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Design optimization to enhance passive energy strategies. The KNOW HOWse project for Solar Decathlon Middle East 2018

Vittorino Belpoliti[a]*, Marta Calzolari[b], Pietromaria Davoli[c], Hasim Altan[d], Reem Nassif[a]

[a]*Architectural Engineering Department – College of Engineering - University of Sharjah, 27272 University City, Sharjah, UAE*

[b]*Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, Parma, Italy*

[c]*Department of Architecture, University of Ferrara, Via della Ghiara 36, Ferrara, Italy*

[d]*Faculty of Architecture & Fine Arts, Final International University, Kyrenia, 99370, Cyprus*

Abstract

The KNOW HOWse project, coordinated by the University of Sharjah in cooperation with the Research Centre Architettura>Energia of the University of Ferrara – Italy, participated to the Solar Decathlon Middle East 2018 in Dubai, an international competition where academic teams design, build, and operate energy-efficient solar-powered houses.

The particular UAE climatic scenario implies consistent use of cooling throughout the year. For this reason, the KNOW HOWse project was developed to maximize the use of passive cooling strategies, in order to limit the electricity demand.

This paper presents a summary of the long design and construction process, aimed at optimizing the building shape to meet the competition functional/size requirements, while at the same time enhancing the passive energy strategies, with particular regards to free-cooling ventilation techniques.

The design focused on the reinterpretation of traditional environmental strategies, such as cross-ventilation, wind tower, and chimney effect, merging them with innovative technologies. Software energy simulation assisted the design optimization.

The resulting morphology of the house indeed showed enhanced natural ventilation within the premises. Furthermore, the recording of the energy consumed for active cooling, during the contest period, showed the positive reduction of air conditioning.

Keywords: Solar Decathlon; passive design; energy simulation; energy monitoring

* Corresponding author. Tel.: 971-563920305
E-mail address: vbelpoliti@sharjah.ac.ae

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1. Introduction

The team coordinated by the University of Sharjah and comprising the Research Centre Architettura>Energia of the University of Ferrara (Italy), Shurooq – Sharjah Investment and Development Authority, and Sheikh Zayed Housing Programme, presented the KNOW HOWse project [1] at the Solar Decathlon Middle East 2018 in Dubai (SDME) [2], a competition patronized by DEWA [3] where academic teams compete to design, build, and operate energy-efficient solar-powered houses. In the 2018 edition, 16 teams from around the world delivered a house to the contest site in Dubai and challenged each other on ten aspects of environmental design and energy management.

This paper presents the partial results of the KNOW HOWse's energy performance during the contest period (10 days, from November 18th to 28th), under constant monitoring by DEWA.

More precisely, the hereby-presented outcomes focus on the passive energy strategies (building shape, envelope construction, and natural ventilation) activated to contrast an initial unexpected consumption due to a device malfunctioning. This paper moves from the state-of-the-art on passive cooling in hot climates, providing measured outcomes that contribute to prove the energy/environmental benefit achievable thank to an optimized design process: from early stage massing and shaping, through the selection of suitable construction techniques and technologies, to the simulation of energy performance and behaviour, the team successfully counteracted an initial energy loss with passive strategies. The team finally ranked 8th and received the Best Middle Eastern University Award.

Nomenclature

S/V	Exposed Surface area / Gross Volume
S_c	Exposed Surface area in Cooling conditions = S minus ground floor area (if adjacent to ground)
S_c/V	Exposed Surface area in Cooling conditions / Gross Volume
SHGC	Solar Heat Gain Coefficient
AC	Air Conditioning system
CLT	Cross-Laminated Timber
PV	Photovoltaic devices
CFD	Computational Fluid Dynamics

2. Architectural Design

2.1. Combining tradition and innovation by means of energy efficiency

The KNOW HOWse design aimed at re-educating locals to their traditional housing identity, including the multiple spaces dedicated to different activities for men and women, originally articulated in the nomadic tent complex, then in the first steady houses, and finally almost overriden by western typologies in the 1970s, after the discovery of oil. The project aimed at merging the housing heritage features with the more efficient compact western typology. The proposed project investigated and reinterpreted the traditional techniques and typological layout of the original Emirati house, updating them by means of contemporary design practices.

3. Energy efficiency through optimized massing and modelling

3.1. Orientation

The orientation of the building was a key feature for the success of its passive energy strategies. Furthermore, the optimal orientation was not easy to achieve, since the design had first to comply to the stringent SDME building code. Figure 1 shows the "solar envelope", an imaginary truncated pyramid defining the volumetric limit that the house could not cross (Fig. 1). Given the above restrictions, the KNOW HOWse succeeded in achieving the best possible orientation related to the final massing. The simple shaped building has the 4 facades oriented to the straight cardinal directions, to activate specific passive energy strategies. The northern face is more open and glazed on both floors. The southern face, with glazing on ground- and first-floor, in the terrace, is protected from the high sun by a deep overhang shed. The West facade, heavily radiated by the direct sunset sun, has smaller windows, while the East one, hit by the morning sun, has a large entrance glazing, shaded by external devices.

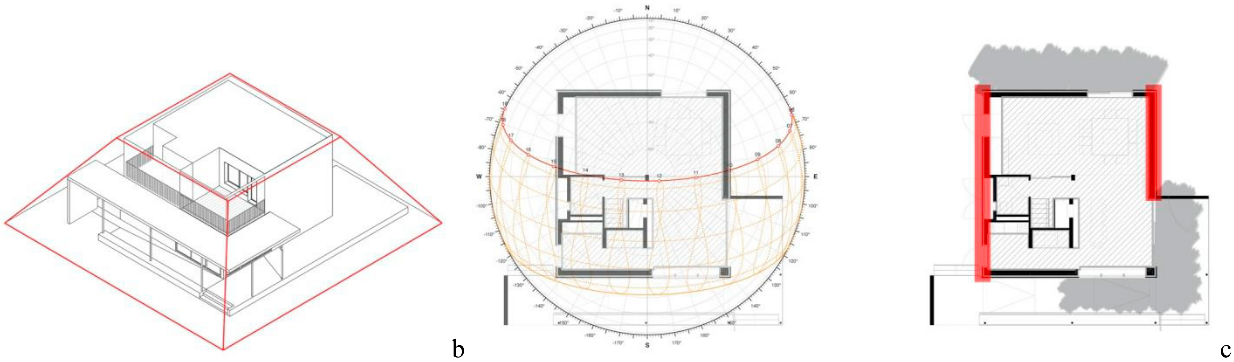


Fig. 1. The volume contained in the "solar envelope" (a), the plan in relation to the sun path (b) and its influence on the design: heavy shield-walls on east and west sides, appropriately shaded openings on north and south (c)

3.2. Project geometry: a case-specific S/V ratio

The building was designed according to the energy conservation approach. As one of the few 2-storey houses on site, it has a compact shape (cube-like) that makes it energy conservative. Table 1 presents a summary of the house dimensions, along with other data relevant to understand its energy performance. Among these features, the S/V ratio is mostly used to estimate the passive performance of the envelope, with particular regard to heat losses (and gains). To this regard, beside the design approach aimed to volume optimization and S/V minimization, this study proposes a novel calculation for the S/V itself, accounting for the difference in heat losses and gains, which are relative in general physics but not in real conditions: while in a cold climate heat gains are a benefit, but also minimal, in a hot climate (like Dubai) heat losses have to be considered a significant benefit, overall in regards to the floor adjacent to the ground, which acts as heat sink. For this reason, this study proposes a cooling-related S/V ratio (S_c/V) where the exposed surface area omits the square meters of the ground floor (Table 1).

3.3. Buffer zones

Within the simple cube-like volume, some spaces can be unoccupied to act as thermal buffers. The main function of buffer zones is the separation of the envelope and isolation of spaces. The house is provided with movable partitions (Fig. 2), not just for flexibility/maximization of space, but also to allow for different reconfigurations of the thermal zones. Among all, the movable floor (Fig. 2c and Fig 3c) allows isolating the higher space that could be non-conditioned, resulting in a reduction of the cooled volume and therefore a potential energy saving (Fig. 3).

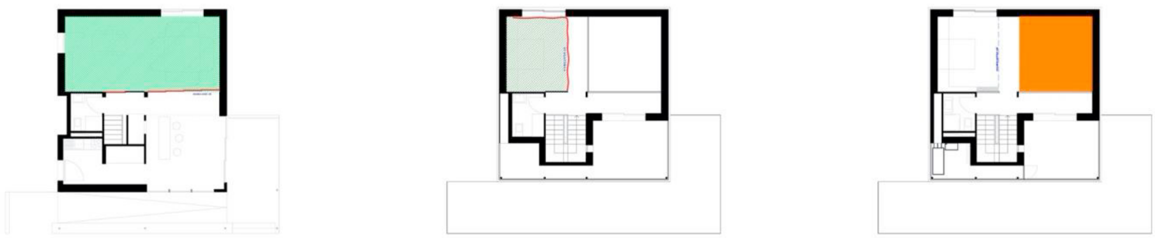
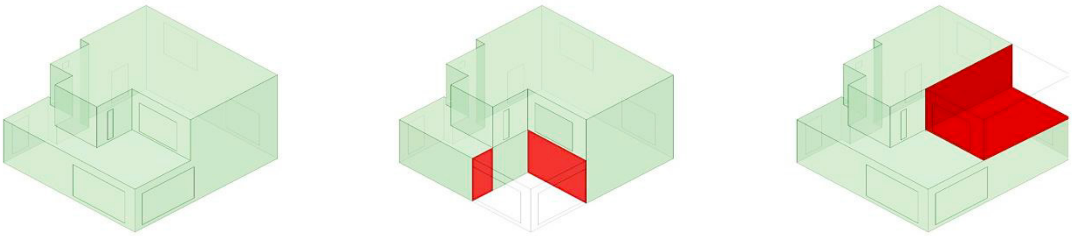


Fig. 2. The flexibility allowed by the movable features: in (a) and (b) the red lines indicate the vertical movable partitions, while in (c) the orange hatch shows the sliding slab that separates ground- and first-floor by halving the double-height space.

The entrance area can be separated by the movable wall, potentially becoming an indoor-outdoor space. Hence, it could be non-conditioned at given times of the year. If the movable floor is active, the ground floor does not have to cool the double height space, but just the ground floor internal net-height. In that case, not only the volume to condition is reduced, but the unoccupied space on the first-floor can act as a thermal buffer for ground floor spaces (if not conditioned and naturally ventilated by opening windows on opposite sides).



a b c

Fig. 3. Mass-model schemes showing the house's whole volume (a), and with active buffer-strategies that reduce the cooled volume: movable partition on ground floor to divide spaces horizontally (b), sliding floor to divide the spaces vertically (c).

4. Energy simulation to optimize the construction systems

The KNOW HOWse innovative structural system is made of structural solid CLT panels. The semi-prefabricated CLT system is characterized by high structural flexibility, it is easy to assemble and less time-demanding than conventional structural materials (i.e reinforced-concrete, mostly used in the UAE construction market). Thanks to the literature review on the topic [4], specific assembly manuals have been prepared to optimize the fabrication, shipping, and assembly of the these house components, as previously documented [5].

With regards to the insulation, the KNOW HOWse uses a reversed strategy for the thermal envelope: the insulation coating (15 cm polystyrene foam), normally applied on the outside, is applied on the inner leaf of the envelope components. In this way, the cooling load is limited to the net volume of the house, and can be easily chilled by the selected convective AC system (otherwise, a massive construction would soak part of the cooling energy supplied to the room, overall if a radiant cooling is used). This strategy would suggest a further revision of the S/V ratio, calculating the S with internal measures (net) and V as the net volume (the air-conditioned space). Such calculation could be a better indicator of the energy-conservation capacity of the house. However, for comparison purposes (with other literature cases) the study kept the S/V calculated as per gross measures. Table 1 lists the thermal features of the building envelope and the calculated S/V.

Then, the envelope is cladded outside with magnesium panels, a dense product that increases the already significant thermal mass granted by the CLT structural timber, and creates a passive efficient shield against sun radiation and overheating. Finally, the outer leaf of the magnesium finishing is coated with a special cool paint, capable of reflecting significant portion of sun radiation and enhancing the thermal property of the envelope. The roof, heavily hit by sun radiation, is as insulated as the walls and coated with the cool paint.

Shading systems are not pivotal to the aim of the study, but for a general understanding of the design, and of the model used for the energy simulations (Fig. 4), the list below describes the different shading devices per location:

- Outdoor window rolling-curtains to stop most of the direct solar radiation;
- Outdoor curtain to shade the first-floor terrace and applied as walls' second-skin, detached from the main envelope by means of aluminium frames to create a micro-ventilated gap;
- Louvers overhang shed protecting the South façade and glazing, and the entrance glazing on the East façade;
- PV array to shade the roof and create ventilation under the PV modules.

Table 1. Building features used to model the building in the software platform, and to run the simulations for its energy optimization

Division	Feature	Dimension	Performance index	
House dimensions	Total built-up area	108.8 m^2		
	Net volume	273.8 m^3		
	Gross Volume (V)	479.1 m^3		
Energy-related parameters	*Standard Exposed Surface area (S)*	412.1 m^2		
	Cooling-related Exposed Surface area (S_c)	323.5 m^2		
	Standard S/V Ratio	0.86		
	Sc/V Ratio (cooling-related)	0.67		
	Window-to-wall ratio	0.20		
House envelope	External Walls	194.8 m^2	U-value:	0.209 W/m^2K
	Ground Floor	88.6 m^2	U-value:	0.265 W/m^2K
	Roof	88.6 m^2	U-value:	0.287 W/m^2K
	Glazing	40.1 m^2	U-value: SHGC:	1.666 W/m^2K 0.45
House systems	Cooling external unit		COP:	6.13
	Whole AC system (with system's losses)		COP:	4.9
	LED Lighting		4 kWh / day	

The house, modelled as shown in figure 4 (and per the features described in table 1) was run through Design Builder [6], a commercial software for advanced simulations of dynamic-state energy performance, to predict its behaviour in both passive and active scenarios, as requested by the competition rules and previously documented for other Solar Decathlon events [7, 8]. The simulations helped to further optimize envelope features (overall in regard to windows' size and shading) and systems; however, as obvious, it did not account for contingencies of something not going according to plan (as it happened, please refer to paragraph 6). For this reason, this paper does not present the mere software energy simulation results.

A more useful software simulation, even if initial and approximated, was run by means of Flow Design [9], a CFD analysis freeware operating preliminary analyses of the environmental air-/wind-flow in regard to any modelled object in a confined space. The software, even with its limitations, was useful to verify the morphology of the building in regard to potential air direction to passively cool the indoor spaces. CFD simulation has already been used for similar scopes, and interesting results can be found in literature [10, 11].

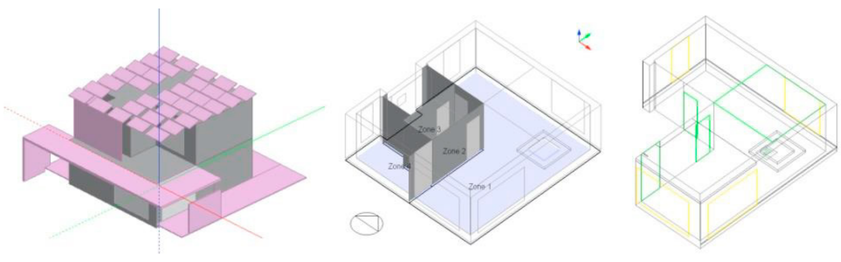


Fig. 4. Image extracted from the modelling space of the dynamic-state energy performance software used for the simulation. The house was modelled in detail, in order to have an accurate energy outcome.

5. CFD-assisted optimization of the building shape to enhance passive ventilation

The KNOW HOWse was designed to reconfigure its interior volume and shape to adapt to the dynamically changing climatic phenomena (temperature, humidity, wind). Orientation of the building was pivotal to the success of its environmental strategies, among which ventilation. Working with aleatory resources such as wind requires for boundary conditions to be known, and fixed. The location of the SDME competition (Dubai desert, about 60 km from the shore) and the contest period (November 2018) allowed planning for passive strategies that make use of the winter wind (hot and dry coming from the desert, cooler and more humid coming from the sea) to assist the active systems in cooling the building.

The building shape makes it act as a wind tower, thanks to the double-height space. Figure 5 (a) shows the behaviour when, in the morning, the south terrace catches the dry desert wind and pushes it inside, naturally conditioning the ground floor area and assisting its cooling.

Furthermore, the house's morphology enhances the stack effect: the double-height living room benefits from the natural temperature gradient, which pushes heat up, keeping the lower occupied area cooler. The first-floor windows can be opened to increase this effect and remove the extra heat. The wind pattern enhances the hot air removal by creating higher pressure on the opposite side of the house. Figure 5 (b) shows the effect occurring with north wind.

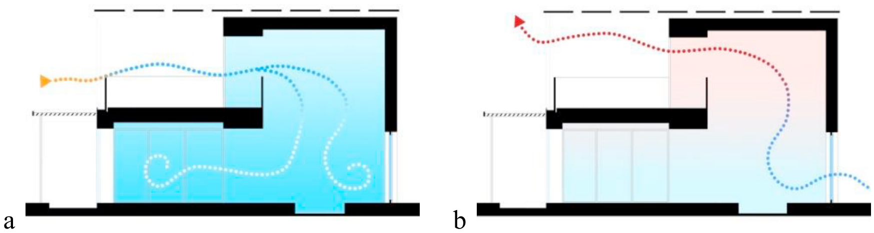


Fig. 5. Early bioclimatic design: section showing the wind tower effect with south wind (a) and the stack effect with north wind (b).

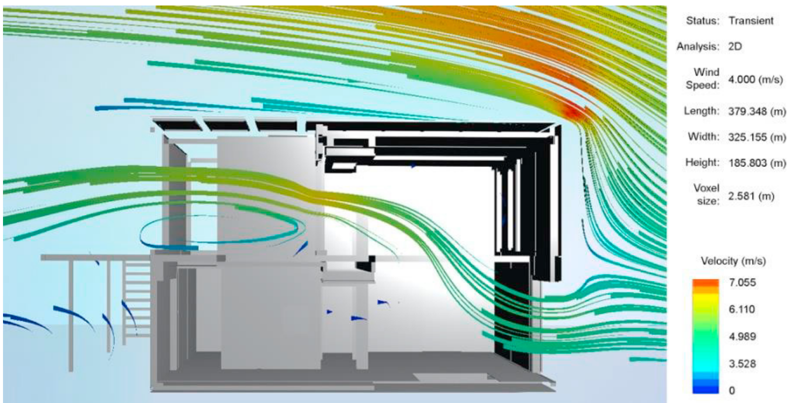


Fig. 6. Preliminary CFD analysis showing the effective airflow (potential passive cooling): stack effect configurations.

Both scenarios have been simulated using the software Flow Design, a freeware tool that can run simple (although approximated) CFD analysis that might not allow to precisely control temperature gradients but can help understanding if the building shape allows activating the predicted airflow, or if it needs remodeling. As an example, figure 6 shows the CFD simulation of the expected efficient air circulation for the stack effect scenario.

6. Energy monitoring: a means to correct energy-inefficient behaviours

The energy performance at contest site (Dubai desert) was duly monitored by means of professional kits of sensors provided by the competition organization. Indoor comfort was monitored by collecting temperature, humidity, CO_2, and lighting levels in three areas of the house (living room, kitchen-dining, and bedroom); 3 energy meters were installed to collect consumption information (AC + lighting, domestic appliances, and PV production); all data were gathered, for each participating team, at sub-hourly steps for the whole duration of the contest (10 days, from November 18th to 28th) and provided live on the SDME website [12] for all teams to see.

The monitoring, that came live on the 3rd day of contest (21/11/2018), could be used by any team to see the other teams' progress and partial ranking, but also to verify their own performance and improve their strategy accordingly.

This is what happened to Team KNOW HOWse when its AC compressors had a malfunction, ending up consuming a very large amount of energy in the first 3 days of measured contest (red-hatched portion in figure 7).

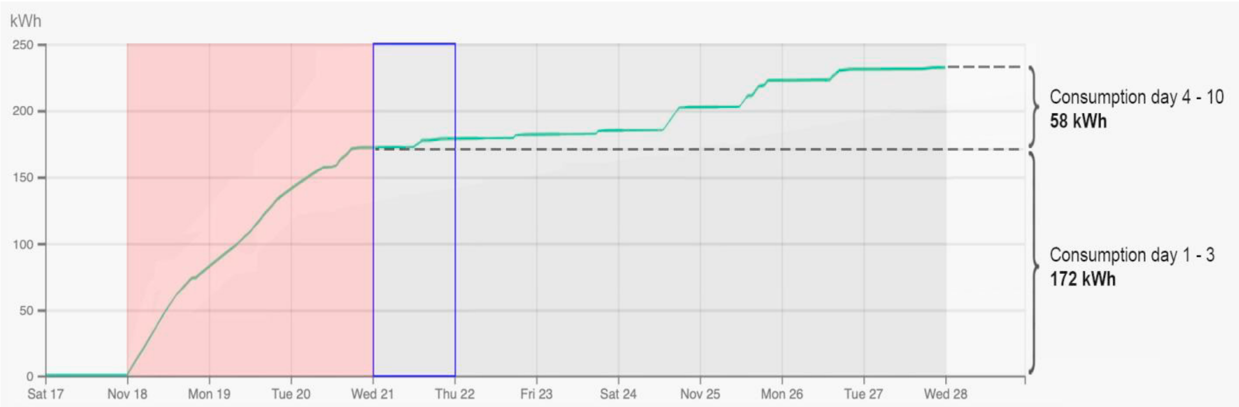


Fig. 7. Combined AC and lighting consumption: the red-hatched portion highlights the first 3 days of contest, when Team KNOW HOWse suffered a malfunction of the AC system that caused overconsumption; the blue box frames day 4 (21/11/2018), first day after correcting the malfunctioning, and therefore assumed as reference day.

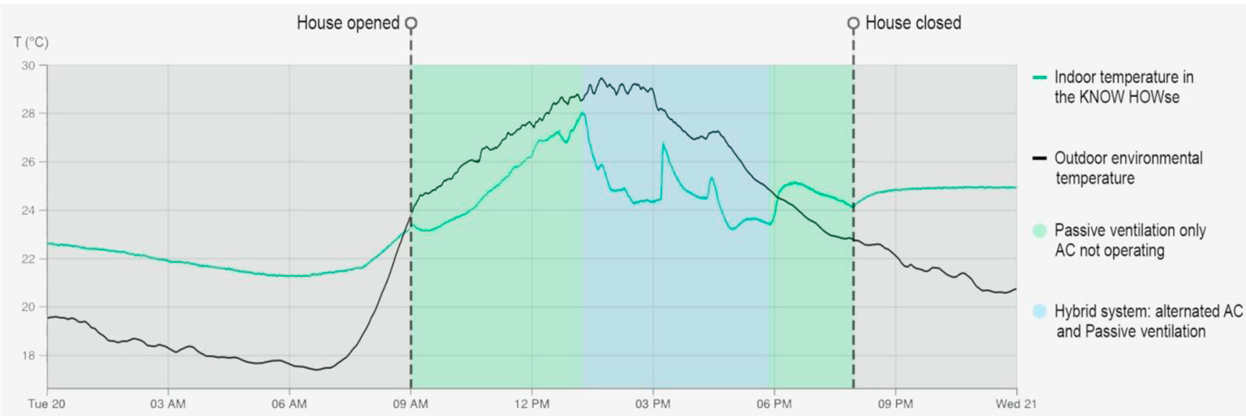


Fig. 8. Temperature monitoring on the reference day (21/11/2018): The chart shows how the passive cooling strategies allowed Team KNOW HOWse to keep the indoor temperature cooler than the outdoor one, without the use of AC (green) or with mixed active passive strategy (blue).

Since the live monitoring was only available from the 3rd day, only by that time the team acknowledged the unexpected consumption and worked out a new strategy to stay competitive for the rest of the contest, relying on passive strategies as much as possible. This included the massive and insulating envelope, but overall the passive ventilation. The chart in figure 7 shows how the team's energy consumption (combined consumption of AC and lighting, as per SDME monitoring) reduced significantly after the 3rd day. Comparing the energy consumption calculations until day 3 and for the rest of the contest shows how Team KNOW HOWse efficiently corrected its behaviour: deducting the lighting demand (estimated in table 1), on a daily basis the team managed to improve its AC consumption from the initial 53.3 kWh/day (first three days) to the 4.3 kWh/day of the typical contest day.

It is hard to quantify the part that passive strategies played in the improvement: the noticeable natural ventilation enhanced by stack effect and wind tower effect cannot be demonstrated, as anemometers were not included in the monitoring kit. However, the sub-hourly temperature values recorded by the sensors show that indoor temperature has kept below the environmental outdoor temperature during the occupation period (9:00 am – 8:00 pm), by using passive strategies only, or mixing passive/active systems during the daily heat peak (figure 8).

7. Conclusions

The paper presents the first performance results of the KNOW HOWse, in particular comparing the design-stage simulations with the outcomes monitored at the SDME 2018 in Dubai. The use of software modelling and simulation helped the optimization of the building shape, its energy conservation, the AC sizing, and the capacity of enhancing natural ventilation and passive cooling. While the functionality of the optimized envelope and AC system can be estimated, it is very hard to do so for the benefits generated by the passive ventilation/cooling. However, the monitoring of the house's performance shows that the combination of passive and active cooling allows keeping the indoor temperature below the outdoor levels, even if slightly above the maximum 26 °C of the comfort zone.

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