

Large diameter earth-air heat exchanger (EAHX) built for standalone office room cooling: Monitoring results for hot and dry summer conditions

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Abstract. Earth-air heat exchangers (EAHX) use the soil thermal capacity to dampen the amplitude of outdoor air temperature oscillations. This effect can be used in hot and dry climates for room cooling and, depending on the EAHX design, this cooling can be achieved with very little resources other than those used during the EAHX construction. This is an obvious advantage compared to the significant energy consumption and operational costs of refrigeration machines traditionally used in room cooling. Despite the large number of papers on EAHX available in the scientific literature, very few deal with large diameter EAHX (with pipe diameters larger than 0.30 m), and even fewer present monitoring data gathered from a built and functional large diameter EAHX. The present paper uses monitoring data and provides a detailed quantitative analysis of the performance of a large diameter EAHX built for standalone cooling of an existing office building. The field monitoring was carried out during a characteristic hot and dry summer period of the south of Portugal. Results show that outdoor air to EAHX exit air temperature gradients reach 9 K and cooling capacities exceed 27 kW. Moreover, the studied EAHX is capable of standalone cooling for outdoor air temperatures up to 33°C and meets more than 50% of the room design cooling demand for outdoor air temperatures as high as 37°C. This evidences that large diameter EAHX have the potential to achieve significant reductions in CO₂ emissions and in energy consumption associated with building cooling in hot and dry climates.

Keywords. Earth-air heat exchanger (EAHX); Monitoring; Load removal; Room cooling; Office building

20 1 Introduction

Building operation accounts for approximately one third of the world's final energy consumption and also for approximately one third of the total energy sector CO₂ emissions (IEA, 2022a). Electricity use in buildings keeps increasing and, with an average annual growth of 4% since 2000 (IEA, 2022b), electricity demand for space cooling is rapidly gaining importance compared to the demand for
25 lighting, equipments or hot water production. The growth in electricity demand for space cooling is linked to the increased use of refrigeration machines—air-conditioning—which, beside increasing consumption, also affects peak electricity demand as a result of the simultaneous operation of air conditioners at full capacity during hot days.

To meet the Net Zero Emissions by 2050 Scenario (IEA, 2022c) the increase in electricity demand
30 for space cooling needs to be stopped; technologies complementary or alternative to the prevailing refrigeration machines, allowing a reduction of both electricity consumption and installed electric capacity for space cooling, should be researched and promoted. Earth-air heat exchangers (EAHX) is one such technology.

According to Santamouris (in Mihalakakou et al., 1997) and Ascione et al. (2011), for the Mediter-
35 ranean region, up to 100% of building cooling demand can be covered by EAHX coupled with appropriate building passive cooling techniques. In general, cooling demand reductions of 30% to 60% are commonly associated with the use of EAHX (Michalak, 2022; Lee and Strand, 2008; Al-Ajmi et al., 2006). These results reveal the extent of the savings in electricity consumption for cooling that could be achieved from a broader use of EAHX. This paper is concerned with the study of a
40 specific type of EAHX: large diameter EAHX. Monitoring data from a large diameter EAHX is used to assess standalone EAHX cooling (replacing a refrigeration machine) of an office building with hot and dry summer conditions.

Despite the large number of papers dealing with EAHX available in the scientific literature, the vast majority concerns EAHX with pipe diameters not exceeding 0.30 m. Smaller pipe diameters
45 are easier to handle, are less expensive and allow increased heat transfer coefficients (Ascione et al., 2011; Lee and Strand, 2008). However, pipe diameter is only one among many parameters influencing heat transfer in EAHX. Pipe length, pipe depth (below soil surface), pipe material, pipe layout and soil thermal properties are also crucial for EAHX performance and can compensate for the smaller heat transfer coefficients of large diameter pipes (see Hollmuller and Lachal, 2014).
50 Sensitivity studies by different authors conclude that the effect of pipe diameter changes in EAHX performance is lower than the effect of changes in pipe length, pipe depth (within a certain range) or airflow velocity (Lee and Strand, 2008; Kopecký, 2008; Hollmuller and Lachal, 2014). Moreover, smaller pipe diameters are not free from disadvantages. For a given airflow rate, pressure losses increase significantly as diameter decreases (Recknagel et al., 2009), incrementing substantially fan
55 installed capacity, fan electricity consumption and EAHX operational costs. Additionally, with increased airflow velocity a reduction in temperature gradient between pipe inflow and outflow takes

place (Lee and Strand, 2008) limiting EAHX use for standalone cooling. To avoid these disadvantages, especially when large ventilation rates are required—as in office building cooling—, compact arrays of small diameter pipes are often used (Blümel et al., 2001; Huber et al., 1996; Pfafferott, 60 2013; Zimmermann, 1999; Hollmuller and Lachal, 2014). However, since compact layouts interrupt the diffusion of heat (Hollmuller and Lachal, 2014), thermal saturation of the soil in the immediate vicinity of the pipes takes place with the consequent reduction in heat exchange with the soil.

An aspect seldom mentioned in EAHX research is related to maintenance. EAHX and the building it serves share the same life expectancy, which can reach 50 years. National and international standards ensuring hygienic condition of ventilation systems (e.g., VDI 6022:, 2018) mandate regular 65 inspections for detection and correction of biological hazards. Internal inspection of small diameter pipes using robots is common but correction of eventual problems (mostly caused by faults during construction and installation) is often difficult for buried pipes. Man-sized larger pipe diameters enabling access for inspection and correction of problems is, hence, a significant advantage 70 (Barnard and Jauzens, 2001). Indeed, maintenance and other non-heat-transfer related aspects, such as availability of unimpeded soil to bury the pipes, commercial availability of materials, contractors' familiarity with EAHX construction techniques and costs, are paramount to EAHX sizing and introduce practical constraints to optimal heat transfer in EAHX. Larger diameter pipes imply larger investments costs (materials and excavation), not only because of the diameter increase but also 75 for the larger pipe length and/or depth required to compensate the reduction in heat transfer; still, EAHX and building construction costs are seldom independent and, in the authors' experience, cost increments related to the use of larger pipe diameters can represent but a small fraction of the total building (systems included) costs¹. In this case, as important as costs is the ability to demonstrate the benefits/energy savings of EAHX, and this depends on experimental evidence. Monitoring results 80 for large pipe diameter EAHX (> 0.30 m) for room cooling are rare and found in association with hybrid EAHX allowing natural ventilation (Zhang and Haghghat, 2009; Ferrucci and Peron, 2018), or with tunnels whose objective is not room cooling (Liu et al., 2014; Xiangkui et al., 2019; Yang et al., 2021). This paper addresses this gap in research literature and uses monitoring data to assess the standalone cooling capacity of a large diameter EAHX delivering a nominal 8000 m³/h flowrate 85 of cooled air to an office building in a region with hot and dry summers.

The present paper is structured as follows. Section 2—materials and methods—describes the office building served by the EAHX, describes the cooling and ventilation system into which the EAHX is included, introduces the indices used to assess EAHX performance and details the monitoring protocol. Section 3—results and discussion—uses monitoring data to characterize the outdoor 90 conditions and challenges posed to standalone EAHX cooling and assesses the large diameter EAHX cooling performance and design. Section 4 presents the conclusions.

¹Naturally, these costs depend greatly on EAHX pipe layout and on the type of soil. As shown in Ascione et al. (2011), a ten-fold or larger increase in excavation cost between sand, clay or gravel and hard rock soils could occur.

2 Materials and methods

2.1 The building served by the EAHX: Location, climate and relevant features

The studied large diameter EAHX serves an office building located in Beja district, Alentejo, in the south of Portugal. Figure 1 provides the geographic location of the building.

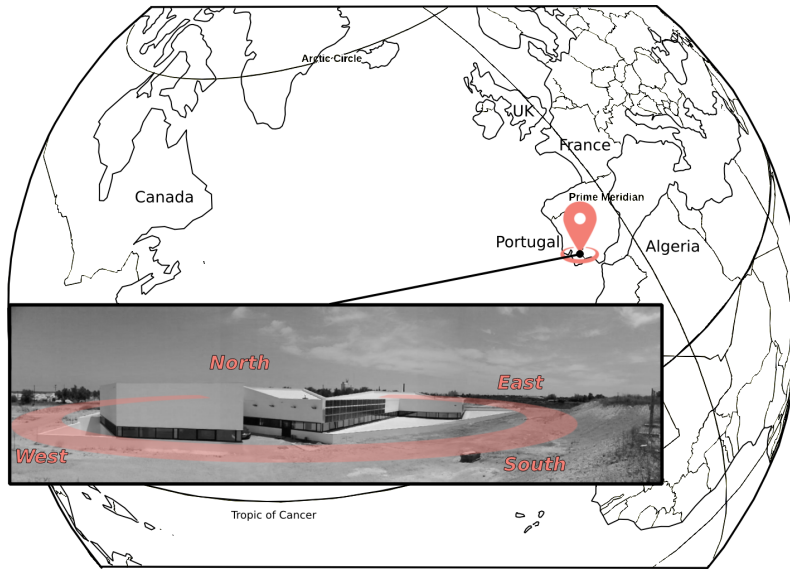


Fig. 1: Location and a panoramic photograph of the west and south façades of the building being served by the EAHX.

Despite the proximity of Alentejo to the Atlantic Ocean, the presence of mountain ranges of Cercal and Grândola block the Atlantic influence, justifying climate varieties Csa—Mediterranean climate with hot and dry summer—and BSk—cold steppe climate of mid latitude (IPMA, n.d.). With large seasonal and diurnal temperature variations, these climate varieties are particularly suited to room cooling with EAHX. The large seasonal outdoor temperature variation, with winter minimum temperatures lower than 0°C and summer maximum temperatures reaching 40°C, justify undisturbed soil temperatures of approximately 17°C (at 3 m or larger depths), allowing, in the hot summer period, significant temperature gradients between outdoor air and soil temperature and, therefore, significant cooling of outdoor air. The large diurnal outdoor temperature variations with nighttime minimum temperatures below soil temperature warrant the uninterrupted cycle of daily heating and cooling of the soil surrounding the EAHX pipes, preventing (or reducing) soil thermal saturation and, in this way, warranting the daily regeneration of the EAHX cooling capacity.

Figure 1 also includes a panoramic photograph of the building west and south façades in the final construction stage. The building is one storey high and develops along the west-east axis. It was designed with NZEB considerations in mind, which justified, besides the adoption of the EAHX for

room cooling, partially buried exterior walls and photovoltaic panels on the south façade. These latter characteristics are visible in the panoramic photograph; namely, the buried walls below the windowsill and the photovoltaic panels extending from the lintel to ceiling height². The EAHX, Air Handling Unit (AHU) and distribution piping, being buried (in the south direction), are not visible.

Table 1 highlights building characteristics relevant to the study of the built EAHX.

Table 1: Building characteristics relevant to the study of the built EAHX.

Architectural

Layout	(a) A laboratory located at the west with larger ceiling height takes approximately 40% of the total building floor area. The remaining area—office area—, with lower ceiling height, extends towards east holding a technical room supporting the laboratory, research and administrative offices, a large meeting/training room, a reception, a restroom, WC and corridors connecting these spaces. Technical room, reception, and corridors lay on the north side of the building whilst offices and meeting room lay on the south side. The building is characterized by a small window-to-wall ratio.
Floor area	(b) Laboratory: 300 m ² ; Office area: 450 m ² .
Room height	(c) For the cooled office area: 3 m.

Envelope (thermal characteristics)

Exterior walls	(d) From the outside to the inside: mortar (30 mm), extruded polystyrene insulation board (XPS, 80 mm), cement bricks (300 mm), mortar (30 mm). U-value of 0.36 W/(m K) (Pina dos Santos and Matias, 2010).
Pavement floor	(e) From the outside to the inside: concrete slab (200 mm), XPS insulation board (60 mm), screed (60 mm). U-value of 0.39 W/(m K) (EN 13370:, 2017).
Ceiling	(f) Occupied spaces separated from an inverted roof (insulated on the outside with 60 mm XPS) by a false ceiling comprised of (from the outside to the inside): mineral wool (60 mm), gypsum board (12mm). U-value of 0.6 W/(m K) (Pina dos Santos and Matias, 2010).
Windows and shading	(g) Double glazed (6 mm + 12 mm + 8 mm) window with solar control (solar factor, 0.33; U-value of 1.4 W/(m K)) and aluminium frame with thermal break. In the summer, slightly recessed windows and photovoltaic panels placed over the windows on the south façade block out direct solar radiation.

Occupancy

(h) Low occupancy density (lower than 0.03 person/m ²), weekdays from 8 to 18 h.
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Considering the low occupancy density, the envelope insulation, the large useful thermal mass;

²The photograph depicts the initial stage of photovoltaic panels installation. Once completed, photovoltaic panels covered the whole south façade.

120 and, the larger indoor temperatures “allowed” by adaptive comfort principles—see Table 2, item
 (m), in Section 2.2—, $20\text{W}/\text{m}^2$ (a specific load, defined per square meter of cooled floor area) was
 the *design* (or peak) cooling demand determined for the cooled rooms. Despite this low value—for
 an office building and hot summer climate—, to the design of an EAHX for standalone office room
 cooling it represents a challenging requirement.

125 **2.2 The cooling and ventilation system**

The installed cooling and ventilation system consists of the EAHX, an AHU, the distribution piping
 buried between the AHU and the building, and the diffusion of air and temperature control in the
 cooled rooms. An outline schematic of this system is presented in Figure 2.

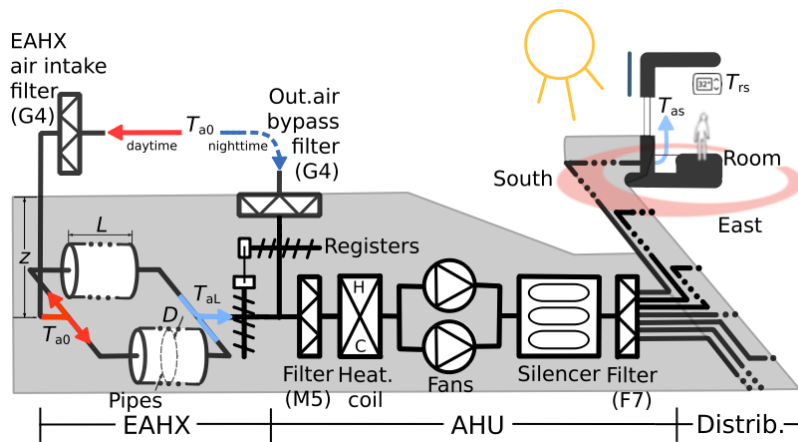


Fig. 2: Outline schematic of the cooling and ventilation system.

130 Figure 2 represents (from left to right): the EAHX, the AHU and the distribution piping. Supply of
 cooled air to a room, along the exterior wall at floor level, as well as a room temperature controller,
 are also depicted. Detailed specifications of the cooling and ventilation system are provided in
 Table 2.

Table 2: Cooling and ventilation system specifications.

EAHX

Pipes	(a) The EAHX consists of two pipes (concrete) with 1 m diameter placed 4 m apart (distance between axes), 70 m long, buried 5.5 m deep (average depth, since pipes are sloped towards the air intake for water drainage). Water resistant coatings prevent the transfer of water across the pipes towards/from the soil. The pipes' inner surface coating has fungicide and bactericide properties to prevent the growth of mold and bacteria.
Air intake	(b) Outdoor air is admitted into the buried pipes at a technical space built above ground. A G4 filter (EN 779:, 2012) installed in this technical space prevents the intake of spores, pollen and coarse dust.
Vegetative cover	(c) To reduce soil surface temperature (during the summer period) species found in tall-grass prairies (e.g., <i>Lolium perenne</i> , <i>Festuca arundinacea</i> , <i>Poa pratensis</i> , <i>Festuca rubra</i>) were planted covering the ground above the EAHX.
Pressure loss	(d) Due to large pipe diameter, pressure loss in the EAHX is related to the air intake filter, which, with its large surface and low face velocity, has negligible pressure loss compared to that in the AHU and in the distribution piping.

AHU

Generic description	(e) In the direction of the airflow the EAHX consists of a mixing chamber fitted with registers to allow EAHX bypass with outdoor air (not used in this study), an M5 filter (EN 779:, 2012), a heating coil (not used in this study), two fans, a silencer and, prior to the air distribution to the rooms, a final F7 filter (EN 779:, 2012) for fine dust particles ($1 \sim 10\mu\text{m}$) preventing the distribution into rooms of bacteria and germs carried on host particles. As for the EAHX air intake, a coarse G4 filter is used at the bypass outdoor air intake. AHU dimensions were intentionally oversized to reduce pressure loss.
Fans	(f) To supply a nominal flowrate of $8000 \text{ m}^3/\text{h}$ of air to the rooms, a redundant set of two electrically commutated plug fans (IE5) with 3.6 kW rated power each are used.
Pressure loss	(g) Design pressure loss in the AHU is 325 Pa.

Distribution piping

Generic description	(h) Cooled air is distributed to the rooms using high density polyethylene (HDPE) corrugated pipes with varying diameter ($< 0.40 \text{ m}$) laid along the south façade of the building. Pipes run inside a rectangular pathway, buried 3.0 to 1.5 m deep, made of cement (bottom) and cement blocks (side walls). This pathway is (inside) insulated with XPS (60 mm) limiting heat loss to the soil (through the sides and bottom).
Pressure loss	(i) Design pressure loss in the distribution piping is 375 Pa.

Diffusion of air and temperature control in the cooled rooms

Generic venti- lation strategy	(j) 100% fresh air system. Forced (cooled) air is supplied to the rooms at the south façade and at the reception through linear air diffusers placed along the exterior wall at floor level. Air flows to corridors and from there to the outside exiting the building behind the south façade photovoltaic panels.
Pressure loss	(k) Linear air diffusers' specification is such that pressure loss associated with the introduction of supply air in the rooms is negligible compared to that in the AHU and in the distribution piping.
Temperature control	(l) Temperature control in the cooled rooms is achieved varying the air-change rate. This control is limited by outdoor air conditions and by heat transfer with the soil. The control law depends (for hot and dry conditions) on room air and room setpoint temperatures, on EAHX exit air temperature, and on outdoor air temperature. To compensate for the system lower room-to-supply-air temperature gradients, large air-change-rates are allowed (Hollmuller and Lachal, 2014; Barnard and Jauzens, 2001). Special attention is given to the specification of linear air diffusers so that larger airflow velocities in the room do not cause local discomfort with draught.
Temperature setpoint	(m) Adaptive comfort principles are assumed allowing free-floating room temperatures correlated to outdoor air temperatures. In other words, room setpoint temperature is allowed to vary and may be larger than setpoints typically associated with refrigeration machine cooling ($> 27^{\circ}\text{C}$).
Nighttime ven- tilation	(n) Nighttime forced ventilation with cold outdoor air is used in two ways. Firstly, in combination with heavyweight building construction materials (insulated on the outside), making use of walls and floor large thermal lag times to decrease room peak cooling requirement and decrease operative room temperatures. Secondly, in combination with the soil covering the insulated rectangular pathway for the distribution piping, allowing the use of the soil thermal mass to increase thermal lag times, contributing to additional daytime cooling of EAHX exit air.

A photograph of the EAHX during construction is presented in Figure 3. This photograph shows a trench, the EAHX air intake at the start of the trench and two parallel pipes leaving this air intake towards the air handling unit (the latter not visible). Sketches of the air intake technical space built above ground and of the airflow pathway in the pipes were superimposed onto the photograph.

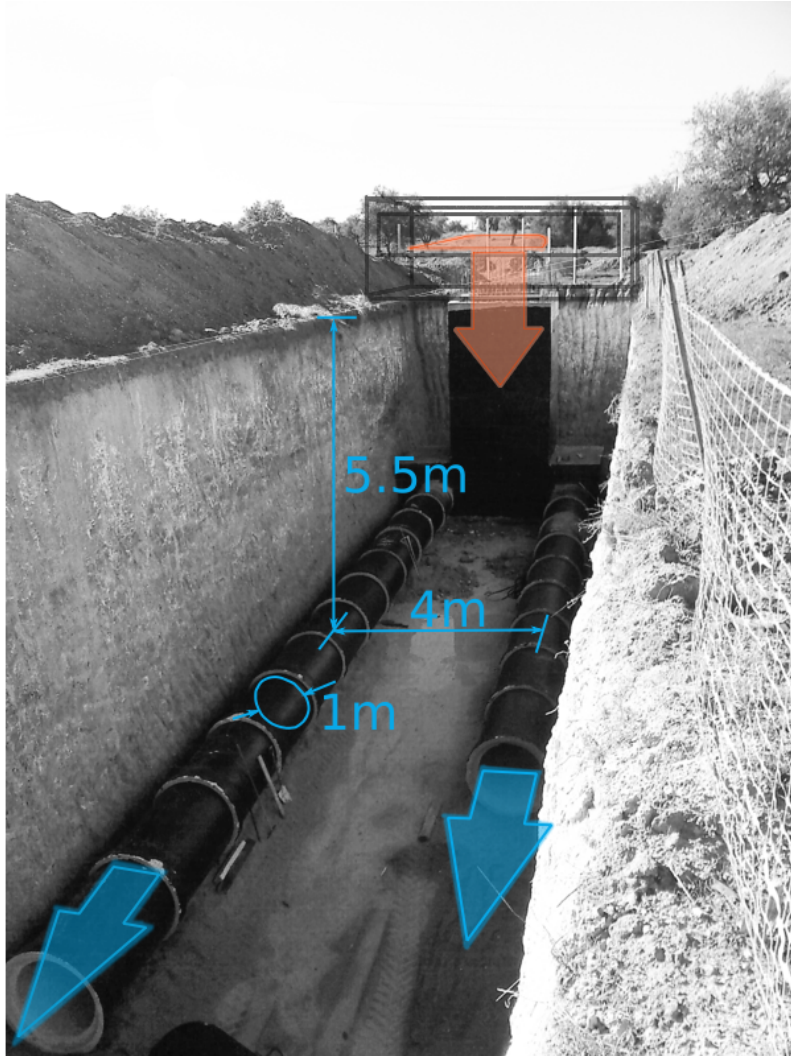


Fig. 3: Photograph of the EAHX while the buried pipes were being installed at an average depth of 5.5 meters below soil surface.

2.3 EAHX performance assesement

Figure 4 sketches, for a typical summer day, outdoor air temperature (T_{a0}), as it enters the EAHX, and EAHX exit air temperature (T_{aL}), as it leaves the EAHX. It also represents room setpoint temperature limits— T_{rs}^U and T_{rs}^L , with superscripts “U” and “L” standing for upper limit and lower limit, respectively—between which thermal comfort in a room is judged appropriate.

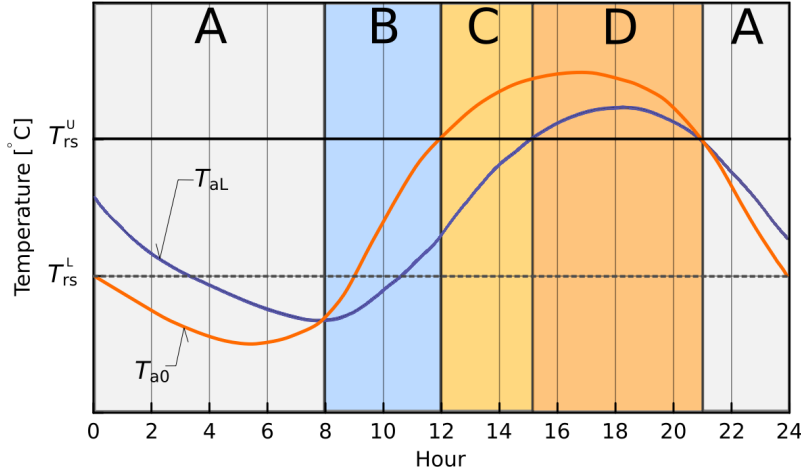


Fig. 4: Sketch of outdoor air (entering the EAHX) and EAHX exit air temperatures for a typical summer day. Room upper and lower setpoint temperatures delimiting office room thermal comfort also represented.

Figure 4 shows that in the morning, with office rooms already being used, outdoor air temperatures (T_{a0}) are lower than the room upper setpoint temperature (T_{rs}^U), allowing free-cooling with outdoor air. In the afternoon, since outdoor air temperatures exceed the upper setpoint temperature, cooling of outdoor air becomes necessary. During the nighttime, outdoor air temperatures lay below the lower setpoint temperature (T_{rs}^L); still, since the office building is unoccupied, there is no need for heating³.

The pattern of the EAHX exit air temperature is similar to the outside air temperature but dampened and slightly forward shifted in time. The extent of the dampening and of the forward shifting determines EAHX cooling performance.

To assess the cooling performance of an EAHX two main indices are used⁴:

- EAHX outdoor air load removal,

$$\dot{Q}_{oa}^{EAHX} = \dot{m}_a c_a \Delta T_{aL,a0} ; \quad (1)$$

- EAHX room load removal,

$$\dot{Q}_r^{EAHX} = \dot{m}_a c_a \Delta T_{aL,rs} ; \quad (2)$$

³Actually, as described in Table 2, item (n), during nighttime, forced ventilation with cold outdoor air can be used in combination with heavyweight building construction elements and with the soil in the buried pathway between AHU and rooms to assist daytime EAHX cooling.

⁴Monitoring data confirms negligible latent heat exchanges in the EAHX during the dry summer period. Further details provided in Section 3.1.

where the gradients $\Delta T_{aL,a0}$ and $\Delta T_{aL,rs}$ are defined as,

$$\Delta T_{aL,a0} = \begin{cases} T_{aL} - T_{a0} & \text{if } T_{aL} < T_{a0} ; \\ 0 & \text{otherwise ;} \end{cases} \quad (3)$$

and

$$\Delta T_{aL,rs} = \begin{cases} T_{aL} - T_{rs}^U & \text{if } T_{aL} < T_{rs}^U ; \\ 0 & \text{otherwise .} \end{cases} \quad (4)$$

165 EAHX outdoor air load removal is a useful performance metric to assess EAHX “total” cooling capacity. However, when studying standalone EAHX cooling, EAHX room load removal is a much more appropriate performance metric, as it assesses EAHX “effective” *room* cooling capacity. Divided by the (cooled) room floor area⁵,

$$\dot{q}_r^{\text{EAHX}} = \frac{\dot{Q}_r^{\text{EAHX}}}{A_r} , \quad (5)$$

170 with units W/m², the specific EAHX room load removal allows a straightforward comparison to room *design* cooling demand, a fundamental parameter in HVAC design.

Given the outdoor air and EAHX exit air temperatures dynamic nature, to assist the detailed analysis of the EAHX performance indices, regions A, B, C and D—see Figure 4—were defined. These regions are characterized as follows:

175 – **Region A:** Nighttime (from evening to the start of the working day) with outdoor air temperature lower than EAHX exit air temperature, $T_{a0} < T_{aL}$.

In this region the EAHX heats the outdoor air, operating, therefore, in heating mode. Since this paper discusses cooling performance, Region A is excluded from the analysis.

180 – **Region B:** From the start of the working day to noon with EAHX exit air temperature lower than outdoor air temperature and both of these lower than the upper room setpoint temperature, $T_{aL} < T_{a0} < T_{rs}^U$.

In this region the EAHX cools the outdoor air, operating, therefore, in cooling mode. Since the outdoor air temperature is lower than the room upper setpoint temperature, EAHX room load removal has two components,

$$185 \quad \dot{Q}_r^{\text{EAHX}} = \dot{Q}_{\text{oa}}^{\text{EAHX}} + \dot{Q}_r^{\text{OA}} = \dot{m}_a c_a \Delta T_{aL,a0} + \dot{m}_a c_a \Delta T_{a0,rs} , \quad (6)$$

⁵In general, $\dot{q}_j^{\text{EAHX}} = \dot{Q}_j^{\text{EAHX}}/A_r$ with $j \in \{\text{ao}, \text{r}\}$.

namely, the EAHX outdoor air load removal component, \dot{Q}_{oa}^{EAHX} , and the outdoor air room free-cooling component⁶, \dot{Q}_r^{OA} , with,

$$\Delta T_{a0,rs} = \begin{cases} T_{a0} - T_{rs}^U & \text{if } T_{a0} < T_{rs}^U ; \\ 0 & \text{otherwise ;} \end{cases} \quad (7)$$

being the outdoor air to room upper setpoint temperature gradient.

190 In region B, due to outdoor air free-cooling, the following inequation applies, $\dot{Q}_r^{EAHX} \geq \dot{Q}_{oa}^{EAHX}$.

– **Region C:** Start of the afternoon with EAHX exit air temperature lower than the room upper setpoint temperature and both of these lower than outdoor air temperature, $T_{aL} < T_{rs}^U < T_{a0}$.

195 In this region outdoor air makes no contribution to room cooling, still, it is customary to distinguish two components in the EAHX outdoor air load removal,

$$\dot{Q}_{oa}^{EAHX} = \dot{Q}_r^{EAHX} + \dot{Q}_n^{EAHX} = \dot{m}_a c_a \Delta T_{aL,rs} + \dot{m}_a c_a \Delta T_{rs,a0} , \quad (8)$$

namely, the EAHX room load removal component, \dot{Q}_r^{EAHX} , and a component for the EAHX outdoor air load removal to “neutral” state, \dot{Q}_n^{EAHX} , with,

$$\Delta T_{rs,a0} = \begin{cases} T_{rs}^U - T_{a0} & \text{if } T_{rs}^U < T_{a0} ; \\ 0 & \text{otherwise ;} \end{cases} \quad (9)$$

200 being the temperature gradient that brings outdoor air to room upper setpoint temperature, i.e., the condition for which outdoor air neither heats nor cools the room (“neutral” state).

In region C the following inequation applies, $\dot{Q}_r^{EAHX} \leq \dot{Q}_{oa}^{EAHX}$.

– **Region D:** During the afternoon, with room upper setpoint temperature lower than EAHX exit air temperature and both of these lower than outdoor air temperature, $T_{rs}^U < T_{aL} < T_{a0}$.

205 In this region, since EAHX exit air temperature exceeds the room upper setpoint, the EAHX is incapable of removing room loads, $\dot{Q}_r^{EAHX} = 0$. The EAHX operates for outdoor air load removal only.

⁶Actually, this component is independant of the EAHX, however, because the flow of outdoor air in large diameter EAHX has negligible added fan cost (negligeable pressure losses), \dot{Q}_r^{OA} is absorbed into \dot{Q}_r^{EAHX} .

The analysis presented for the distinct regions—A, B, C and D—highlights the following conclusions:

- 210 – In region B the EAHX complements free-cooling with outdoor air, increasing room load removal.
- In region C the EAHX replaces free-cooling with outdoor air, increasing the duration of room load removal.
- A prime sizing requirement for standalone EAHX cooling is to avoid region D, i.e., for cooling
- 215 design conditions inequations $T_{aL} < T_{a0}$ and $T_{aL} < T_{rs}^U$ should stand.

A final aspect relevant for standalone EAHX cooling performance is the definition of room upper setpoint temperature. When room cooling relies on refrigeration machines⁷, “close control” of indoor air temperatures is possible, hence, a constant room setpoint is defined for the whole summer period. With standalone EAHX cooling, constant indoor air temperature can not be guaranteed.

220 Indeed, standalone EAHX cooling resembles much more closely natural ventilation with window opening, with room temperature varying according to outdoor conditions. For naturally ventilated rooms, standard EN 15251: (2007) specifies free-floating room setpoint temperatures in accordance with adaptive comfort principles (Nicol and Humphreys, 2002; de Dear and Brager, 2002; Raja et al., 2001). Given the resemblance to natural ventilation, previous researchers applied standard

225 EN 15251:2007 and the adaptive comfort viewpoint to the study of EAHX (Ascione et al., 2011; Maerefat and Haghighi, 2010). This viewpoint is also used in this paper with free-floating room upper (U) setpoint temperatures defined as (EN 15251:, 2007),

$$\begin{cases} T_{rsIII}^U = 0.33\theta_{rm} + 18.8 + 4 \Leftarrow \text{Category III} ; \\ T_{rsI}^U = 0.33\theta_{rm} + 18.8 + 2 \Leftarrow \text{Category I} ; \end{cases} \quad (10)$$

and free-floating room lower (L) setpoint temperatures defined as,

230

$$\begin{cases} T_{rsI}^L = 0.33\theta_{rm} + 18.8 - 2 \Leftarrow \text{Category I} ; \\ T_{rsIII}^L = 0.33\theta_{rm} + 18.8 - 4 \Leftarrow \text{Category III} ; \end{cases} \quad (11)$$

with subscripts III and I denoting acceptable and high comfort expectancy levels, respectively (EN 15251:, 2007).

⁷Including the case of EAHX designed solely for outdoor air pre-cooling with a downwind refrigeration machine.

235 Equations (10) and (11) resort to the definition of running mean outdoor temperature, θ_{rm} , determined from (EN 15251:, 2007),

$$\theta_{rm} = (1 - \beta) (\theta_{ed-1} + \beta\theta_{ed-2} + \beta^2\theta_{ed-3+\dots}) , \quad (12)$$

where

- 240
- β is a constant between 0 and 1 (0.8 is used in this study);
 - θ_{ed-1} is the daily mean external temperature for the previous day;
 - θ_{ed-2} is the daily mean external temperature for the day before, and so on.

2.4 Monitoring

Use of Equations (1) and (2) to assess EAHX performance requires monitoring of: outdoor air
245 temperature (to determine T_{a0} , θ_{rm} and T_k^U with $k \in \{\text{rsIII}, \text{rsI}\}$); EAHX exit temperature (T_{aL}); and, airflow rate through the EAHX (\dot{V}_a). To assess the relevance of latent heat exchanges in the EAHX, outdoor air relative humidity (ϕ_{a0}) was also monitored. To have an estimate of undisturbed soil temperature ($T_{s\infty}$) at the EAHX depth, outdoor air temperature was monitored for a whole year and the average annual outdoor air temperature was determined (see Givoni and Katz, 1985).

250 A weather station (Vaisala, 2012) was installed at the EAHX location and started collecting outdoor data in late May. The built and functional EAHX was monitored during the summer period from June 1st to September 30th. During this period the EAHX operated in continuous mode, 24 hours per day, 7 days per week, at the nominal airflow rate of 8000 m³/h (4000 m³/h per pipe). Table 3 characterizes the sensors used for data collection.

Table 3: Characteristics of the sensors used to monitor the performance of the built EAHX.

Outdoor air (Vaisala weather station (Vaisala, 2012))

Out.air temp.sensor, T_{a0}	<p>Duration: 1 year.</p> <p>Log.frequency: 1 min.</p> <p>Sensor location: Outdoor, ~1.5 m above ground in a unobstructed area.</p> <p>Range: -53 to +60°C.</p> <p>Accuracy: $\pm 0.3^\circ\text{C}$ (at 20°C).</p>
Out.air rel.hum.sensor, ϕ_{a0}	<p>Duration: 1 year.</p> <p>Log.frequency: 1 min.</p> <p>Sensor location: Outdoor, ~1.5 m above ground in a unobstructed area.</p> <p>Range: 0 to 100%.</p> <p>Accuracy: $\pm 3\%$ (from 0 to 90%); $\pm 5\%$ (from 90 to 100%).</p>

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EAHX

Exit air temp. sensor, T_{aL} (Onset datalogger (Onset, n.d.))	<p>Duration: From June 1st to September 30th.</p> <p>Log.frequency: 15 min.</p> <p>Sensor location: AHU mixing chamber.</p> <p>Range: -20 to +70°C.</p> <p>Accuracy: $\pm 0.35^\circ\text{C}$ (from 0 to 50°C).</p>
Airflow rate, \dot{V}_a (Fan controller module (Ziehl-Abegg, n.d.) measuring airflow rate from fan diff.pressure)	<p>Duration: From June 1st to September 30th.</p> <p>Log.frequency: 15 min.</p> <p>Sensor location: AHU.</p> <p>Range: 0 to 1000 Pa.</p> <p>Accuracy: $\pm 1.3\%$ (max).</p>

3 Results and discussion

3.1 Outdoor conditions and challenges facing standalone EAHX cooling

Figure 5 presents outdoor air temperature (T_{a0}) data for the summer period between June 1st and September 30th.

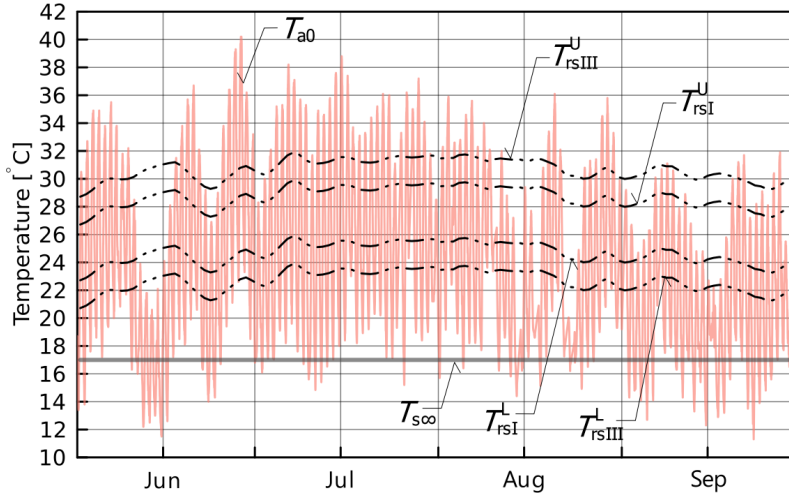


Fig. 5: Timeseries of outdoor air temperature (T_{a0} , monitored data); upper and lower room setpoint temperatures (T_k^U and T_k^L with $k \in \{\text{rsIII}, \text{rsI}\}$ determined from Equations (10) and (11) using monitoring data); estimate of undisturbed soil temperature ($T_{s\infty}$, determined from average annual outdoor air temperature data).

For the time period depicted in Figure 5, Table 4 presents monthly and summer (Jun-Sep) statistics of outdoor air temperature and of outdoor air relative humidity.

Table 4: Statistics for outdoor air temperature and relative humidity (T_{a0} and ϕ_{a0} , respectively). Obtained from summer monitoring data between June 1st and September 30th.

		Jun	Jul	Aug	Sep	Summer (Jun-Sep)
$T_{a0} [^\circ\text{C}]$	max.	40.2	38.8	36.1	31.9	40.2
	Q_3	29.3	31.1	28.2	24.7	28.3
	median	23.6	25.7	23.5	20.5	23.3
	Q_1	19.3	21.0	19.3	17.5	19.1
	min.	11.5	14.9	14.4	11.3	11.3
$\phi_{a0} [\%]$	max.	93	88	90	92	93
	Q_3	57	62	67	71	65
	median	41	44	51	54	47
	Q_1	26	28	36	39	32
	min.	9	9	8	15	8

Table 4 shows that monthly median air temperatures exceeded 20°C reaching 26°C in July. Outdoor air temperature range is largest in June with maximum and minimum temperatures of 40°C and 12°C , respectively. Temperature range decreases in subsequent months, but maximum temperatures

remain higher than 35°C in July and August.

Table 4 also presents monthly and summer statistics of outdoor air relative humidity (ϕ_{a0}). Confirming dry summer conditions, relative humidity interquartile range is defined between 32% and 65% with a median of 47% (Jun-Sep). An increase in monthly median relative humidity is observed from June (41%) to September (54%).

Using summer outdoor air temperature and relative humidity data, median and 95% percentile dew point temperatures of 11 and 16°C (respectively) were determined (ASHRAE, 2005). Since these values are significantly lower than EAHX (pipes inner) surface temperatures (see Section 3.2), condensation in the EAHX has low likelihood, supporting the assessment of the EAHX cooling performance based on sensible heat exchanges (based on Equations (1) and (2)).

Figure 5 presents upper and lower room free-floating setpoint temperatures obtained from Equations (10) and (11) using monitoring data to derive running mean outdoor temperature (Equation 12). In spite of the large outdoor temperature variations (with daily ranges exceeding 15 K), room setpoint variance is small. Statistics for these setpoints are presented in Table 5.

Table 5: Upper and lower free-floating room setpoint temperatures (categories III and I). Obtained for summer monitoring data between June 1st and September 30th.

	T_{rsIII}^U [°C]	T_{rsI}^U [°C]	T_{rsI}^L [°C]	T_{rsIII}^L [°C]
max.	31.9	29.9	25.9	23.9
median	30.8	28.8	24.8	22.8
min.	28.7	26.7	22.7	20.7

Table 5 confirms small variance in setpoints along the summer period with differences between median and maximum setpoints of only 1 K and setpoint ranges not exceeding 3 K.

It is obvious from Figure 5 that outdoor air temperatures exceed room upper setpoint temperatures throughout the whole summer. Furthermore, outdoor air temperatures lower than the room lower setpoint temperatures are also common. When discussing Figure 4, in Section 2.3, outdoor air temperatures above and below comfort limits were associated with daytime and nighttime, respectively. Since office rooms are unoccupied during nighttime, it was concluded that room heating was unnecessary. Figure 6 presents violin- and box-plots for outdoor air temperatures measured at different hours of the day.

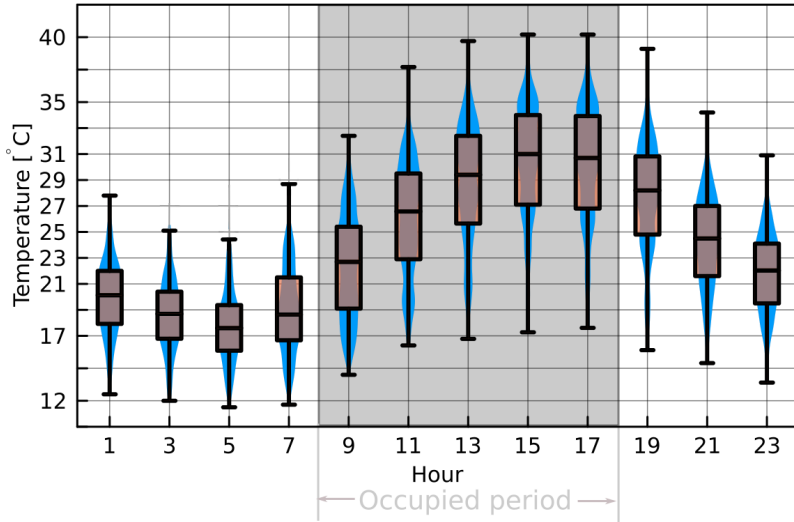


Fig. 6: Hourly violin- and box-plots for outdoor air temperature. Obtained from summer monitoring data between June 1st and September 30th. Grey shading highlights room occupied period.

Figure 6 confirms that the lowest outdoor air temperatures, with median values lower than 19°C, happen during nighttime, when office rooms are unoccupied. The significant reduction in median temperatures between daytime and nighttime also confirms that forced nighttime cooling with outdoor air can be used as a passive cooling technique, as described Table 2 item (n) and as mentioned in the scientific literature (Zimmermann, 1999; Barnard and Jauzens, 2001; Soares et al., 2021).

Returning to the analysis of Figure 5, a line for the estimate of the undisturbed soil temperature ($T_{s\infty}$) at 5.5 m (the built EAHX burial depth) is also presented. Given the large temperature difference between this soil temperature estimate (17°C) and Table 5 room upper setpoint medians (31°C/29°C for Category III/ I), the feasibility of EAHX use for standalone room cooling is confirmed. Considering the temperature difference between these medians and the maximum outdoor air temperature (40°C; see Table 4), it is concluded that for standalone EAHX cooling, inflow to outflow temperature gradient ($\Delta T_{aL,a0}$) should be larger than 9 K/ 11 K (Category III/ I). EAHX design, i.e., pipe length, depth, material and/or layout should be such that the soil succeeds in reducing the outdoor air temperature in this order of magnitude, avoiding region D conditions.

3.2 EAHX exit air temperature: Assessing EAHX room load removal

Figure 7 presents EAHX exit air temperature (T_{aL}) and EAHX airflow rate (\dot{V}_a) data for the summer period between June 1st and September 30th. To simplify the comparison to Figure 5, EAHX air exit temperatures are superimposed into a background of outdoor air temperature data and upper and lower room setpoint temperatures (categories III and I) are also depicted.

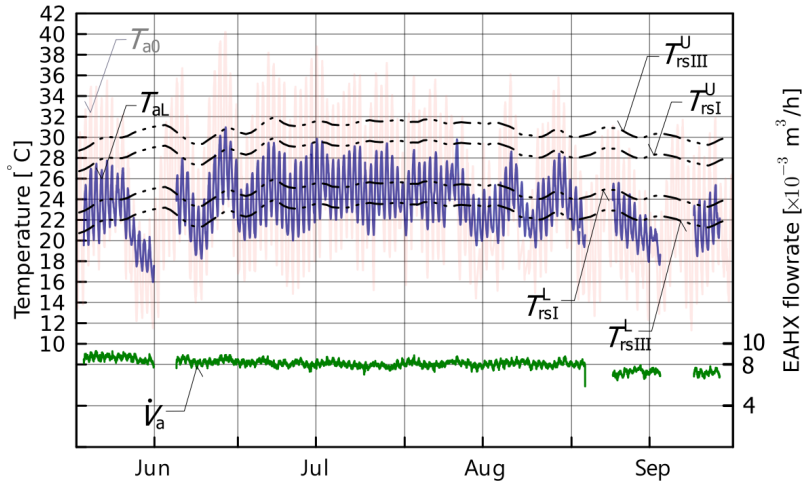


Fig. 7: Timeseries of EAHX exit air temperature (T_{aL} , monitored data) and EAHX airflow rate (\dot{V}_a , monitored data). Upper and lower room setpoint temperatures and outdoor air temperature data also included.

Figure 7 confirms that ventilation rate was kept (approximately) constant at the nominal 8000 m^3/h rate. It also confirms a consistent reduction in air temperature amplitude between EAHX inflow (at outdoor temperature) and outflow (at EAHX exit temperature). Comparing timeseries of room upper setpoints with EAHX exit air temperatures shows daily maximum exit temperatures seldom exceed Category I and never exceed Category III comfort expectancy levels. The built EAHX avoids, therefore, region D conditions for acceptable comfort expectancy level (Category III) during the whole summer (Jun-Sep). For a higher comfort expectancy level (Category I) the built EAHX fails to deliver the required cooling with region D conditions in late June.

Table 6 presents monthly and summer (Jun-Sep) statistics of EAHX exit air temperature (T_{aL}).

Table 6: Statistics for EAHX exit air temperature and for absolute value of EAHX exit air to outdoor air temperature gradient. Obtained from summer monitoring data between June 1st and September 30th.

		Jun	Jul	Aug	Sep	Summer (Jun-Sep)
T_{aL} [°C]	max.	31.0	29.9	29.8	25.6	31.0
	Q_3	25.4	26.7	25.5	22.6	25.4
	median	23.0	24.4	23.7	21.1	23.3
	Q_1	20.5	22.7	22.0	20.1	21.4
	min.	16.0	20	19.3	17.6	16.0
$ \Delta T_{aL,a0} $ [K] ^a	max.	10.9	9.1	9.2	7.1	10.9
	Q_3	5.9	5.8	5.4	4.2	5.5
	median	3.7	4.2	3.9	2.5	3.7
	Q_1	1.6	2.2	1.8	1.1	1.7
	min.	~0	~0	~0	~0	~0

a) Cooling only. Instants with $T_{aL} > T_{a0}$ excluded.

Comparing summer (Jun-Sep) statistics in Tables (6) and (4), the decrease in maximum temperature from 40 to 31°C and the increase in minimum temperature from 11 to 16°C are observed; median outdoor air and EAHX exit air temperatures remain, however, equal (23.3°C).

325 Table 6 includes statistics for the absolute value of temperature gradient $\Delta T_{aL,a0}$. Maximum and median summer (Jan-Sep) gradients are 11 and 4 K, respectively, and July is the month with the largest median gradient.

Figure 8 presents a scatter plot of temperature gradients $|\Delta T_{aL,a0}|$ used to obtain the statistics in Table 6 as a function of outdoor air temperature, T_{a0} .

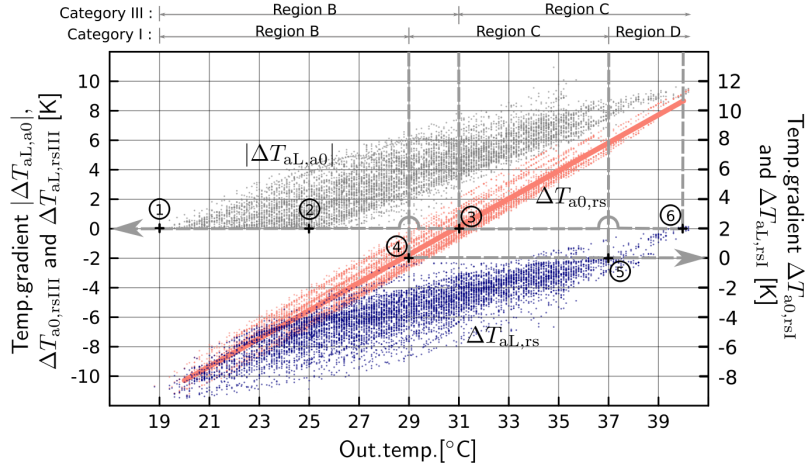


Fig. 8: Various EAHX temperature gradients as a function of outdoor air temperature and trendline for $\Delta T_{a0,rs}$. Obtained from monitored data (between June 1st and September 30th; cooling mode only, $T_{aL} < T_{a0}$; 8000 m³/h nominal airflow rate). Left axis applies to $|\Delta T_{aL,a0}|$, $\Delta T_{a0,rsIII}$ and $\Delta T_{aL,rsIII}$; right axis applies to $\Delta T_{a0,rsI}$ and $\Delta T_{aL,rsI}$.

From $|\Delta T_{aL,a0}|$ values in Figure 8 it is concluded that EAHX cooling mode starts when outdoor air temperature is approximately 19°C (point 1, Figure 8). Since cooling is only possible when the EAHX (pipes inner) surface temperature is lower than the outdoor air temperature, 19°C is an estimate of the lowest EAHX surface temperature for cooling operating mode. Since null temperature gradients $|\Delta T_{aL,a0}|$ extend from 19°C to 25°C (from point 1 to point 2), this range is an estimate of the surface temperatures for which EAHX shifted between cooling and heating modes from June 1st to September 30th.

Figure 8 also depicts temperature gradients $\Delta T_{a0,rs}$ and $\Delta T_{aL,rs}$. Directing the attention to these gradients, given that $|\Delta T_{aL,a0}|$ is often approximately zero in the 19°C to 25°C range, gradients $\Delta T_{a0,rs}$ and $\Delta T_{aL,rs}$ are approximately equal, overlapping in Figure 8 for this range. As outside air temperature increases, $|\Delta T_{aL,a0}|$ also increases, therefore, differences between $\Delta T_{a0,rs}$ and $\Delta T_{aL,rs}$ become visible: values of $\Delta T_{a0,rs}$ are well approximated by a straight line whilst values of $\Delta T_{aL,rs}$ follow a curved line. For outdoor air temperatures of 31°C and 29°C—room upper setpoints for comfort categories III and I, respectively—temperature gradient $\Delta T_{a0,rs}$ becomes 0 K (see point 3 and point 4; use left and right axes for $\Delta T_{a0,rsIII}$ and $\Delta T_{a0,rsI}$, respectively). When outdoor air temperature increases to the maximum 40°C, temperature gradient $|\Delta T_{aL,a0}|$ increases to ~ 9 K, precisely the difference between gradients $\Delta T_{a0,rs}$ and $\Delta T_{aL,rs}$.

With the help of gradients $\Delta T_{a0,rs}$ and $\Delta T_{aL,rs}$, regions B, C and D are delimited in Figure 8 for room comfort expectancy levels III and I. Figure 8 confirms, once more, that for Category III the built EAHX avoids region D ($T_{aL} < T_{rsIII}^U$). It provides further insight for the analysis of comfort Category I, showing the EAHX is incapable of room cooling for outdoor air temperatures exceeding

37°C (to the right of point 5, $T_{aL} > T_{rsI}^U$). Note, however, that according to ASHRAE (2005), for Beja (close to where the built EAHX is located), the 0.4%, 1.0% and 2.0% annual cooling dry-bulb design outdoor air temperatures are 37°C, 35°C and 33°C, respectively. This means that for Category I comfort level, the most demanding design criterion used in “traditional” (refrigeration machine) HVAC design—outdoor air temperature of 37°C—equals the upper threshold for which the built EAHX is capable of room cooling. For Category III comfort level, according to Figure 8, the upper threshold exceeds 40°C (see point 6, with $T_{aL} \leq T_{rsIII}^U$), allowing EAHX room load removal when outdoor air temperatures exceed the most demanding 0.4% design criterion.

360 3.3 EAHX room load removal: Assessing standalone EAHX cooling and EAHX design

This section presents results for room comfort expectancy level III (Category III) which, according to the results of the previous section, allows room cooling with the most demanding outdoor air design condition (37°C) specified in ASHRAE (2005).

From EAHX temperature gradients and EAHX airflow rate data, EAHX load removal was determined using Equations (1) and (2). Figure 9 highlights, for the room occupancy period between 8 and 18 h, hourly statistics of specific⁸ values (and absolute values) of EAHX room load removal \dot{q}_{rIII}^{EAHX} (\dot{Q}_{rIII}^{EAHX}) and of EAHX outdoor air load removal, \dot{q}_{oa}^{EAHX} (\dot{Q}_{oa}^{EAHX}).

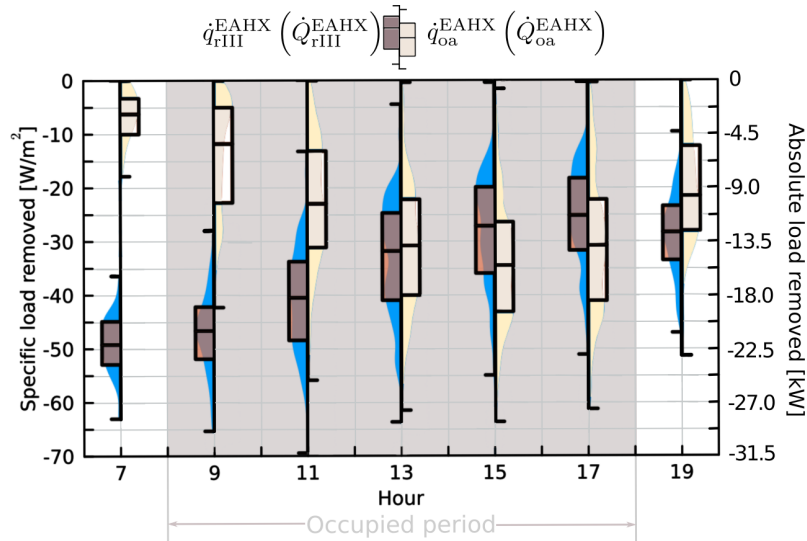


Fig. 9: Hourly violin- and box-plots for specific (and absolute) EAHX room load removal— \dot{q}_{rIII}^{EAHX} (\dot{Q}_{rIII}^{EAHX})—and for specific (and absolute) EAHX outdoor air load removal— \dot{q}_{oa}^{EAHX} (\dot{Q}_{oa}^{EAHX}). Obtained from monitored data (between June 1st and September 30th; cooling mode only, $T_{aL} < T_{a0}$; 8000 m³/h nominal airflow rate) considering Category III comfort expectation level. Grey shading highlights room occupied period. Left and right axis depict specific and absolute load removal, respectively.

⁸Using Equation (5) and the cooled office room floor area, 450 m². See Table 1 item (b).

As mentioned in Section 2.3 and confirmed in Figure 9, EAHX room load removal is larger during the morning, region B (the result of the added outdoor air free-cooling component, \dot{Q}_r^{OA}), whilst EAHX outdoor air load removal is larger during the afternoon, region C (the result of the added component \dot{Q}_n^{EAHX}). Figure 9 presents large absolute outdoor air load removal ($|\dot{Q}_{oa}^{EAHX}|$) during afternoons, with medians and maxima exceeding 13.5 kW and 27 kW, respectively. As regards specific room load removal ($|\dot{q}_{rIII}^{EAHX}|$), from Figure 9 it is concluded that median values of this performance index are always higher than 20 W/m², the room *design* (or peak) cooling demand (recall Section 2.1). However, during the afternoon, when summer outdoor conditions are more demanding and when the design outdoor air temperature typically applies (ASHRAE, 2005), interquartil ranges for $|\dot{q}_{rIII}^{EAHX}|$ are very wide extending from ~ 0 W/m² (Q_1) to above 50 W/m² (Q_3). It is, hence, important to assess in more detail the actual EAHX room load removal for hot afternoons.

Using monitoring data, Figure 10 presents the following conditional probability distributions, $P(|\dot{q}_{rIII}^{EAHX}| \geq \dot{q}_r^{BLDG} | T_{a0} = T)$ with $\dot{q}_r^{BLDG} \in \mathbb{R}$ and $T \in \{33^\circ\text{C}, 35^\circ\text{C}, 37^\circ\text{C}\}$, i.e., the probability that the EAHX delivers a specific (room) cooling capacity greater or equal to the specific room cooling demand, \dot{q}_r^{BLDG} ; conditional to outdoor air temperature being equal to Beja's 2%, 1% or 0.4% design dry-bulb outdoor air temperatures⁹ (ASHRAE, 2005).

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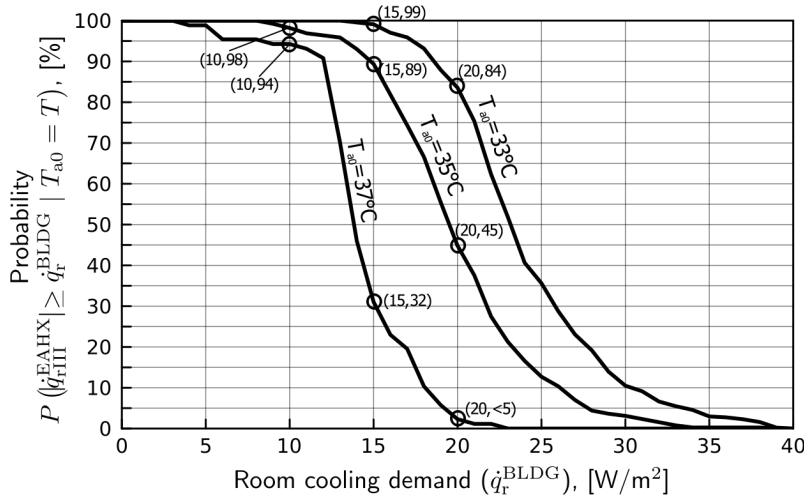


Fig. 10: Probability that the EAHX specific (room) cooling capacity is greater or equal to a specific room cooling demand, \dot{q}_r^{BLDG} ; conditional to outdoor air temperature being equal to T . Obtained from monitored data (between June 1st and September 30th; cooling mode only, $T_{aL} < T_{a0}$; 8000 m³/h nominal airflow rate) considering Category III comfort expectation level.

Figure 10 shows that for Beja's 2% design dry-bulb outdoor air temperature ($T_{a0} = 33^\circ\text{C}$) the probability that the EAHX meets the 20 W/m² room peak cooling demand is 84%. Therefore, considering this (less demanding) outdoor air temperature design criterion, standalone use of the

⁹Actually, T represents the interval $[T - 0.5, T + 0.5[$.

built EAHX for office room cooling is accepted.

390 For the 1% design dry-bulb outdoor air temperature ($T_{a0} = 35^{\circ}\text{C}$) the probability that the EAHX
meets the 20 W/m^2 room peak cooling demand reduces to 45%, and for the most demanding 0.4%
design criterion this probability is less than 5%. For these moderate and more demanding criteria
($T_{a0} \geq 35^{\circ}\text{C}$) it is concluded that standalone use of the built EAHX does not provide sufficient
cooling and does not warrant room temperatures below the upper setpoint. Still, Figure 10 shows that
395 the built EAHX delivers room cooling capacities of 10 W/m^2 with approximately 100% probability,
and delivers room cooling capacities of 15 W/m^2 with 32% to $\sim 100\%$ probabilities (from 0.4% to
2% design dry-bulb outdoor air temperatures). This means that despite insufficient, a significant part
of the room design cooling demand (at least more than 50%) is already provided by the built EAHX.

As regards the built EAHX standalone use, these results lead to the following conclusions:

- 400 i) The built EAHX operates in standalone mode, delivering the required room *design* (or peak)
cooling demand and providing acceptable comfort in the cooled rooms (Category III, EN
15251:, 2007), if outdoor air temperature does not exceed 33°C (2% annual cooling design
dry-bulb outdoor temperature, ASHRAE, 2005).
- ii) For outdoor air temperatures exceeding 33°C , the built EAHX allows room cooling during the
405 whole summer, however, room load removal is insufficient to meet the room *design* cooling
demand. If room comfort Category III is judged appropriate, the built EAHX provides, on its
own, more than 50% of the room *design* cooling demand.
- iii) If high room comfort is expected (Category I, EN 15251:, 2007), the built EAHX ceases room
cooling for outdoor temperatures exceeding 37°C (the 0.4% annual cooling design dry-bulb
410 outdoor temperature, ASHRAE, 2005).

To meet/deliver the additional room cooling demand necessary for cases (ii) and (iii) above, the
following strategies could be implemented:

1. Alter the EAHX design; for example, increase pipe length, change pipe layout.
2. Complement EAHX room load removal with passive cooling techniques, e.g., forced night-
415 time ventilation and appropriate use of building thermal mass.

The first of the above strategies is useful for future EAHX design, not for the built one.

The second strategy is described in Zimmermann (1999) and several other authors (Barnard and
Jauzens, 2001; Hollmuller and Lachal, 2014), and is available with the researched cooling and ven-
tilation system, as already mentioned in Table 2, item (n). The analysis of the performance of the
420 hybrid EAHX-TM cooling and ventilation system (as classified by Soares et al. (2021), with TM
standing for building thermal mass), requiring the joint research of the built EAHX and the existing
building/distribution piping, falls out of the scope of this paper. However, considering experimen-
tal results found in studies dealing with building nighttime ventilation (Barnard and Jauzens, 2001;

Geros et al., 1999; Givoni, 1998), with significant room peak temperature reductions (~ 2 K) and
425 the significant decrease in refrigeration machine cooling need (up to 50% reduction, Blondeau et al.,
1997), the built hybrid EAHX-TM system should extend the range of outdoor air temperatures for
which room *design* cooling demand is met.

4 Conclusion

In this study the thermal and energy performance of an existing large diameter earth-air heat ex-
430 changer (EAHX) was evaluated as a strategy for standalone cooling of a small existing office build-
ing. The study used monitored data gathered during the summer period at the EAHX location, in
Alentejo, a region in the south of Portugal characterized by hot and dry summer conditions. Outdoor
and EAHX outflow air temperatures were registered and the loads removed in the EAHX were de-
termined for the nominal airflow rate ($8000 \text{ m}^3/\text{h}$). From the analysis of the experimental data and
435 from the discussions presented, the paper's findings can be summarized as follows:

- The large temperature difference between the undisturbed soil temperature ($\sim 17^\circ\text{C}$) and the
room upper setpoint ($\sim 30^\circ\text{C}$, considering adaptive comfort principles, EN 15251:, 2007) con-
firmed the feasibility of EAHX standalone cooling.
- Daily maximum EAHX outflow temperatures can be 9 K lower than the simultaneous outdoor
440 air temperatures and results confirm that air exits the EAHX at temperatures that never exceed
room upper setpoint for Category III, and that seldom exceed room upper setpoint for Category
I comfort expectancy levels (EN 15251:, 2007).
- Median values of EAHX specific room load removal are larger than $20 \text{ W}/\text{m}^2$, the room *design*
cooling demand; however, smaller EAHX room load removal occurs during the afternoon,
445 precisely when room cooling demand is higher.
- A detailed analysis of EAHX room load removal shows that the EAHX is capable of stan-
dalone cooling when outdoor temperatures do not exceed 33°C . When this temperature is
exceeded, standalone cooling would require changes in the EAHX design. Despite this lim-
itation, the built EAHX is capable of delivering more than 50% of the required cooling (for
450 Category III comfort expectancy) when outdoor temperatures are as high as 37°C (the most
demanding outdoor air temperature criterion used in “traditional” HVAC design, ASHRAE,
2005), and the combined use of the EAHX and passive cooling strategies (i.e., nighttime ven-
tilation) should increase the cooling delivered, meeting the room *design* cooling demand.

Although this study has focused on monitoring data for a particular case, it showed that cooling
455 with large diameter EAHX is a viable and interesting technology that fits the needs of buildings
located in hot and dry climates. Used in standalone mode or in combination with building passive

cooling techniques, large diameter EAHX extend the use of free-cooling with outdoor air and can replace refrigeration machines for room cooling.

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Nomenclature

A	area, m^2	III	denotes Category III comfort expectancy level
c	specific heat, $J/(kg\ K)$, in this paper $c_a = 1020\ J/(kg\ K)$	a	denotes air
D	diameter (EAHX pipe), m	$a0$	denotes air entering the EAHX
\dot{m}	mass-flow rate, kg/s (in this paper $\rho_a = 1.2\ kg/m^3$)	aL	denotes air exiting the EAHX
Q_1	first quartile, n.a.	as	denotes air supplied to a room
Q_3	third quartile, n.a.	oa	denotes outdoor air
\dot{Q}	heat-transfer rate, W	r	denotes (cooled) room
\dot{q}	specific heat-transfer rate, W/m^2 (of cooled floor area)	rm	denotes running mean
T	temperature, $^\circ C$	rs	denotes room setpoint
\dot{V}	EAHX airflow rate, m^3/s	$s\infty$	denotes undisturbed soil
z	depth (soil), m	Superscripts and abbreviations	
β	coefficient (taken as 0.8) used in Equation (12), none	AHU	denotes air handling unit
ΔT	temperature gradient, K	BLDG	denotes building
θ	outdoor daily mean temperature, $^\circ C$	EAHX	denotes earth-air heat exchanger
ϕ	relative humidity, %	HVAC	denotes heating, ventilation and air-conditioning
Subscripts		L	denotes lower (setpoint)
I	denotes Category I comfort expectancy level	NZEB	denotes nearly zero energy building
		TM	denotes (building or soil) thermal mass
		U	denotes upper (setpoint)

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