare it to integrated dynamic building simulation (with ventilation temperature given by the associated passive cooling system).

We therefore reach back on a previous study [8] which focused on the potential of the various passive cooling techniques of section 2 for the case of an administrative building, located in the moderate climate of Geneva. This study analyses the simulated building cooling demand for a variety of constructive and operational configurations (thermal mass and insulation, window-to wall ratio, solar protection, internal gains), with a specific attention to normal versus a hot summer (as given by 2004 and 2003 urban meteorological data).

The building consists of 20 m^2 / 50 m^3 offices distributed on both sides of a broad central corridor. In terms of simulation, this typology results in a thermal model made up of three zones: two offices, on opposite facades separated by the central corridor, with lateral boundary conditions given by identical interior climate (neighbor offices). The parameters and options that govern the thermal behavior of the building are as follows:

- Thermal mass is mainly determined by 28 cm thick slabs, either in heavy option (full concrete: 510 kJ/K.m^2) or in medium option (combined wood structure with concrete filling: 350 kJ/K.m^2). In both cases, separation walls between offices add an additional 170 kJ/K.m^2 (relative to slab surface).
- Thermal insulation is either of low 1980's quality (6 cm, double glazing windows), or of high quality as given by the Swiss Minergie standard (20 cm, triple glazing insulating windows).
- Solar access is determined by an East-West orientation on a low 5° horizon, along with a 20%, 50% or 80% window-to-wall ratio.
- Efficient external solar protection is activated when direct radiation on the façade exceeds 10 W/m^2 (overall g-value: 13% with 1980 windows, 7% with Minergie windows). Alternatively, the building can also be simulated without solar protection (overall g value: 68% with 1980 windows, 42% with Minergie windows).
- Internal gains are 10, 20 or 35 W/m^2 (during occupation: 8-18 h) with a reduction at noon (see figure 7 top left: reduction of Qcool at noon due to lower occupation/internal gains).

The total combinations of the preceding parameters correspond to 72 building configurations, which are considered in the context of the 2 meteorological datasets (2003 and 2004), representing a total of 144 reference cases (without passive cooling). For all of these reference cases, the ventilation from outdoor during occupation is 72 m^3/h per office(approximately 1.5ach – 1.5 air changes per hour), dropping at night to 6 m^3/h (0.1 ach).

So as to investigate the impact of the passive cooling systems on the thermal behavior of the referred buildings and so as to validate the model defined in section 3, all preceding reference cases were also simulated in combination with the 18 passive cooling systems presented in section 2. Finally, associated to these systems, 3 possible controlled flow rates (and associated system sizes) are considered:

- Same nominal rate as for reference cases (72 m^3/h ≅ 1.5 ach), however also activated at night if the ventilation temperature is cooler than the building.
- Twice the reference rate (144 m^3/h ≅ 3 ach), activated as long as the ventilation temperature is cooler than the building (else reduced to the reference flow).
- Four times the reference rate (288 m^3/h ≅ 6 ach), activated according to the same rule.

In this way, we study 54 passive cooling configurations (18 systems in combination with 3 flow rates).

Altogether, the 54 passive cooling configurations associated to the 72 building and 2 weather data sets represent a total of 7776 (54x72x2=7776) integrated system cases, as schematically represented in Figure 5.

Simulation over the summer period (May-September) is carried out in two steps, with an automated overall approach:

For both the meteorological data sets, the passive cooling systems are simulated by way of the specific analytical models developed previously described in section 2, yielding hourly data over an entire year. System control and building response are then simulated within TRNSYS [33].

5. Results and discussion

5.1 Effective savings

Before exploring the simplified UCP method developed in section 3, we start by giving a synthetic overview of the effective savings in cooling demand, as obtained by numerical simulations. Focus is set on direct ventilation, 12h phase shifting and combination of both, each being associated or not with evaporative cooling. Each of the 6 systems is associated with the 3 possible airflow rates (with corresponding system size) and the two meteorological data sets.

In figure 6, each symbol represents the overall annual simulation result for one of the 144 reference cases referred above. The value on the x-axis corresponds to the cooling demand of the particular configuration in absence of passive cooling (Q_{cool}, reference cases), while the value on the y-axis (ΔQcool) corresponds to the savings in cooling demand when using the passive cooling system. The general structure of these plots illustrates the discussion held in section 3: while a low flow rate (small system) allows 100% covering of low cooling demands, it only covers a fraction of higher demands, where its contribution is eventually limited to a maximum value given by the available cooling potential over the entire cooling season. On the left side of the plots (especially in the case of evaporative cooling), the similar contribution of the different flow rates shows that limited cooling can be completely covered with small systems.

A comparison between the different systems brings about the following general insights:

- As compared to direct ventilation, standalone thermal phase shifting carries only small additional annual savings in cooling demand (15% in average over all buildings and years). The basic reason therefore relates to the fact that the systems works on storage of the day-night temperature oscillation, a function which can basically also be achieved by the building if it has enough thermal inertia.
- In this regard, combination of phase-shifting with direct night ventilation, which takes advantage of the night cooling peak "twice a day", allows an average of 58% additional savings (with relatively important variations from case to case, depending in particular on the airflow rate and the meteorological year under consideration).
- Finally, at least in the particular case of Geneva, direct evaporative cooling brings about an important potential, even for buildings with important cooling demand. Furthermore, the discrepancy between the standard summer of 2004 and the hot summer of 2003 is reduced, due to relatively similar water content of the air (similar wet bulb temperature).

A more detailed discussion on these points can be found in the specific publication concerning the numerical study [8].

5.2 Dynamic over a typical week

The relation between the simulated savings and the simplified UCP method will now be illustrated for a specific building (50% window-to-wall ratio, external solar protection, 35 W/m^2 internal gains, Minergie standard thermal insulation), and a hot summer (2003). The 3 passive cooling systems are those of section 5.1, without evaporative cooling.

Figure 7 shows the hourly evolution of the outdoor, indoor, and ventilation temperatures, as well as the ventilation flow rate and resulting cooling demand over a typical summer week.

In the reference case, ventilation at standard 1.5 ach (72 m^3/h) flow rate is activated during occupation (8 - 18h). During this period, internal gains (and to minor extent outdoor temperature and solar radiation) result in a significant cooling demand (up to 42 W/m^2 on day 5), which drops when internal gains are reduced (at noon) or null (during the week end, day 6 and 7). As a first alternative, direct cooling from outdoor with 3 ach (144 m^3/h) allows to store the freshness of the night in the building, resulting in a lower cooling demand during the following day. Note that when the outdoor temperature rises above that of the building (in particular during occupation/daytime), the flow rate is reduced to its reference value; on the contrary, when the outdoor temperature remains below that of the building (day 2), enhanced ventilation can extend over 24h. As a second alternative, by inverting the day/night oscillation, the 12h phase-shifting device allows for enhanced ventilation and corresponding passive cooling during daytime, resulting in a further reduction of the cooling demand, and particularly of the peak load. Finally, combination of phase-shifting and direct ventilation allows for almost constant over-ventilation with "fresh" air, and hence for a further reduced cooling demand.

Figure 8 allows comparison of the climatic potential (CCP), which is calculated from mere knowledge of the reference flow rate and set point temperatures (equation 6 or 7), with the effective savings in cooling demand which result from simulation. In the case of direct ventilation from ambient, the effective savings occurring during daytime are of the same order of magnitude as the CCP, which is available during night time, illustrating the effect of the building´s thermal inertia. On the contrary, in the case of 12h phase-shifting the CCP synchronizes fairly well with the demand and hence with the savings. In this particular case we also note a short negative value in energy saving and CCP in the morning when the temperature of the phase-shifting device: i) is lower than the building, enabling for enhanced ventilation for cooling; ii) is still higher than outdoor, resulting for the reference flow rate in a lower cooling potential than with direct ventilation (see equation 7). As a last alternative, combination of phase-shifting and direct ventilation results in a CCP available twice a day, which induces increased savings as compared to preceding alternatives.

Table 1 presents the results of the 3 systems as integrated over the entire summer (May – September): i) the reference cooling demand and the effective savings, as given by simulation; ii) the climatic cooling potential and the useful cooling potential, as calculated via equation 8, as well as the relative error in relation to the effective saving.

In the case of direct ventilation, numerical simulation yields 13.0 kWh/m^2 savings as related to 31.7 kWh/m^2 demand for the reference case. UCP correlates quite unfairly with these savings when calculated on an hourly basis (63% underestimation). This is due to the fact that the CCP and cooling demand take place at different moments and do only correlate via the building inertia, which is not taken into account by the UCP calculation. The best correlation with the effective savings is obtained when the UCP is calculated on a daily basis (8% over estimation), but reasonable values are also obtained on weekly or monthly basis. In the case of 12h phase-shifting, the effective savings amount to 15.5 kWh/m^2. This value is again underestimated with a UCP calculated on hourly basis, indicating a remaining mismatch between hourly CCP and demand. Very good values are however obtained with higher integration time steps (around 5% error in each case). Finally, similar results are obtained for the combination of phase-shifting with direct ventilation. It is worthwhile mentioning that, in all cases, the UCP method gives a much better estimation of the effective savings than the previously developed CCP method, which does not take into account the building demand.

5.3 Simplified method versus numerical simulation

The previous analysis is finally carried out for all the combinations of the 72 buildings, 2 weather data sets, 3 airflow rates and 18 passive cooling systems, presented in section 5.1. For each configuration, the relation between the effective savings and the corresponding UCP over the entire period (May – September) is presented in Figure 9 (one symbol per configuration in each plot).

As pointed out in section 3, and as discussed for a particular case in section 5.2, calculation of the UCP on an hourly basis underestimates the effective savings by an average of 31% (as given by linear regression), due to the fact that the building´s thermal inertia is not taken into account. In comparison, calculation of the UCP on a daily basis reproduces the effective savings with less than 1% error in average. Calculation on a weekly or monthly basis tends on its turn to overestimate the effective savings (average of 6% and 11%), due to overestimation of the available thermal inertia.

These average correlations vary according to the passive cooling system (table 2). As pointed out before, the worst correlation goes for direct ventilation from ambient (without evaporative cooling), for which the daily UCP calculation leads to an average 47% underestimation, and the monthly UCP to an average 31% overestimation. All other systems remain, in average, within the 7% error in daily calculation, respectively within the 23% error in monthly calculation.

The dispersion in relation to these average values will now be analyzed for the particular case of daily and monthly calculation of the UCP. In a first step, the analysis concerns the error of the UCP method relatively to effective savings ΔQ_{cool} given by simulation. In daily basis, the absolute difference between UCP and effective savings ΔQ_{cool} never exceeds 6.8 kWh/m^2, and in half of the cases (2nd and 3rd quartiles of each class) this difference remains below 2.7 kWh/m^2. The dispersion is relatively uniform across the different classes. As a consequence, the relative error (figure 10) is much more important for low than for high values of ΔQ_{cool}: up to 38% error for effective savings in the range of 0-10 kWh/m^2 (although the error remains below 8% for the 2nd and 3rd quartiles), but always less than 10% for effective savings above 50 kWh/m^2 (below 4% for the 2nd and 3rd quartiles). In the case of calculation in a monthly basis, the dispersion is much more important, as well in terms of absolute error as in terms of relative error (with a maximum error of 140% in the range of 0-10 kWh/m^2).

However, depending on the importance of the reference cooling demand, a low value of effective savings may or not represent an important passive cooling fraction $\Delta Q_{cool}/Q_{cool}$ (see figure 6). As a consequence, preceding dispersion analysis is extended to the error of the UCP method relatively to the passive cooling fraction (figure 11). When calculated on a daily basis, the UCP method reproduces the passive cooling fraction very well. In extreme cases, an underestimation up to 20% may occur for high passive cooling fractions (in particular when related to low cooling demands, hence to low absolute savings), but in half of the cases (2nd and 3rd quartiles) the error remains below 6%. When computed on monthly basis, the UCP method tends to overestimate the passive cooling fraction. Hence, in extreme cases, the method indicates close to 100% coverage of the demand whereas the effective fraction only amounts to 30% (70% error). However, for half of the cases of each class (2nd and 3rd quartiles) the error remains below 20%.

6. Conclusions

We developed and tested a simplified method for computing the building´s cooling demand savings by use of passive cooling systems based on ventilation (direct ventilation, air-soil heat exchangers, controlled thermal phase-shifting, evaporative cooling, as well as possible combinations thereof).

The systems are characterized in terms of a climatic cooling potential, independently of any building. In a second step, the climatic cooling potential is compared to the cooling load of a particular building, yielding the associated useful cooling potential. Key point of the method is to choose an appropriate time resolution, for taking into account of the building thermal inertia.

The method is tested against an extensive numerical simulation campaign, combining diverse passive cooling systems and sizes with diverse constructive and operational modes for an administrative building situated in Geneva (7776 configurations). In a first step, correlation between the two methods is analyzed in terms of annual energy savings. Calculation of the useful cooling potential on an hourly basis underestimates the effective savings by an average of 31%, due to the fact that the building thermal inertia is not taken into account, while calculation of the useful cooling potential on a daily basis reproduces the effective savings with less than 1% error in average. Calculation on a weekly or monthly basis tends on its turn to overestimate the effective savings (average of 6% and 11%), due to overestimation of the available thermal inertia. The dispersion in relation to these average values is analyzed for the particular case of daily and monthly calculation basis. Focus is set on the passive cooling fraction (fraction of the demand which can be covered by the passive cooling system). It is shown that, if the data is available in monthly values, the model will tend to overestimate the passive cooling fraction. The error remains below 20% for half of the cases, although it may be quite more important (up to 70%) for extreme cases, in particular in cases where the model indicates close to 100% coverage and the associated cooling demand is low.

As a main result, the method can hence be used for setting up of a climatic potential database in monthly time step, for rough assessing of the potential of these passive cooling techniques on a large spatiotemporal scale (some hundreds or thousands of km, some decades). Much more precise results could be obtained with data in daily resolution (less than 6% error in half of the cases), which however would require setting up of a very extensive database of the climatic potential, as well as knowledge of the corresponding building cooling demand. In this respect, finer evaluation of a particular case should rather use integrated simulation of the passive cooling system and building in hourly time step. Finally, for additional insight, both methods (UCP and detailed numerical simulation) should further be compared to results from real scale installations.

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Figures

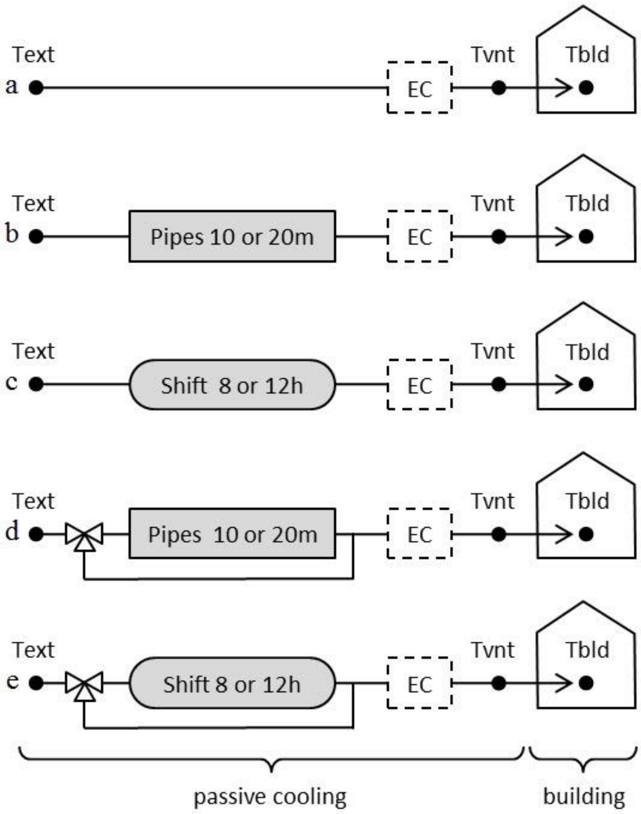

Figure 1: Schematic layout of passive cooling systems: (a) direct ventilation, (b-c) buried pipes and thermal phase-shifting, (d-e) buried pipes and thermal phase-shifting, combined with direct ventilation. All systems are considered with or without evaporative cooling (dashed box).

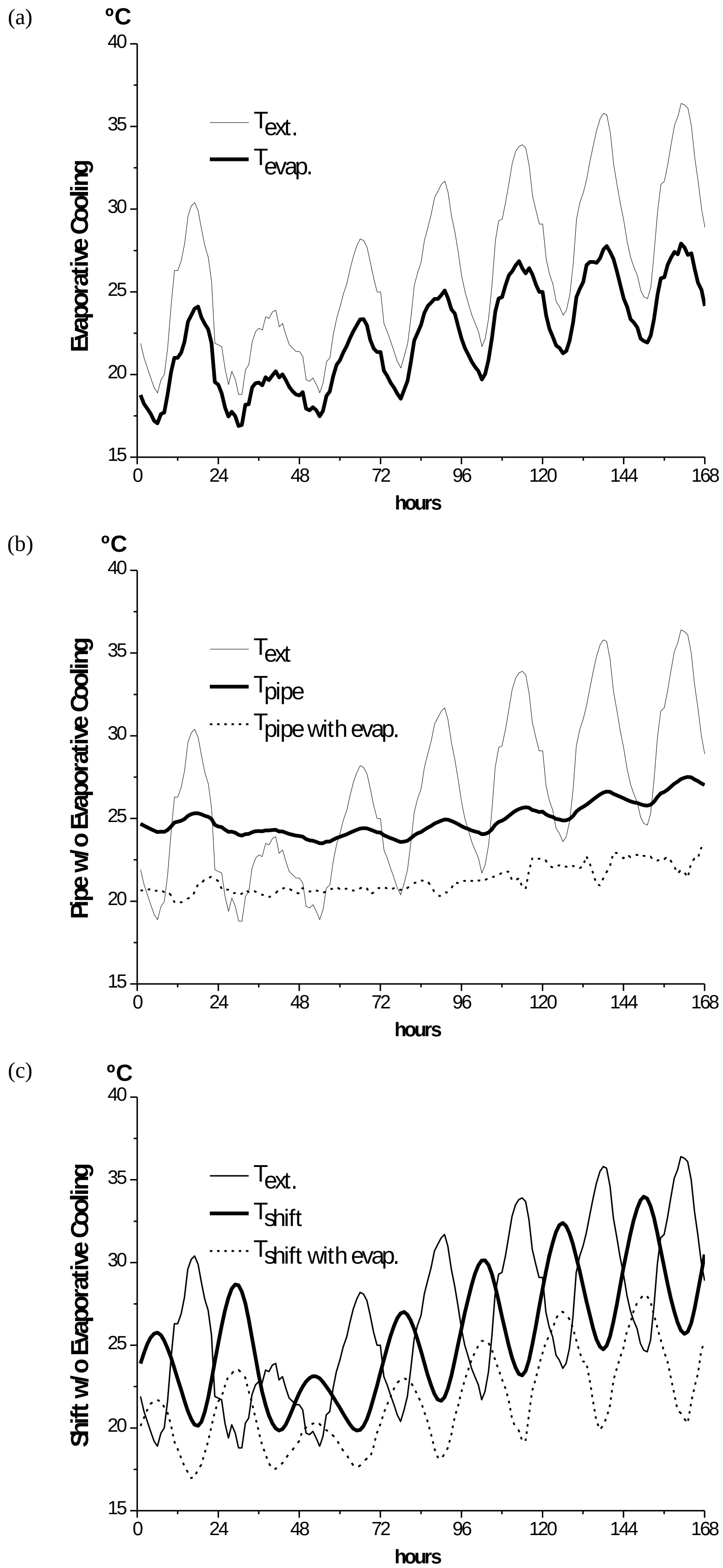

Figure 2: Simulated passive cooling systems on a hot summer week. External temperature and output temperatures for the different cooling systems: (a) evaporative cooling system (50% efficiency), (b) buried pipes system (20 m), with and without evaporative cooling, and (c) phase-shifter system (12 h), with and without evaporative cooling.

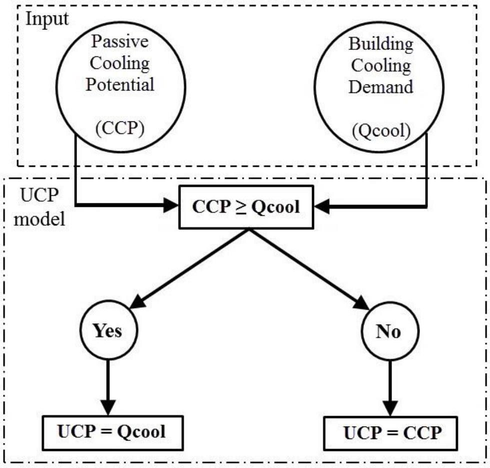

Figure 3: Schematic of UCP model.

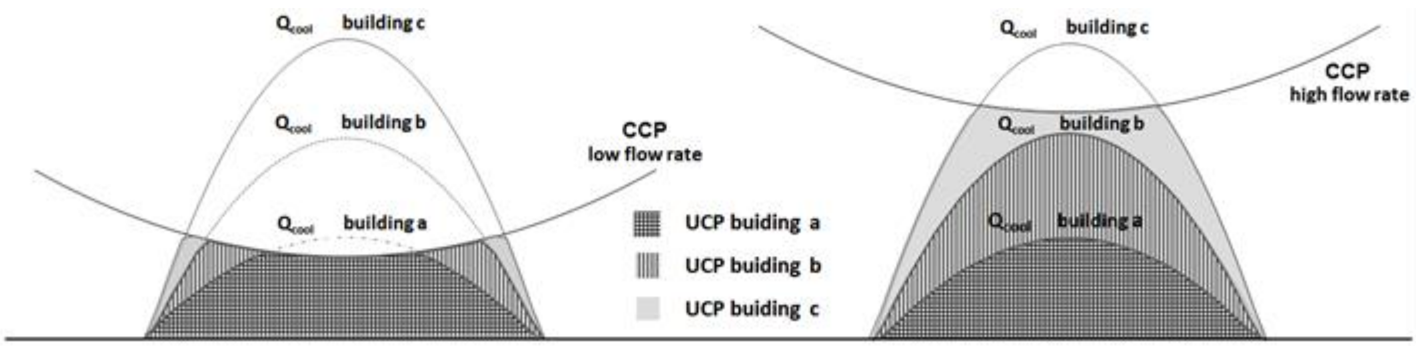

Figure 4: Schematic evolution and relation of climatic cooling potential (CCP) and useful cooling potential (UCP) over time, for 2 different rates of ventilation (left and right) and 3 different cooling demands.

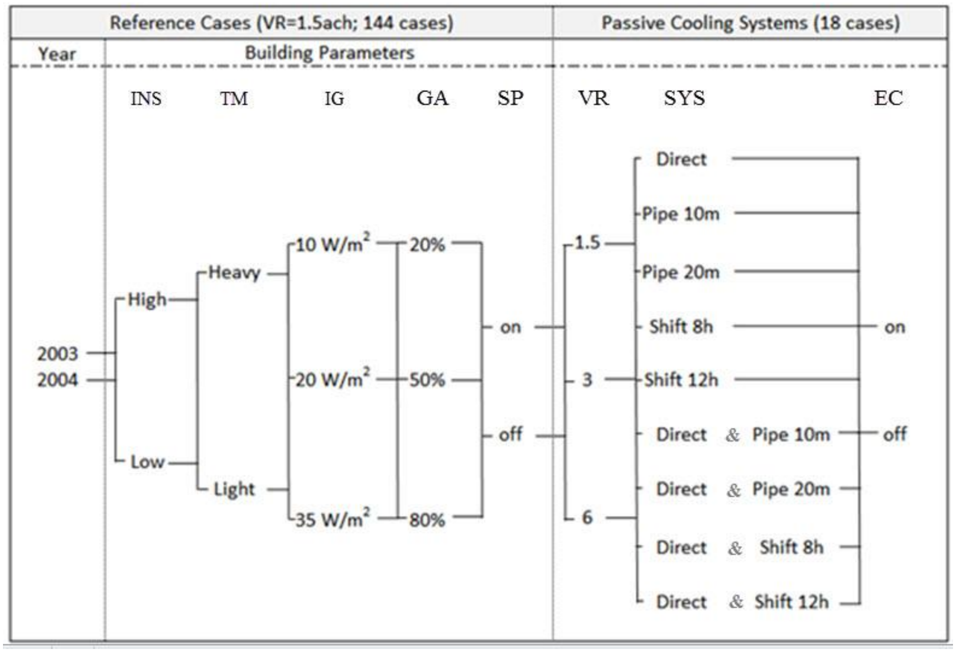

Figure 5: Overview of the 7776 simulated combinations: 2 weather data sets, 72 buildings, 18 passive cooling systems, 3 flow rates / system sizes (INS: insulation; TM: thermal Mass; IG: internal Gains; GA: glazing area; SP: solar protection; VR: ventilation rate;.SYS: passive cooling system; EC: evaporative cooling).

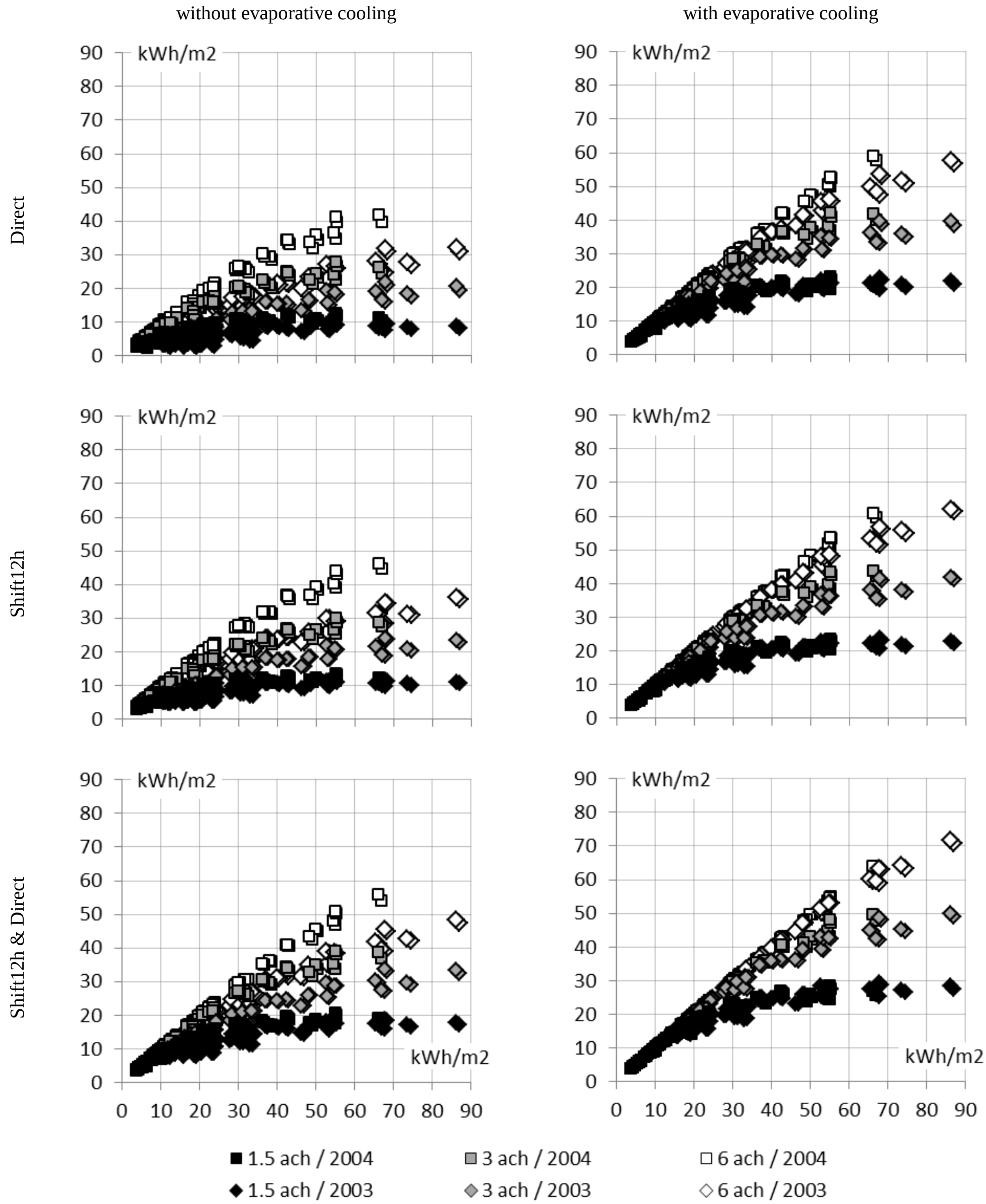

Figure 6: Savings in cooling demand (ΔQcool: vertical axis) in function of cooling demand in absence of passive cooling (Qcool: horizontal axis) for the 72 reference buildings and the 2 meteorological data sets (144 reference cases).

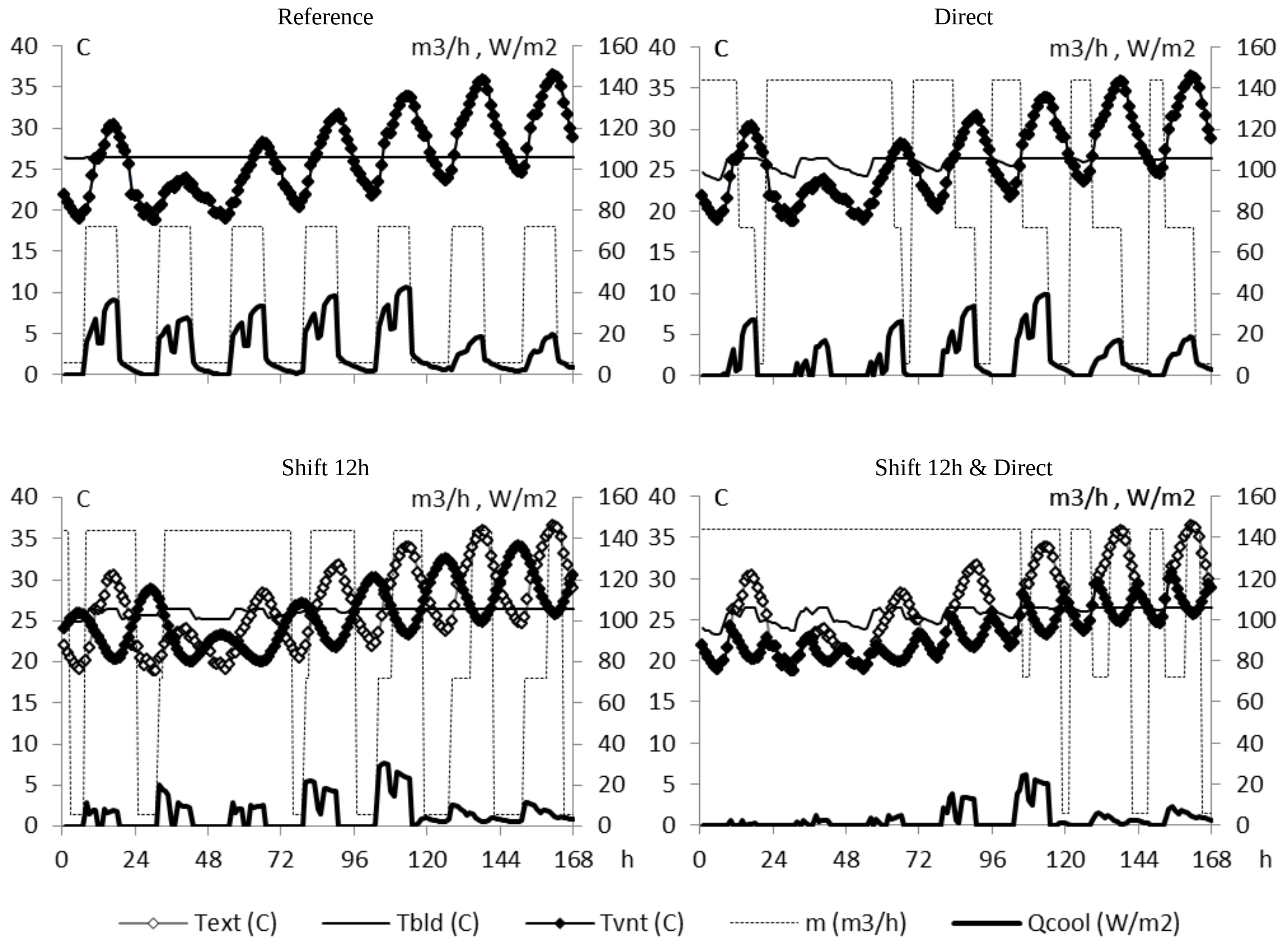

Figure 7: Outdoor, building and ventilation temperatures (Text, Tbld, Tvnt), as well as ventilation flow rate and resulting cooling demand (m and Qcool) over a typical summer week.

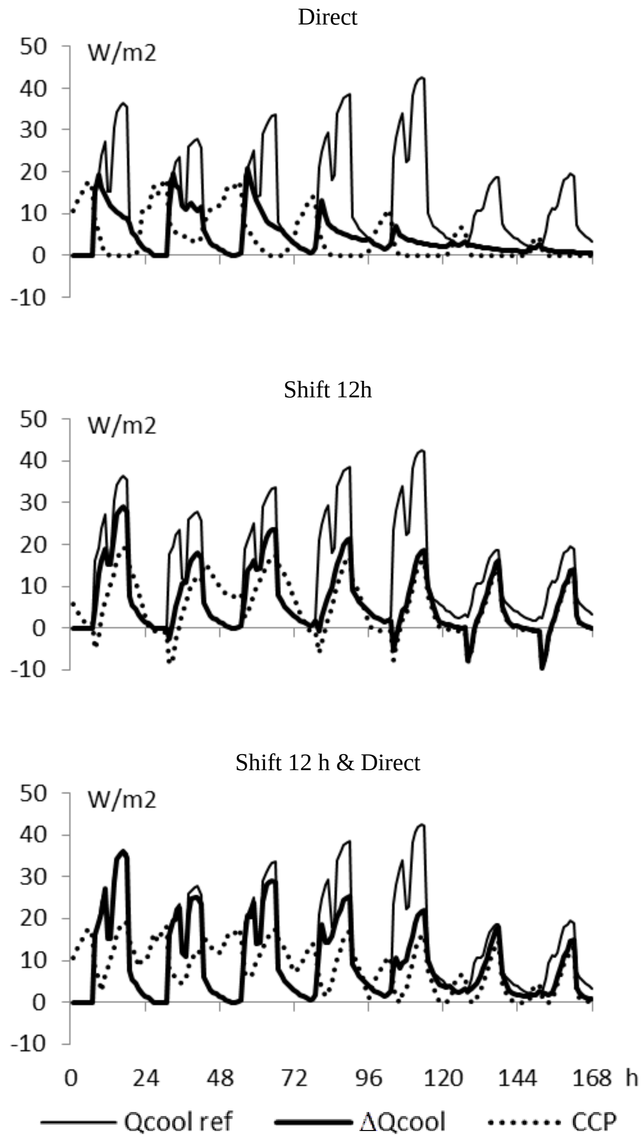

Figure 8: Climatic cooling potential (CCP) and effective savings in cooling demand (ΔQcool), as well as cooling demand of reference case (Qcool ref) over a typical summer week.

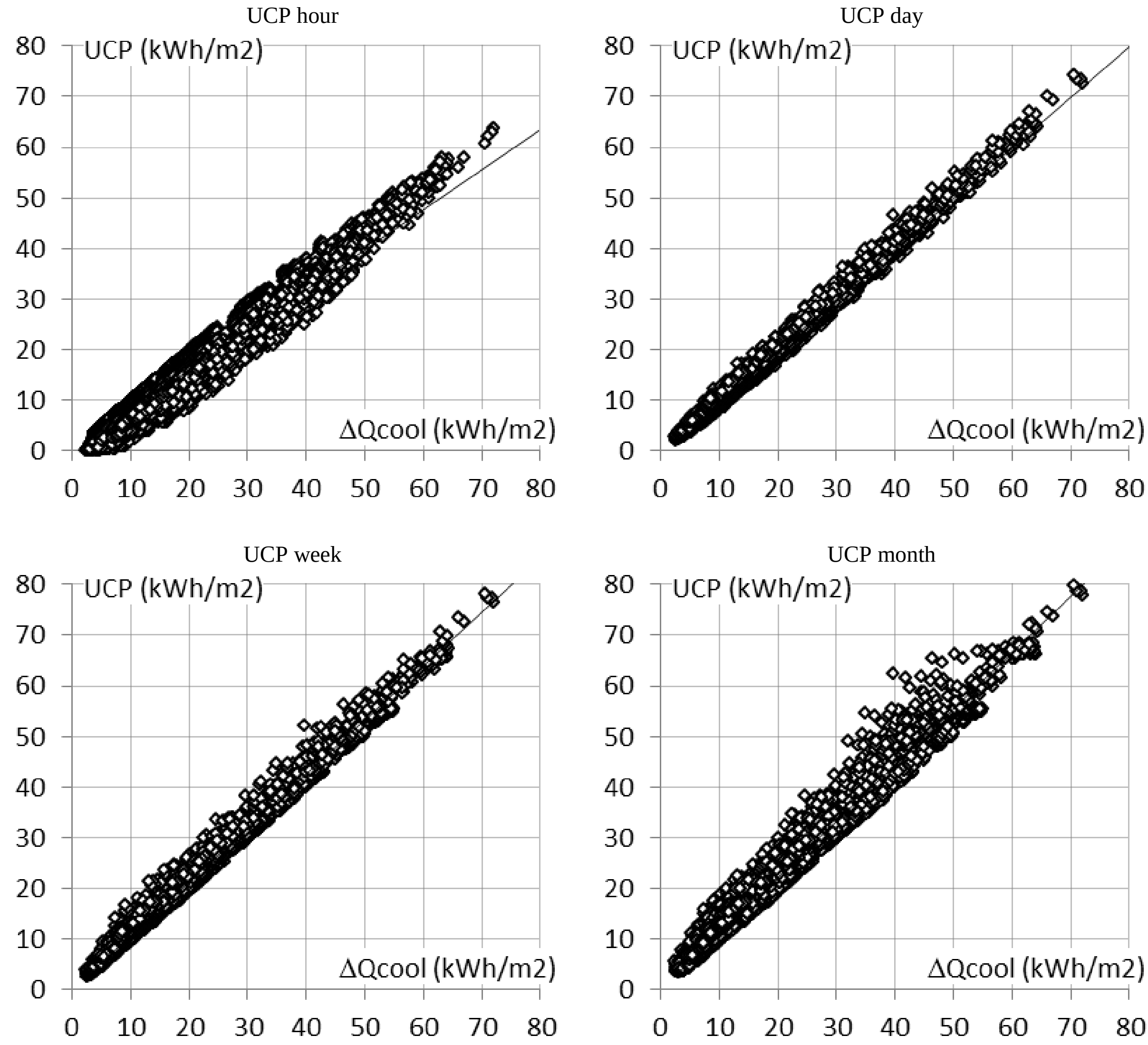

Figure 9: Useful cooling potential (UCP) versus effective savings ΔQcool, for the different passive cooling systems and buildings.

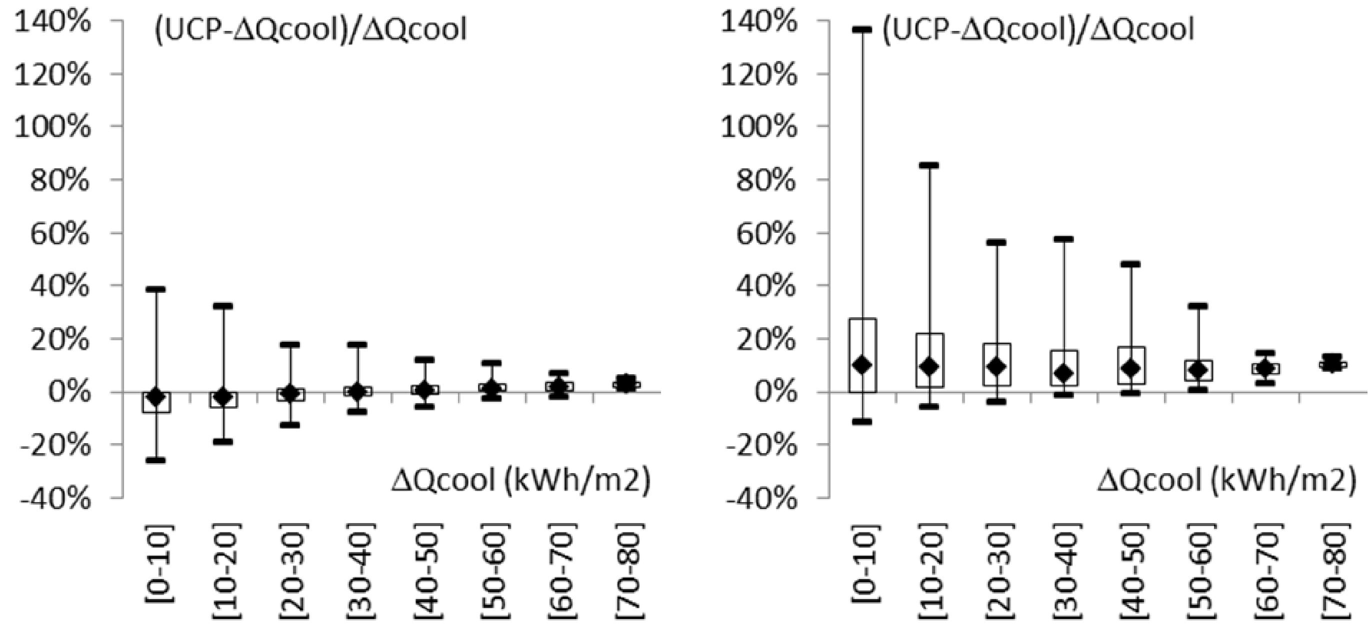

Figure 10: Relative error of the useful cooling potential (UCP) method (min, max, median, 2nd and 3rd quartiles), in daily and monthly basis, relatively to effective savings ΔQcool.

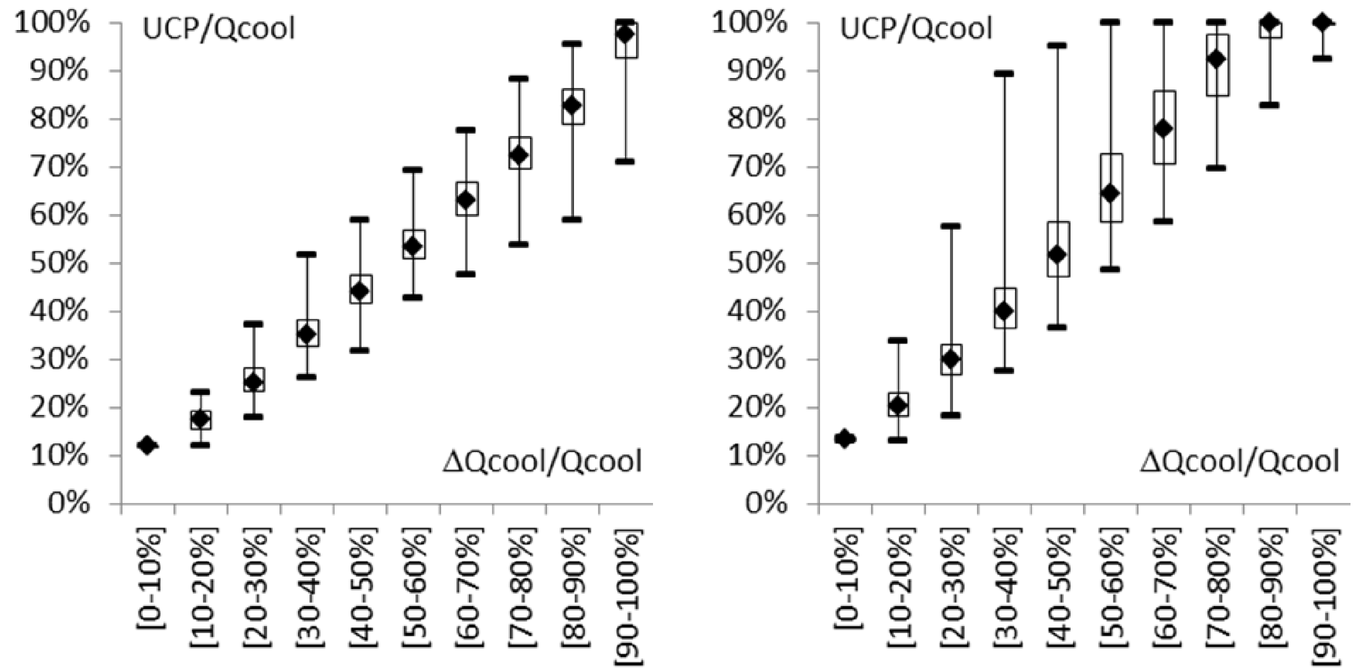

Figure 11: Relative error of the useful cooling potential (UCP) method (min, max, median, 2nd and 3rd quartiles), in daily and monthly basis, relatively to the passive cooling fraction ΔQcool/Qcool.

revised tables

Table 1: Integrated savings in cooling demand for 3 passive cooling systems: i) reference cooling demand and effective savings (Qcool and ΔQcool); ii) climatic and useful cooling potential (CCP and UCP), as well as relative error in relation to the effective savings.

	Direct	Shift12h	Shift12h & Direct
	kWh/m^2	kWh/m^2	kWh/m^2
Qcool	31.7	31.7	31.7
ΔQcool	13.0	15.5	20.9
CCP	33.2	33.7	49.3
UCP.hour	4.8	11.1	14.5
UCP.day	13.9	14.6	20.4
UCP.week	15.5	16.5	23.5
UCP.month	15.3	16.2	24.4
ΔUCP.hour	-63%	-28%	-31%
ΔUCP.day	8%	-6%	-3%
ΔUCP.week	19%	7%	12%
ΔUCP.month	18%	5%	17%

Table 2: Average correlation (linear regression) between useful cooling potential UCP and effective savings ΔQcool, for the different passive cooling systems, with and without evaporative cooling (Dry/Hum).

	UCP.hour		UCP.day		UCP.week		UCP.month	
	Dry	Hum	Dry	Hum	Dry	Hum	Dry	Hum
Direct	0.53	0.74	1.07	1.01	1.21	1.08	1.31	1.11
Pipe10m	0.70	0.81	1.03	1.00	1.13	1.05	1.23	1.08
Pipe10m & Direct	0.66	0.80	1.04	1.01	1.14	1.05	1.22	1.08
Pipe20m	0.76	0.83	1.02	1.00	1.09	1.04	1.19	1.07
Pipe20m & Direct	0.71	0.82	1.03	1.01	1.12	1.05	1.18	1.07
Shift8h	0.82	0.87	0.93	0.97	1.06	1.03	1.14	1.06
Shift8h & Direct	0.78	0.85	0.98	0.99	1.08	1.03	1.13	1.06
Shift12h	0.76	0.84	0.96	0.99	1.09	1.05	1.18	1.08
Shift12h & Direct	0.76	0.83	0.99	1.00	1.09	1.04	1.15	1.06
All systems	0.79		1.00		1.06		1.11	