Thermal comfort study in MSMEs in Cairo using onsite measurements and optimization algorithm

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Abstract

Micro, Small & Medium Enterprises (MSMEs) in the hot climates in Egypt face many challenges with increased heat stress, reduced labour productivity and adverse occupational health effects, often leading to work injuries and heat stroke. This study investigates an MSME case study in Cairo, Egypt, dedicated to car maintenance in planned service areas. These workplaces suffer from poor thermal comfort and indoor conditions that significantly contribute to climate resilience and thus require immediate action. The study aims to evaluate the indoor thermal comfort conditions in the case study MSMEs using actual measurements and identify opportunities for improving indoor conditions using the Ladybug Tools in a Rhino-Grasshopper platform and genetic algorithm optimization approach. Through monitoring activities and thorough investigation, a validated model has been effectively established. The findings of this analysis have proven the capacity for performance enhancements by implementing parametric optimization methods in such limited time and conditions.

Highlights

- Poor environmental conditions at the MSMEs in Cairo
- Onsite monitoring of indoor environment at MSMEs
- Using parametric simulation tools in validating and optimizing an existing case study.

Introduction

Climate change results in significant risks to our building stocks and occupants in the hot climate, including overheating, higher energy demand for cooling, increased thermal discomfort in buildings, and energy poverty. Buildings have to utilise passive measures to decrease their energy use and the consumption of fossil fuels. The potential consequences of the climate crisis affect the increase of greenhouse gas emissions (GHG). Applying climate change mitigation measures is recognised globally in the United Nation's Sustainable Development Goals (SDGs) (Josef Korbel School of international studies university of Denver, 2018). As a response to global warming, building adaptation is needed to cope with higher temperatures and more extreme weather in the future. Egypt is one of the countries with the greatest vulnerability to climate change. The average temperature of Cairo, the capital of Egypt, is projected to rise by 4°C due to global warming by 2060. The industrial sector in Egypt is responsible for about 36% of energy Consumption (Makumbe et al., 2017). Further, MSMEs provide employment for a large portion of the population (Helmy Elsaid et al., 2014). In this regard, It is essential to study the thermal comfort conditions (Sharmin, Steemers and Humphreys, 2019) in workplaces of Micro, Small & Medium Enterprises (MSMEs) as one of the main elements affecting people's productivity and health (International Labour Office, 2018). It is noted that international standards have been issued that specify maximum recommended heat exposure levels and prescribe regular rest periods at workplaces for acclimatised and non-acclimatised workers (International Organization for Standardization (ISO), 2006; ASHRAE et al., 2009).This pilot study investigates MSMEs dedicated for car maintenance and repair, a common land use in planned service areas. Nevertheless, these workplaces suffer several problems in terms of high energy consumption, poor thermal comfort and indoor conditions as well as high emission levels (Lowe et al., 2012). All of these are major contributors against climate resilience and require immediate action, especially that they exist in several planned urban areas acting as a repetitive unit in an urban cluster (Lila, Jabi and Lannon, 2017; Javanroodi, Nik and Mahdavinejad, 2019; Lila and Lannon, 2019).

This study addresses MSMEs in Sherouq new city located in Cairo governorate, Egypt. This workshop area is dedicated for car maintenance and repair, including equipment maintenance, and car service as shown in Fig. (1) and (2). The street length is 654m and the urban cluster is 654 square meters. Hence, it is an average of 50 small workshop spaces, each with a total average area of 350-370 meters square. It has medium occupancy, hosting an average of 150 full-time and 250 transient occupants daily. Moreover, the place is characterized by poor indoor air quality and a poor work environment for workers. Thus, the study investigates the current level of thermal comfort and discomfort hours to suggest alternatives for improving thermal comfort in the work provide city's services centre. It has medium occupancy, hosting an average of 150 full-time and 250 transient occupants daily. It is noted that the functional activity extends beyond the limits of the functional space to occupy the street as well. Moreover, the place is characterized by poor indoor air quality and a poor work environment for workers. Thus, the study investigates the current level of thermal comfort and discomfort hours to suggest alternatives for improving thermal comfort. This study focused on getting a simulation model validated and optimized to act as a proof of concept for future studies. This could act as a pilot project in new cities to mitigate the problem of climate change and provide simplified adjustments to local owners to excute these mitigitations on thier own workplaces when possible.

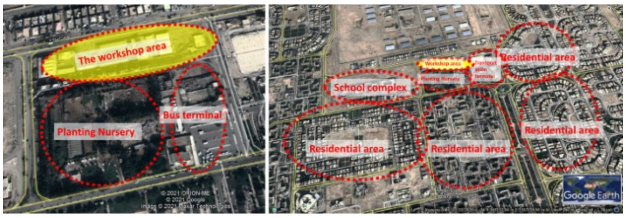


Figure 1. The urban context of the workshop area

Method

The workshop is located in Cairo, representing the hot-desert climate (BWH) according to the Köppen-Geiger climate classification. Table 1 refers to the details of Cairo climatic conditions. According to ASHREA Standard 55, thermal comfort conditions in summer range between the temperature 25 – 27°C and 21 -26°C in winter. The relative humidity is between 10% - 80%. Consequently, there is a need to control temperature and humidity in this climate to achieve the required thermal comfort conditions.

Table 1: Cairo Climatic Conditions

Köppen–Geiger climate classification	BWh
Latitude & Longitude	30.13 N, 31.4 E
Dry-bulb Temp.	Min 13 C, Max 28 C
Relative Humidty	45-68%
Summer Temp Range	Hot humid 22-35 ^{0}C

The case study is a standalone building with three floors; the ground and first floors are working spaces, an office and a storage. The second floor includes the workers' living area. The workshop is open every day, but each room has its own operational schedule. The whole building is naturally ventilated.

Figure 2. To the left is the location of the building, the western façade of the building, to the tight the northern and southern façades of the building

Monitoring activities

Site visits were conducted to specify the spaces to study, data loggers' time frame and choosing the monitoring points.

Six workshop spaces were chosen for monitoring as shown in (Fig. 3 ,4):

Code	Floor	Orientation	Description
(1)	Ground floor	Western facade	-
(2)	Ground floor	Southern façade	-
(3-G)	Ground floor	Southern façade	with two doors south and north (cross ventilation)
(3-1)	First floor	Southern façade	3 & 4 is a double height workshop.
(4-G)	Ground floor	Southern façade	-
(4-1)	First floor office	Southern façade	above (4-G)

For monitoring, two types of equipment were uses: mini data loggers for temperature and humidity (Testo 174H), and Van anemometer (Testo 410).

Figure 3. The workshop building with the six work places to be monitored.

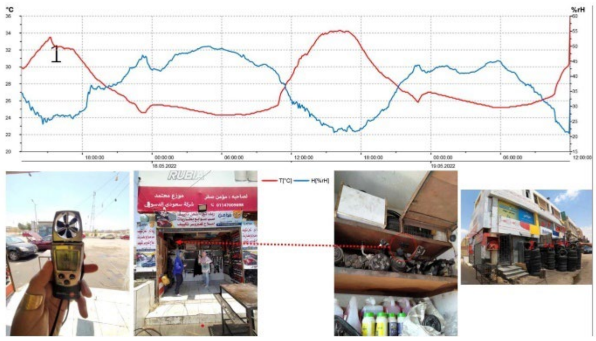


Figure 4. The testing phase

The final monitoring phase was scheduled for a week starting from May 28 to June 4. Site visits took place on a daily basis at 12:00 pm to check the loggers and to record wind speed by using anemometer at 20 points (indoors, outdoors, and at windows and doors). Additionally, space dimensions and its interior furniture and settings were recorded as shown in Figures 5,6. Figure 8 presents some indoor photos of the workshops.

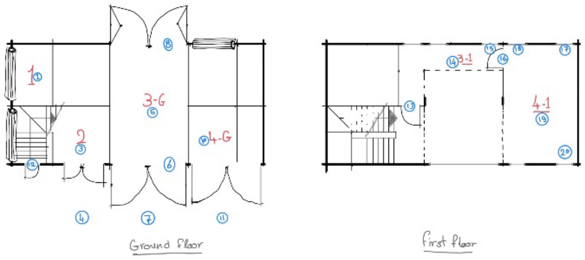
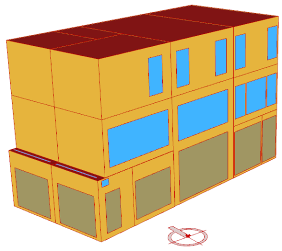


Figure 5. the locations of every day anemometer monitoring during the site visit

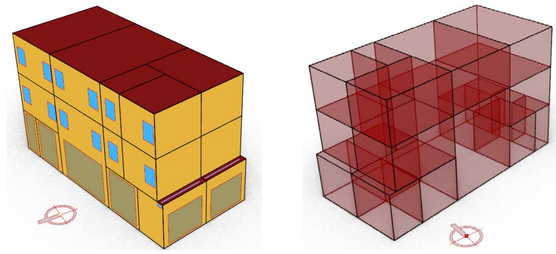
Figure 6. Actual photos from the site to the selected six workplaces

Baseline Energy Model

Fig.7 shows the final energy model in Rhino Grasshopper with the apertures being defined as windows and doors within the associated thermal zones. Simulation was performed using "Lenovo Legion Y520"(7th Generation Intel® Core™ i7-7700HQ Processor). Figure.8(a) shows each workshop position in the model with its reference code. The energy model settings went through different stages of iterations in order to reach for the optimal validated model for workshop number 1 as a starting phase. The purpose was to focus on enhancing the preliminary model using one workshop to assure the energy model mimics reality as much as possible and to get the least possible differences between the measured and simulated data before moving to other workshops. The initial, one example from the inbetween stages and final validated model settings are shown in Table 2. Figure. 8 (b) shows the first two stages of the model were both models had all apertures assigned as windows, the initial model does not include the modeling of cracks and projection (edits made by workers), and the second model includes them all.



(a)



(b) **(c)**

Fig. 7. (a) Shows energy model south-west view in Rhino Grasshopper. (b) Shows energy model south-west view in Rhino Grasshopper. (c) Thermal zones of the simulated building.

Figure 8a. Workshops position and code.

(a) (b)

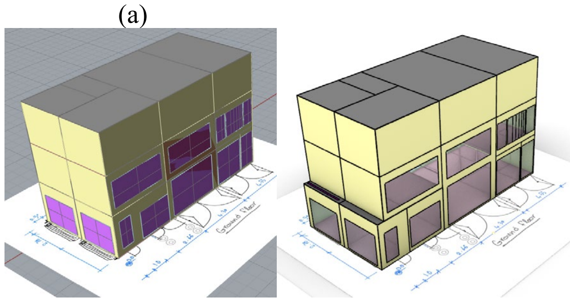


Fig. 8b. (a) The initial energy model in Rhino grasshopper. (c) The energy model in Rhino grasshopper after editing workshop 1 modeling and fenestration.

Table 2. Shows initial, example of a middle stage, and final energy model settings.

Parameter	Model (1)	Model (2)	Final model
Zones number	18	19	19
Shading	No shading	No shading	No shading
Program	Default: open office	Warehouse: Bulk	Warehouse: Bulk
Conditioned	Not conditioned	Not conditioned	Not conditioned
Ext & int walls	CBECS1980-2004 EXTWALLMASS CLIMATEZONE 2B 1 IN Stucco 8 IN CONCRETE HW RefBldg Mass NonRes Wall Insulation-0.43 ½ IN Gypsum	CBECS1980-2004 EXTWALLMASS CLIMATEZONE 2B 1 IN Stucco 8 IN CONCRETE HW RefBldg Mass NonRes Wall Insulation-0.43 ½ IN Gypsum	Ext.: Heavyweight masonry 0.25m thickness Int.: Heavyweight masonry 0.12m thickness
Walls U-value	3.57 W/m-K	3.57 W/m-K	0.90 W/m-K
Walls density			1850 Kg/m3
Walls specific heat			840 J/Kg-k
Roof	CBECS BEFORE-1980 EXTROOF IEAD CLIMATEZONE 1-3	CBECS BEFORE-1980 EXTROOF IEAD CLIMATEZONE 1-3	Heavyweight concrete 0.07m thickness
Roof layers	1/2IN Gypsum AtticFloor NonRes Insulation-1.76 1/2IN Gypsum Roof Membrane IEAD NonRes Roof Insulation-1.76 Metal Decking	1/2IN Gypsum AtticFloor NonRes Insulation-1.76 1/2IN Gypsum Roof Membrane IEAD NonRes Roof Insulation-1.76 Metal Decking	
Roof U-value	0.637262 W/m-K	0.6373 W/m-K	0.73 W/m-K
Roof density			1800 Kg/m3
Roof specific heat			840 J/Kg-k
Glazing	ASHRAE 189.1-2009 EXTWINDOW CLIMATEZONE 2	ASHRAE 189.1-2009 EXTWINDOW CLIMATEZONE 2	Solid glass 0.006m thickness
Glazing layers	Theoretical Glass [197]	Theoretical Glass [197]	
Glazing conductivity	13.83 W/m-K	13.83 W/m-K	0.90 W/m-K
Glazing transmittance			0.85
Glazing reflectance			0.075
External doors	No doors	No doors	Typical Uninsulated Steel Framed Exterior Wall
Ventilation schedule for workshop 1	Default	Opens 9 /closes 11 p.m	Opens 7 a.m. / closes 12 p.m.
Ventilation schedule for all other zones	Default	Default	Opens 7 a.m. / closes 12 p.m.

We faced many challenges in the validation stage. For example, we were not able to find a source for the building construction materials due to the lack of execution drawings for the building. Therefore, we added ASHRAE materials in reference to Cairo climate zone in the initial and middle stage. We also tried alternatives for the materials (Fig.8a) to be able to understand their impact on changing the simulation results. We concluded from this trials that the materials have a low impact on changing simulation results. Therefore, we fixed the Ashrae materials in the initial and middle phases and started working on alternative ventilation scenarios as ventilation proved to have a great impact on changing simulation results (Fig.8b). Ventilation was also another important challenge as we could not get accurate ventilation schedules for the workshops. This is because the workers stated different alternatives for opening and closing the workshops. In addition, we were not able to know if they tended to close any of the workshops during the working time for some reason or not. As it is hard for any of the researchers to keep observing the five workshops for 24 hrs per the monitored days. Therefore, we tried many ventilation scenarios for the first five measured days. Fig.8(b) shows graphs for different simulations performed with different ventilation scenarios for workshop 1.

Another important challenge is modelling the thermal zones, an example is that the first model in the two first phases had 18 thermal zones only (Fig. 3 & Table 1) as the second workshop and the staircase were regarded as one thermal zone, but later on the model was edited in the last two phases as to differentiate the discovered cracks in staircase from workshop 2 space. Another example is the modeling of workshop 3 as it is too complicated with variety of interior openings and interlocking spaces. Therefore, it was regarded as one double-height rectangular shaped room as shown in figure 10 (a).

We also had to analyze the photos and surveyed data many times to make sure we are mimicking the real building as much as possible. In a different phase, we discovered extrusion hide behind panels in the exterior wall of the first workshop main façade. In addition, we discovered cracks or gaps in the top part of workshop 1 and added them as windows opened for 24 hrs (Fig.6). Another challenge was that we were not able to add the doors of the workshops as opaque steel doors, but rather they were regarded as glazed windows and were assigned a ventilation schedule. This was fixed by upgrading to Honeybee and ladybug last version that allowed for the addition of ventilated opaque steel doors (figure 9). The building program was set to warehouse with the automatically assigned energy model loads available in Table 2a. Its important to note that the urban heat island effect and overshading from neighboring buildings were not accounted for due to the time and scope limitation of this pilot project. Therefore, future work might be directed towards accounting for urban scale simulation aspects.

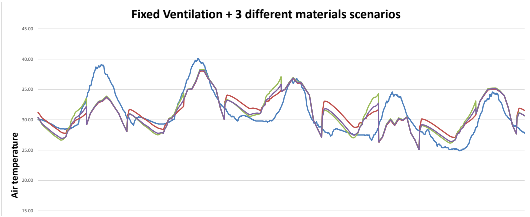


Fig.8a. Shows simulations for different constructions scenarios compared against the monitored data.

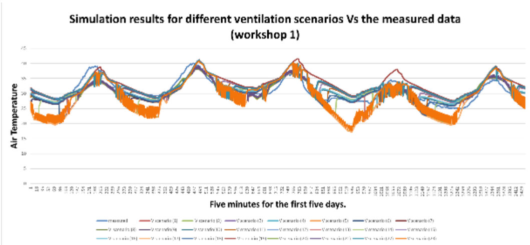


Fig.8b. Shows simulations for different ventilation scenarios compared against the monitored data.

Table 2a. Automatically assigned loads to the energy model (warehouse).

Load	Value
People	*0.021/m2*
Lighting	*3.6 w/m2*
Electric Equipment	*2.6 w/m2*
Infiltration	*0.000227 m3/s-m2*

Validation

Validating the model using such a new tool was a challenge especially with the consideration of project budgets and time limitations. The energy model is validated using ASHRAE 14-2014 that states the accepted calibration errors for hourly data using standard Statistical Indexes is 30% cumulative variation of root mean square error (CV (RMSE)). In the light of that study, EQ(1) is showing the equation that was used to calculate CV (RMSE) where M_i is the hourly measured data and S_i is the hourly simulated data:

$$CV\,(RMSE) = \frac{\sqrt{\sum_{i=1}^{24}(M_i - S_i)^2\,/24}}{\sum_{i=1}^{24} Mi/24} \qquad (1)$$

Each workshop is validated using the five minutes measured air temperatures for six days starting from 29, May 2022 till 2, June 2022. These measured data are converted to average hourly measured air temperatures and are compared to hourly simulated air temperatures. The following sections explain the validation results in detail for each of the five workshops:

Simulation and optimization

Optimization algorithms and parametric modelling have a significant role in developing sustainable building designs. This paper presents a calibration methodology consisting of different stages of adjusting the simulation settings and parameters until it reached to acceptable correlation with the monitored measurements. The energy simulation is carried out using the Honeybee plug-in for the Rhino-Grasshopper platform which facilitated the testing of relevant building parameters (building material construction, schedules for different openings and parametric shading modelling) through a number of iterations. Honeybee is part of the Ladybug Tools (Sadeghipour and Pak, 2013) working as an interface to multiple validated simulation engines such as EnergyPlus for energy modelling and simulation (U.S. Department of Energy's (DOE), 2016) and Radiance for lighting simulation (Ward, 1994). This set of tools and its equivalents have been used and validated in multiple simulation studies due to its added value of conducting automatic iterative simulations automatically leveraging from the generative nature of the grasshopper platform

(Bouchahm, Fatiha and Bouketta, 2012; Lila, Jabi and Lannon, 2017). In this study the Cairo weather file (.epw) available in (https://energyplus.net/weather) is used to perform the simulations using energy plus engine in Honeybee.

This research aims to use this framework to look for optimal solutions to enhance indoor environmental conditions through a genetic optimization algorithm following previous studies (Khalil, Tolba and Ezzeldin, 2021, 2023; Yan, Yan and Ji, 2022). This aim was to get a proof of concept of this framework and try to feedback the results to different stakeholders (owners, local policy makers, … etc) so it can guide future work.

In this study, the adaptive thermal comfort model of ASHRAE 55 is used to evaluate the summer solstice thermal comfort of the case study. The adaptive thermal comfort model is used to assess the interior of buildings that do not have a heating or cooling system and have the option of opening windows for natural ventilation.

Research in the architectural field generates new configurations as alternatives for building elevations, space planning, envelopes, and massing through search algorithms such as Particle Swarm, and Ant Colony Optimization (Kheiri, 2018). This is an application of how research is utilising optimization methods and principles to find an optimal solution to a problem in this research. It is more focused on the workshop indoor environment optimization towards better thermal comfort conditions

(De wilde, 2018). Octopus (Vier, C. by R., Groups, 2021) in Grasshopper is one example of these optimization algorithms used through coupling with a building performance simulation tool to optimize a specific building for minimising energy consumption

The suitability of using Octopus in optimizing building parameters for thermal performance was demonstrated in many recent studies. The genetic algorithm parameters were set to be 0.2 mutation probability, 0.5 elitism, 0.8 crossover rate, 0.9 mutation rate and 100 population size.

Base case simulation and thermal comfort simulation was performed using the validated model as the base case. Adaptive thermal comfort is used as the indicator for thermal comfort as it is suitable for non-conditioned buildings. The base case model was examined for the worst-case scenario for the summer solstice when adaptive thermal comfort is within acceptable limits for 43.64% of time.

Following that, optimization was performed through adding horizontal shading devices as the only dynamic parameter. Each floor in the four facades had a horizontal shading device (with Honeybee default assigned materials) attached to its top concrete slab with values starting from 1m to 2 m. These parameters were designed to provide a quick applicable and cheap solutions for the owners to act as an initiative of the desired enhancement for these workshops and its surroundings. The parametric modelling was introducing three tiers of horizontal shading for each façade and it can variate between these three tiers for each floor individually. Table 3 presents dynamic parameters (shading devices number in each façade) and their values (protrusion of each shading device in meters long).

Table 3 dynamic parameters.

Dynamic parameter	Three horizontal shadings for each floor in the north facade	Three horizontal shadings for each floor in the south facade	Three horizontal shadings for each floor in the east facade	Three horizontal shadings for each floor in the west facade
Variables no.	3	3	3	3
Values in meter	1, 1.5, 2.	1, 1.5, 2.	1, 1.5, 2.	1, 1.5, 2.

Results

Monitoring results

The results (Fig. 12) showed that the highest temperature was found in the in workshop 1 in the morning. The two loggers in the double height workshops recorded very close monitoring. It was also noted that indoor humidity ration was very close in all spaces. Finally, spaces 4-G & 4-1 indicated similar pattern of data but 4-1 showed different results owing to the cross ventilations.

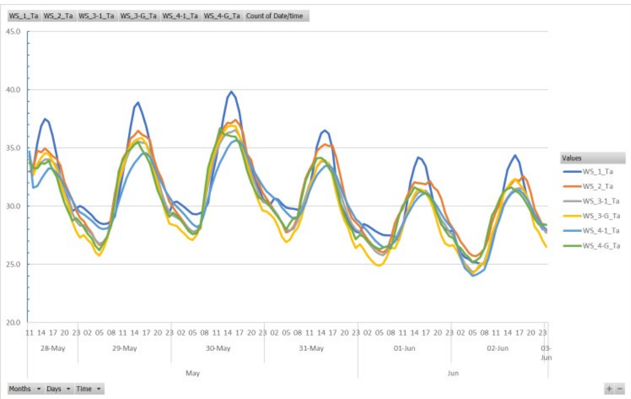


Figure 11. Air temperature comparison for the workshop spaces

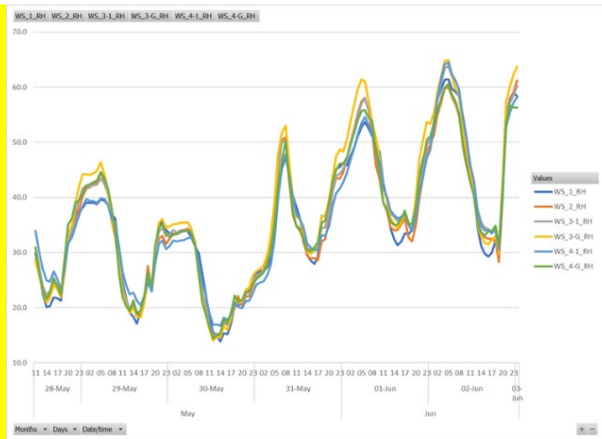


Figure 12. Relative humidity comparison for the workshop spaces

The highest air temperature (39.8^{0}C) was noted in WS_1 on 30 May at 15:00 and the lowest temperature (24.0^{0}C) was recorded in WS_4-1 at 5:00 on 2nd June. The difference between the maximum temperatures in these two workshops is 4.2^{0}C. The data statistics of the workshop spaces are presented in Table 4. This shows highest fluctuation (14.8^{0}C) of temperature is observed in WS_1 which also has the highest average temperature (31.2^{0}C).

Table 4 temperature fluctuations for each workshop

Table 2. Showing air temperature data across the workshop spaces

	WS_1_Ta	WS_2_Ta	WS_3-1_Ta	WS_3-G_Ta	WS_4-1_Ta	WS_4-G_Ta	Difference
Min	25.0	25.7	24.3	24.2	24.0	25.2	1.7
Max	39.8	37.4	36.5	36.9	35.7	36.7	4.2
Avg	31.2	31.0	30.3	29.9	30.3	30.3	1.3
Range	14.8	11.7	12.2	12.7	11.7	11.5	3.3
St. Dev	3.5	3.1	3.0	3.3	2.6	2.9	0.9

According to the Adaptive Comfort Model (Fergus Nicol, Michael Humphreys, 2012), the acceptable indoor operative temperature can be determined from the mean monthly outdoor air temperature as expressed in the following equation (2):

$$T_{o(comf)} = 0.31\ T_{a(out)} + 17.8 \qquad (2)$$

Here, $T_{o(comf)}$ is the optimum comfort operative temperature in °C and $T_{a(out)}$ is the mean monthly outdoor air temperature in °C.

Further, the 90% acceptability limits of indoor operative temperature can be calculated as follows (De Dear and Brager, 2002):

$$90\%\ \text{acceptability limits} = T_{o(comf)} \pm 2.5\ °C \qquad (3)$$

According to Adaptive comfort standards the indoor conditions in the workshop spaces are very far from the optimum comfort operative temperature and the comfort zone which is detrimental to the health, wellbeing and productivity of the occupants.

Final simulation results have shown acceptable accuracy in correlation to the measurements from the site for the workshop. This allows for optimizing the thermal performance of the spaces and reaching for acceptable predictions for its simulations.

Validation

All the workshops simulation results are validated against 6 days measurements. Fig. 13 presents graphs for each of the six days for Workshop-1 that show averaged hourly measured air temperatures against hourly simulated ones. In addition, Table 5 show the statistical index values for each of the 6 days that shows all values for CV (RMSE) are less than 30%.

Table 5 Workshops RMSE statistical index values for each of the 6 days

Days	Workshop (1) CV (RMSE) (%)	Workshop (2) CV (RMSE) (%)	Workshop (3) CV (RMSE) (%)	Workshop (4-G) CV (RMSE) (%)	Workshop (4-1) CV (RMSE) (%)
29/5	17.1628	16.14	15.3	14.9552	17.4043
30/5	11.3592	10.07	9.63	10.1982	11.7615
31/5	4.65884	3.606	6.43	4.2387	8.30333
1/6	15.1224	14.32	14.3	14.1495	17.7581
2/6	8.4631	9.384	10.9	9.91088	12.3511
3/6	7.61174	5.566	7.4	6.95453	10.3259

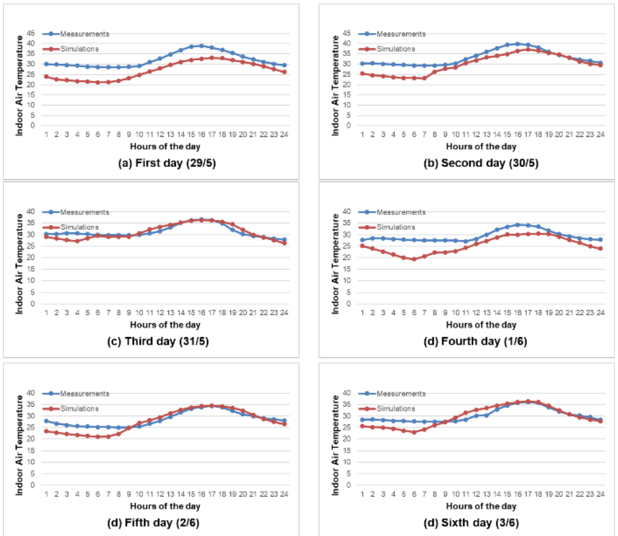


Fig. 12. Shows measured and simulated air temperature (C) results for each of the six days for workshop (1).

Optimization

The validated model was used for the following stage of optimizing these workshops to reach better thermal comfort for the users. The optimization aimed to create simplified building alternations. This was to reach for a proof of concept and to try to have accessible solution that could be shared to the owners and constructed by them. The horizontal shading was suggested as it would impact the direct solar exposure to the zones and it is an easily applicable solution to the workshops geometry (Lila and Lannon, 2017).

After testing 506 iterations in the optimization, adaptive thermal comfort is enhanced by 4.38% in comparison to the base case model. Fig.13 shows perspectives for the optimal solution when adaptive thermal comfort is within acceptable limits for 47.92% of time compared to the base case model where adaptive thermal comfort were within acceptable limits for 43.64% of time.

This have shown how such a simplified alteration can cause an enhancement in adaptive thermal comfort during the summer solstice in hot arid zones. It also opened the door for further investigation for other geometrical parameters like wall construction and insulation. Also, it shows the potentiality of expanding the scope of this research to include longer periods of monitoring and apply further detailed simulation and validation process to include the bespoke furniture and measured human interaction in the space and try to reach for a real application to these optimization results to test it on the existing site.

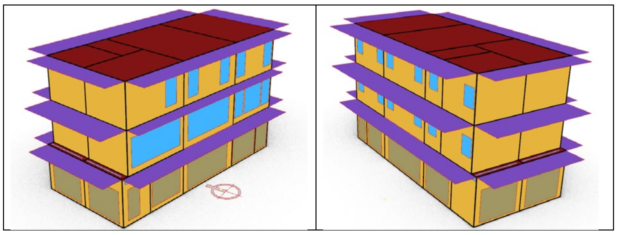


Fig. 13. Shows perspectives for the optimal solution with the north direction (Adaptive thermal comfort: 47.92 %).

Conclusion

Indoor environmental measurements were carried out in six MSME workshops for a week during May-June, during the summer. The measurements included air temperature, relative humidity, and wind-speed using ISO-certified equipment. According to the adaptive model for free-running buildings in Egypt, neutral temperature ranges between 26 and 31 °C in summer with a wider comfort range between 18 and 31 °C for the whole year. From the on-site measurements, all MSMEs were found far above the optimum comfort operative temperature with the maximum air temperature reaching up to 39 °C which is detrimental to the health, well-being, and productivity of the occupants. Final simulation results have shown acceptable accuracy in correlation to the measurements from the site for the workshops. This allows for optimizng the thermal performance of the spaces and reaching for acceptable predictions for its simulations in the next steps. After testing 506 iterations in the optimization, adaptive thermal comfort is enhanced by 4.38%. These results have highlighted the potentialities of running such an indicative monioring and simulation process and reach for beter MSMEs environment within 4 months. It opens the door for further investigation of optimization paramers. The process and results of the study will help architects and designers to find a more sustainable design for the MSMEs.

Acknowledgements

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