Informing early-stage design decisions: Comprehensive spatial and temporal analyses of outdoor thermal comfort to maximise the use of schoolyards

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Abstract

This paper develops a post-processing method for visualizing annual spatial and temporal variations in Outdoor Thermal Comfort (OTC) to inform the design of schoolyards. The method synthesizes hourly annual OTC simulation results into maps that are useful to design decision-making in early-stage design. These maps display areas in comfort and under moderate heat stress in schoolyards with the respective maximum number of children that can potentially be hosted in them. They are easy-to-use visualizations with metrics that are familiar to designers, enabling them to develop mitigation strategies that can maximize the use of schoolyards throughout the year.

Key Innovations (1 to 5 bullet points)

- Post-processing and visualization method to enable better schoolyard designs.
- Easily identifiable locations of comfort and moderate heat stress areas within the schoolyard with the associated number of pupils hosted by them.
- Design-friendly maps and metrics useful to decision-making that are transferable to multiple contexts.

Practical Implications

A proposed method to iteratively design and assess decisions and mitigation strategies related to building form, position on site and beyond to maximize the use of schoolyards throughout the year.

Introduction and background

Outdoor thermal comfort (OTC) is gaining considerable attention with climate change challenges and increased heat stress in cities (Chen and Ng, 2012). Benefits of improving outdoor comfort conditions include mitigating the urban heat island effect, enhancing human health and well-being as well as promoting and affecting the amount and intensity of outdoor activities (Fergus Nicol and Roaf, 2017). However, improving outdoor comfort conditions is particularly challenging in hot arid climates, with extreme heat stress during the summer and potential cold stress during the winter (Cohen *et al.*, 2019). In this context, thermally comfortable schoolyards are important to promote learning and physical activities, playing a significant role in children's health and well-being as they are considered more vulnerable to heat stress than adults (Antoniadis, Katsoulas and Papanastasiou, 2020).

Despite the several metrics developed specifically to gauge outdoor thermal conditions (Fang et al., 2018; Binarti et al., 2020; Haghshenas et al., 2021), none of the existing outdoor thermal comfort models have been developed for children (Cheng and Brown, 2020). Thus, designing outdoor areas for children based on adult thermal comfort models might not necessarily result in areas that are thermally comfortable for them (Antoniadis, Katsoulas and Papanastasiou, 2020). A study by Cheng and Brown, (2020) tried to modify the COMFA model into a children's energy budget model through the consideration of the heat exchange of a child, but far more research is needed in this area so specific models for children can be developed. Creating policies and guidelines for mandating certain OTC strategies for schoolyards remains difficult in the absence of a comprehensive assessment of the thermal environment.

Simulating OTCs

Integrating modelling and simulation methods in early-stage design enables exploring different test scenarios which could support and better inform design decisions. Some studies have employed this integrated approach to develop digital workflows for multivariate environmental analysis which includes OTC evaluation (Naboni *et al.*, 2019; Evola *et al.*, 2020; Natanian and Auer, 2020). However, most studies focused on certain dates and times (e.g., typically hot and cold days) when analysing OTC. Similarly, studies that investigated the thermal conditions of schoolyards using simulation tools (El-Bardisy, Fahmy and El-Gohary, 2016; Zhang *et al.*, 2017; Elgheznawy and Eltarabily, 2021) only evaluated OTC at specific periods (e.g. break times in a hot summer day, the hottest hour in a school summer day) rather than providing a comprehensive annual analysis, thus not reflecting hourly and seasonal variations when displaying results by space. These spatial and temporal representations of cold and heat stresses only shed light on worst-case scenarios, not providing a clear indication of the usability of outdoor spaces throughout the year.

Most thermal performance metrics that considered spatial and temporal variations were developed for indoor environments (Carlucci and Pagliano, 2012), e.g., Thermal Autonomy. First proposed by Levitt *et al.*, (2013), Thermal Autonomy indicates the ability of internal space to provide acceptable thermal comfort through passive means only. Similarly to Daylight Autonomy (Reinhart, Mardaljevic and Rogers, 2013), Thermal Autonomy states "the percent of occupied time over a year where a thermal zone meets or exceeds a given set of thermal comfort acceptability criteria through passive means only" (Levitt *et al.*, 2013). The metric was adapted by Aghamolaei *et al.*, (2020) to develop a weighted temporal OTC performance metric and a framework to assess the impact of geometrical features of neighbourhoods on the OTC conditions.

Besides this, only a few studies have considered the spatial and temporal variations of OTC on an annual basis: (i) The thermal comfort guidelines issued by the City of London, which provided an approach for developers to assess the impact of new development on overall OTC, besides acceptability criteria to be used during the planning process (Danks *et al.*, 2021) and (ii) the study from Nazarian, Acero and Norford (2019), which proposed the Outdoor Thermal Comfort Autonomy (OTCA) index, a performance metric for assessing OTC in urban design which also builds on the "autonomy" concept proposed for the indoor environment despite accepting different thermal comfort indices (e.g. SET, UTCI). The former proposed usage categorization criteria by correlating adults' perception of what is acceptable with outdoor thermal conditions in a temperate climate whereas the latter adopts an arbitrary threshold of 50% of the time for the Spatial OTCA to identify the percentage of outdoor space area within acceptable comfortable conditions, based on an analogy with the Spatial Daylight Autonomy index.

To the best of the authors' knowledge, there are no studies on outdoor thermal comfort specifically focusing on comprehensively analysing the annual thermal performance of schoolyards, an environment which requires special considerations because these spaces are: (i) used by vulnerable people for specific purposes, (ii) configured as a result of or deliberately from the arrangements of school building shape and position on-site and in relation with its surroundings, (iii) used at specific times of the day, according to school-specific prescriptive schedules.

This study extended the existing digital workflows by adding a post-processing and visualization method that aims to comprehensively analyse the spatial and temporal variations of the OTC in schoolyards. This method enables building designers to visualise ***where*** thermal issues are in the schoolyard and understand ***how many students*** can be accommodated in acceptable comfort conditions for every hour of the year. Design actions can then be aimed at maximising this number for the required hours of usage during the teaching year.

Therefore, the study helps answering the following research and design questions: How often can these yards be used without thermal stress during spring and autumn? How and where in the yard can children be protected from heat stress during playtime in the summer? Will the yards be useful for most of the winter period? None of the existing modelling workflows properly address these types of design questions, therefore missing opportunities to properly configure schoolyards which can be useful for as long as possible throughout the year.

The proposed post-processing and visualization method are presented step-by-step followed by a case study of its use in Egypt. Results are discussed in terms of how useful they are to inform design decisions considering simple questions related to the usage of the courtyard throughout the academic year. The method is developed using Grasshopper enabling it to become part of designers' digital libraries.

The Method

Prior to the development of the post-processing method, a fit-for-purpose simulation workflow was put in place to assess OTC conditions. This simulation workflow leveraged the proposals from (Evola *et al.*, 2020; Natanian and Auer, 2020) created in Grasshopper and used the Universal Thermal Climate Index (UTCI) metric to assess OTC conditions. Besides allowing the coupling of several simulation engines, it is also suitable for the iterative process of early-stage design (Naboni *et al.*, 2019; Natanian and Auer, 2020).

The Universal Thermal Climate Index (UTCI) metric was adopted in this study to assess OTC conditions of schoolyards for several reasons: (i) it is appropriate to assess OTC in all climate zones and seasons (Broede *et al.*, 2010; Fang *et al.*, 2018), (ii) it uses a sophisticated and advanced Human thermal comfort model (Broede *et al.*, 2010), (iii) it is integrated within the parametric design tools of the Ladybug toolkit (Naboni *et al.*, 2019), (iv) it is sensitive to changes in the Mean Radiant Temperature MRT, and wind speed WS (Blazejczyk *et al.*, 2012; Haghshenas *et al.*, 2021), (v) it has lower computation time, which is a significant benefit for urban-scale assessments that require a large number of simulations (Danks *et al.*, 2021).

The universal thermal comfort index (UTCI) metric (Broede *et al.*, 2010) was calculated based on four different atmospheric parameters, namely dry bulb temperatures, mean radiant temperatures, relative humidity and wind speed. The first three parameters were calculated by coupling several validated simulation engines using the Ladybug toolkit for Grasshopper (Figure 1). The workflow does not incorporate Computational Fluid Dynamics (CFD). This was to speed up simulation time as its proposed primary use is in the early design stages to assess building shape and position on site. Minimising computation time is a key obstacle to overcome to encourage its use in these stages.

The UTCI calculation workflow was divided into four main parts:

1) Modelling of a school building and its surroundings using Rhinoceros with a 5m x 5m outdoor grid located at 1.2m height from the schoolyard ground to represent a standing person.

2) Adding microclimate and Urban Heat Island (UHI) effects to the model by including TMY hourly air temperatures and humidity through the Urban Weather Generator (UWG) (Bueno *et al.*, 2012). This was done using the Dragonfly plugin that runs UWG while the wind velocity and the global horizontal solar irradiance are retained from the original TMY file.

3) Computing the Mean Radiant Temperatures (MRT) based on longwave and shortwave radiation using Honeybee (following Mackey *et al.*, 2017). First, the longwave MRT was computed based on hourly surface temperatures and factored by view factors for each test point on the grid. Then, the contribution of both radiation coming from the sky vault and short-wave radiation was used to adjust the MRT longwave value.

4) Calculating the resulting hourly UTCIs for each test point of the aforementioned grid also using the Honeybee plugin.

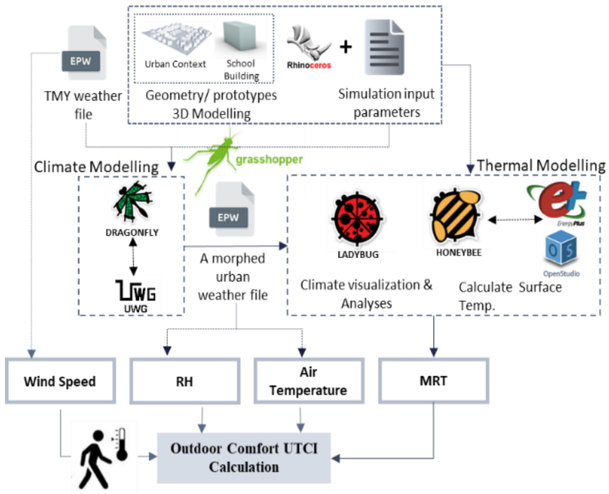

Figure 1 UTCI calculation workflow, software plugins, inputs, and outputs.

Post-processing to inform design.

Hourly UTCI results were post-processed in several steps aiming to be useful in informing design decisions (Figure 1). An exploratory analysis was initially undertaken to investigate the annual distribution of the UTCI values per season. This analysis aimed to investigate UTCI results in relation to the "no thermal stress" category (+9 to +26 °C), the target comfort level in this study, as well as to visualise the different types of thermal stress likely to happen in each season (Figure 4).

Post-processing started with a seasonal analysis, calculating the percentage of hours in comfort and illustrating them in space i.e. for each point of the grid in the schoolyard through spatial maps (step 1 Figure 2). This was complemented with bar charts to show the type and frequency of time thermal stress occurred in the schoolyard i.e. frequencies in which cold stress, no thermal stress, and heat stress occurred (Figure 5) at each season.

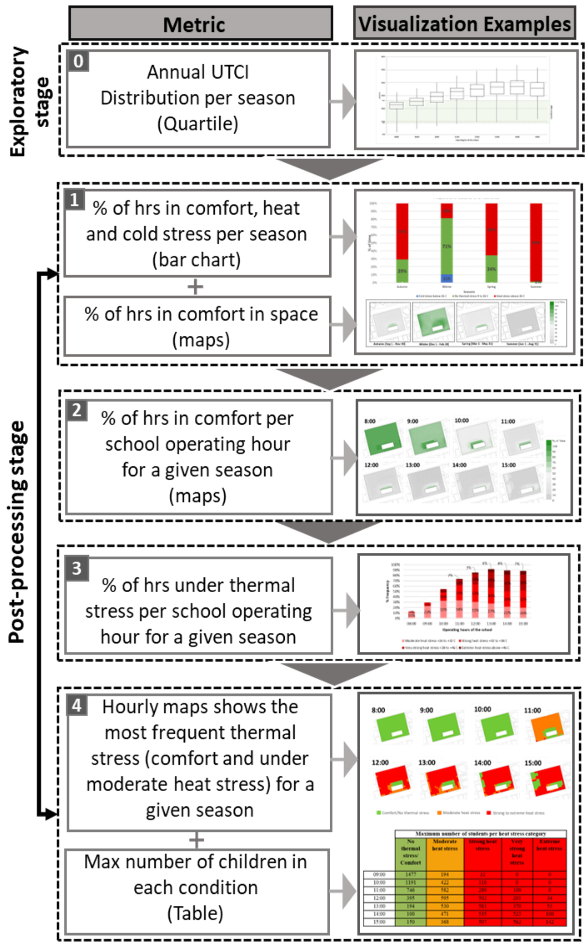

Figure 2 Post-processing and visualization workflow.

Hours in comfort were calculated based on Equation 1. The same procedure was undertaken to calculate the percentages of time within any UTCI stress category, e.g., heat or cold stress over each season based on UTCI ranges above 26°C and below 9°C, respectively. TS is the percentage of time over a season or a prescribed period of time where the schoolyard meets a UTCI thermal stress range, i.e. comfort range, moderate stress range, etc.

$$TS = \frac{1}{N}\frac{1}{n}\sum_{k=1}^{N}\sum_{h_r=h_i}^{h_f} TC_{k,h_r} \quad (1)$$

$$TC_{k,h_r} = \begin{cases} 1 \; if \; SET \in x \\ 0 \; otherwise \end{cases}$$

Equation 1 – Frequency of time in comfort or under stress based on (Nazarian, Acero and Norford, 2019)

Where TC_{k,h_r} is the UTCI thermal comfort or stress index at each test point at a specific day and hour, which is calculated at hourly intervals or the time-averaged value over a specific hour. N is the total number of days in a given season, h_i and h_f represent the initial and final hour of the school day, and n is the total number of hours in a school day ($n = h_f - h_i$). x is the UTCI comfort range or stress category range.

It is important to note that UTCI values were not averaged. They were counted for each UTCI stress category and expressed as frequencies. Averaging the data would not deal well with seasonal, weekly and daily disparities common in OTC conditions.

To illustrate *when* and *where* stress happened during typical school days, temporal and spatial results for comfort conditions were aggregated per school *operating hour for each season* also using Equation 1 (step 2 Figure 2).

Hourly maps were used to illustrate the spatial distribution of comfort at each school operating hour (Figure 6) per season. These maps were followed by hourly bar graphs showing frequencies of different types of thermal stress (Broede *et al.*, 2010), for each school operating hour (Figure 2, step 3) aggregated per season (Figure 7).

Based on step 3, it was possible to calculate the amount of area of the schoolyard under the prevailing stress category per school operating hour for each season. This was done by first calculating the frequencies of each stress category affecting a given test point at a specific hour over a season, to then identify the predominant stress category affecting the specific point. Then the total area of each prevailing stress per school operating hour for each season was calculated using Equation 2.

$$A_{TS} = \sum_{i=1}^{TB} A_{TPB} \qquad (2)$$

Equation 2 – Amount of area under prevailing UTCI thermal stress categories per school operating hour at a given season.

Where A_{TS} is the total area within a prevailing UTCI stress category (e.g., in comfort or under thermal stress) at a specific hour of a school day over a season. TB is the test points in the grid. A_{TPB} is the area of an individual test point boundary in the test grid within a specified thermal stress range (e.g., comfort, moderate heat stress, etc.) at each operating hour over a season.

Prevailing areas in comfort and under different stress categories were associated with the minimum area per student prescribed by the building regulations for students' share of the outdoor spaces in the schoolyard ($5m^2$/Student according to (GAEB, 2018)). Calculations were undertaken following Equation 3, for each dominant stress category part of the grid at each school operating hour in a given season.

$$S = A_{TS} \div 5 \qquad (3)$$

Equation 3 – Amount of area within comfort or under thermal stress expressed as a maximum number of students allowed outdoors per school operating hour at a given season.

Results from Equation 3 are displayed in Table 1, for the Spring season and complemented with maps showing the most frequent thermal stress for each test point of the grid (Figure 8), i.e., comfort, moderate heat stress and strong to extreme heat stress.

General application of post-processing and visualization method to an Egyptian school

The method was tested on an existing school site (9266 m^2) in Cairo, Egypt, for a five-storey linear form public school building (with a ground floor area occupying 618 m^2 of the site) detached from site boundaries. This is a common school form built by the Egyptian government. The building was designed according to the (GAEB, 2018) regulations and accommodates 33 classrooms.

Cairo is characterised by a hot-dry climate (BWh) according to Koppen's climatic classification. Its latitude is 30°03'45" N, and its Longitude is 31°14'58" E (Kottek *et al.*, 2006). The mean annual temperature is 22°C, with the highest average hourly temp. of 35°C in July and the lowest average of 9°C in January. Relative Humidity is between 49-68%. Solar radiation is high most of the year, with average hourly global horizontal radiation reaching up to 1000 Wh/m^2. Climate characteristics are summarised in Figure 3.

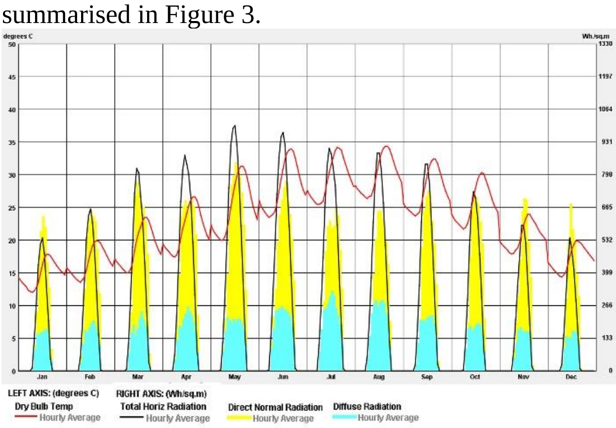

Figure 3 - Hourly averages Climate characteristics of Cairo – Egypt - created by Climate Consultant 6.0.

Simulations were run for the whole year over the four seasons during the school operating hours from 8:00 to 15:00, including summer holidays, to account for summer activities the yard might host. Simulation inputs considered geometrical and construction parameters prescribed by the General Authority of Educational Buildings (GAEB, 2018) in Egypt.

Results and discussion

Results were reported from a designer's perspective, i.e., after deploying the workflow (Figure 1) to the case study school, metrics and visualizations from each stage of Figure 2 were discussed with regard to their usefulness to help inform design decisions.

The UTCI value distributions (Figure 4) showed that the median exceeded the comfort range for more than 75% of the year and reached the highest of 42°C at 14:00 in summer which is considered very strong heat stress. This type of stress cannot be ignored in design decision-making as it is likely to expose children to high temperatures and high solar radiation if the yard is used, potentially causing sunburns and dehydration, or simply means the yard cannot be used unless mitigation strategies are put into place.

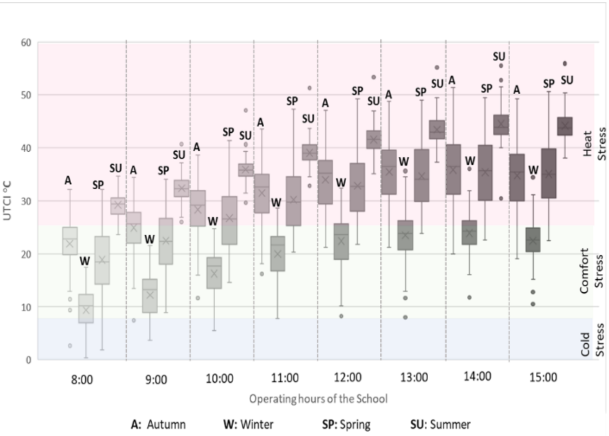

Figure 4 – Exploratory stage: UTCI values distribution at each hour of the school day over the seasons.

The exploratory analysis was useful to demonstrate the distribution of UTCI results in relation to comfort levels. It showed the schoolyard would be suffering from heat stress for large parts of the year focusing design priorities towards making decisions to address heat stress. However, this overview of priorities is of little use to designers if no indications of *when, where* and *for how long* heat stress happens in the yard. The absence of spatial information about the distribution of heat stress prevents designers from proposing mitigation strategies directly where they are needed. Thus, post-processing started by following step 1 of the workflow proposed in Figure 2.

Results for Step 1 were displayed in Figure 5, illustrating the overall thermal performance of the schoolyard across the four seasons. Seasonal results displayed a comfortable winter, a very uncomfortable summer, and predominantly uncomfortable mid-seasons, as both Autumn and Spring were under heat stress for 71% and 66% of the time respectively. The graph (Figure 5) showed seasonal variations in terms of the frequency of heat stress. However, it did not show where these heat stresses are likely to happen in the schoolyard. Therefore, seasonal maps were added to this graph to illustrate where comfort happens within the schoolyard, enabling seasons to be compared to each other with regard to how much of the schoolyard would be in comfort during different parts of the year. By considering these seasonal graphs, designers could adopt strategies that maximize mid seasons and summer comfort without compromising the comfortable conditions during winter (e.g., installing retractable shading devices to potentially not affect winter favourable conditions).

Maps showed that the yard area adjacent to the school building tends to be the most comfortable, probably due to shading casted by the building itself. They also showed that the impact of overshadowing from neighbouring buildings was minimal, meaning that relying alone on the shadow casted by the school building and surroundings in this site will not create a thermally comfortable condition for most of the schoolyard. This analysis illustrates *where* comfort could be achieved *seasonally* in the schoolyard, as well as how long comfort conditions would last in relation to seasonal heat and cold stresses. However, this information still does not allow designers to identify *when* and *where during the day* stresses happened; important pieces of information for this type of open space where several outdoor activities are held throughout the school day.

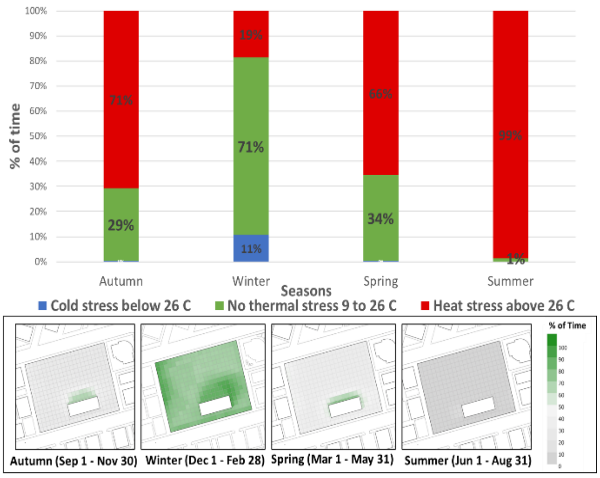

Figure 5 Workflow Stage 1 – Bar chart shows percentages of time in comfort and discomfort per season. Maps present the percentage of time the schoolyard is in comfort in each season.

Step 2 of the workflow allows the generation of hourly maps for the Spring season, as shown in Figure 6. Good comfort conditions were seen across the whole yard in the first two hours of the morning. These conditions rapidly deteriorated around 10 am, after which comfort remained only in the areas immediately adjacent to the building, probably due to building shading. These maps are useful as designers need to consider mitigation strategies in alignment with school schedule (Antoniadis, Katsoulas and Papanastasiou, 2020). The maps also guide coordinating the number of students playing in comfortable areas outdoors during break times and/or planning different types of outdoor activities happening throughout a typical school day. However, they contain little information about how permissive designers could be in allowing the use of areas which are not in comfort. This is because they do not show the degree and frequency of different types of heat stress happening in the courtyard, therefore not showing priority areas where mitigation strategies should be implemented.

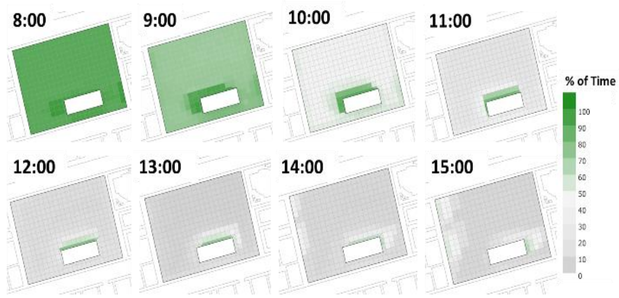

Figure 6 Workflow stage 2 – Maps present the percentage of time the schoolyard is in comfort at each operating hour during the Spring.

Figure 7 illustrates the frequencies for different types of heat stress happening in the schoolyard for each school operating hour during Spring. Interestingly, between 20%-34% of the yard is under moderate heat stress (UTCI between 26°C and 32°C) potentially still acceptable to host children's outdoor activities if designers are more permissive in terms of what can be considered still useful space despite not being in comfort. The literature shows that in hot climates comfort acceptability levels could be higher (Potchter *et al.*, 2018) due to acclimatization and physiological conditions among other reasons (Nazarian, Acero and Norford, 2019), meaning there is room to explore the usability of moderate stress areas.

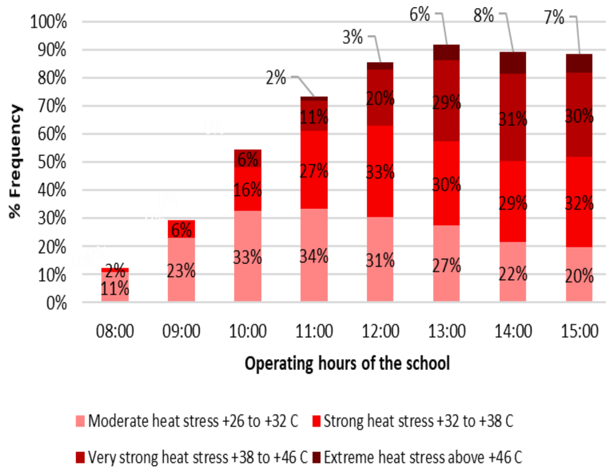

Figure 7 Workflow stage 3 – Percentage of time for each heat stress category in the Spring

However, Figure 7 shows only the percentage of time under moderate heat stress or above; It does not show *where in the yard these areas of moderate discomfort happen.* Therefore, designers do not have information on which parts of the yard are still considered useful and which parts of the yard need mitigation strategies to be in place to potentially become useful. In addition, designers do not yet know, from the visualisations produced, the maximum number of students that can be hosted by areas in comfort and by areas with moderate heat stress, to assess the number of student cohorts that can be safely out at each hour of the day.

Table 1 illustrates results for the last step of the workflow showing the number of pupils affected by the most prevailing type of thermal stress at every hour of the day in the Spring. Associating areas under thermal stress with students' numbers provides a familiar metric for designers to act. The results showed that if designers accept moderate heat stress, the schoolyard could accommodate between 294 (15:00) to 1729 (9:00) during the day. The table shows the areas in comfort were dramatically reduced after 11:00. Figure 8 together with Table 1, displays where these areas are in the yard. When used along with Table 1, the designer has various hourly and spatial limits for the number of students that can be accommodated in areas with predominant comfort and moderate heat stress, respectively.

Table 1 Number of pupils affected by the most prevailing type of heat stress in the schoolyard at each hour of the day in the Spring.

	Maximum number of students per prevalent heat stress category				
	Comfort	Moderate	Strong	Very strong	Extreme
08:00	1729	0	0	0	0
09:00	1729	0	0	0	0
10:00	1718	11	0	0	0
11:00	211	1485	33	0	0
12:00	71	182	1477	0	0
13:00	112	286	377	954	0
14:00	126	64	92	1448	0
15:00	236	58	425	1011	0

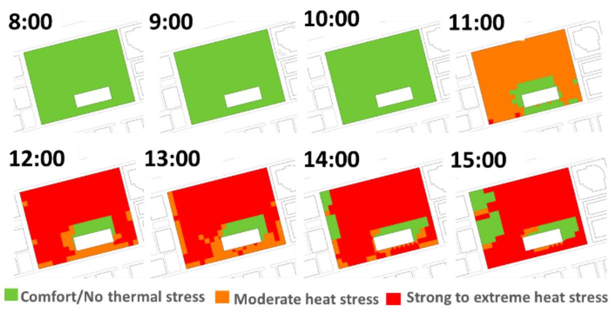

Figure 8 – Workflow stage 4 – Maps presenting the most frequent thermal stress at each hour of the school day during spring and highlighting the boundaries between zones in comfort, moderate heat stress and strong heat stress or above.

In this case study, the maximum number of students per classroom for these types of schools is 40 students according to public school regulations (GAEB, 2018). Data from Table 1 and Figure 8 shows that the areas in comfort and under moderate heat stress can accommodate together, in theory, between 42 student cohorts at 11 am, down to about 4 cohorts at 2 pm. However, maps show these areas are mainly continuous around the school building, meaning it is unlikely that students will also use the 'pocket' areas under moderate stress around the site boundaries before 2 pm as children might not spread enough in the yard to reach them if the rest of it is under strong heat stress. This type of information is relevant to designers because it shows where strategies should be focused to ameliorate the persistent heat stresses and connect these favourable areas so they can be used effectively.

Since the case study school was designed to accommodate 1320 students (based on public schools regulations (GAEB, 2018)), using the example school timetable for grade 9 shown in Table 2, it is possible to predict the maximum number of cohorts that would be out simultaneously at break times and for other prescribed outdoor activities, considering the thermal conditions of the yard.

Analysing data from Table 1 and Figure 8, together with data from Table 2, it is possible to see that during the 10 am break time, all cohorts can be out together, mostly in comfortable areas. However, during lunchtime, in theory, only 6 cohorts could be able to be outside together, as most of the schoolyard is under strong heat stress or above. This again calls for designers to propose mitigation strategies to connect these areas to the areas around the building to maximize the use of the yard, for instance through shading systems (Elgheznawy and Eltarabily, 2021) and/or vegetation (El-Bardisy, Fahmy and El-Gohary, 2016). This also suggests a need for staggered lunch breaks if design mitigation strategies are not in place to enable all children outdoors together during lunch breaks.

In addition, Table 2 also shows that the time currently chosen for physical education activities is at the very end of the school day, when most of the schoolyard is under strong to extreme heat stress. Areas in comfort and under moderate heat stress at this time of the day do not have the best configuration and position in the yard to host physical activities. Therefore, mitigation design strategies must be put in place for children to safely perform these activities.

Table 2 example of a grade 9 timetable showing break times and physical education (P.E.) classes for Rowad el-Sedeque school.

	Sun.	Mon.	Tue.	Wed.	Thu.
1st: 8:00-9:00	Math	Sc.	Arabic	Math	Social
2nd: 9:00-10:00	Steam	Arabic	Eng.	F/G	Math
10:00-10:10	Break				
3rd: 10:10-11:10	Eng.	Math	Sc.	Sc.	Rel.
4th: 11:10-12:10	Arabic	F/G	Social	Eng.	Arabic
12:10-12:40	Break				
5th: 12:40-13:40	Sc.	Social	Rel.	Arabic	Comp.
6th: 13:40-14:40	Eng.	Art	Math	Social	P. E

Conclusion

This paper presents the development and testing of a method to post-process annual OTC simulation results into useful data for design decision-making. The work presented showed step-by-step how the complexities behind OTC results were communicated to designers through visualisations and metrics that would enable them to undertake design decisions, ending with comfort iso-thermals of prevailing stresses and the corresponding maximum number of children allowed in the areas formed by them. These communicate OTC results in a clear way that is informative for design decisions in early-stage design.

The results also enable designers to clearly identify how many student cohorts were allowed to simultaneously stay in outdoor areas in comfort or under moderate heat stress for every school operating hour for a given season. They also enabled designers to understand not only where these areas are but also how interconnected they are, flagging the potential need for further design strategies to connect these areas to maximise the use of the yard. In addition, results also show the best parts of the yard to place areas for physical education activities, flagging the need for mitigation strategies to enhance their usability during the school year, in case they are placed in areas with persistent heat stress, i.e., high frequency of strong heat stress or above.

The study displayed the combined effect of building and site potential to improve OTC conditions. They can be understood as a preliminary diagnostic of OTC conditions resulting from defining building shape and position on site and therefore seen as the base-case scenario from which to start developing mitigation strategies to enhance thermal conditions to improve the usability of schoolyards. However, the method is not restricted to the effects of surroundings and building position on site, but can also be extended to assess the effectiveness of mitigation strategies that attempt to increase the amount of outdoor area in comfort. To this end, it is flexible to accommodate diagnosis as well as to assess design solutions.

Further studies could investigate modified UTCI comfort ranges based on a thermal subjective perception of students in Egypt, as this study used the standard UTCI comfort range. They could also define thresholds for comfort frequencies that should be considered in schoolyards and identify the thermal requirements of various school outdoor activities to guide the design and thermal assessments of schoolyards. In addition, wind effects could be included within feasible simulation times as the study did not incorporate CFD to speed up simulation times, an essential factor in early design stages.

All steps of this workflow were developed in Grasshopper and can easily be integrated into the early stages of the design process and be made part of digital design libraries so they can be recalled as a method to be used whenever needed. Its different steps can be either displayed individually or run in automation in the background so only the last and conclusive step is shown to designers. The workflow is shareable and transferable to any school building in different locations.

The shareable workflow supports the evaluation and trade-offs between different mitigation strategies, showing where and when these strategies are mostly needed to provide thermally comfortable schoolyards and maximize the usability of the space for different outdoor learning and physical activities throughout the year.

These studies are important in helping educators, designers, and policymakers to create schoolyards that support the health, and well-being of children while at the same time enhancing the potential learning outcomes from student outdoor activities.

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Nomenclature

OTC: Outdoor Thermal Comfort.

UTCI: Universal Thermal Climate Index.

UWG: Urban Weather Generator.

MRT: Mean Radiant Temperature.

GAEB: General Authority of Educational Building.

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