A novel decision support tool for climate-responsive urban design

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Abstract. With the increase of temperature, a tropical country like Singapore will face the challenge of mitigating the anthropogenic heat emissions and urban heat storage to maintain its quality of urban life. However, due to the complex nature of climate and urban fabric, it is difficult for urban planners to make climate-sensitive informed decisions on how to achieve better Outdoor Thermal Comfort (OTC) in an intuitive while holistic way. We develop a holistic and principled decision process via an implementation of a decision support tool which interactively visualizes how climatic factors, urban design scenarios, importance of spatial use, and various acceptability criteria impact the OTC assessment in a simple step-by-step manner. The advantage of this tool is that it serves as an agent-based climate-responsive urban design system that presupposes planner’s trust. A complete working example is provided which demonstrates how a user could choose the optimal scenario for a new public housing estate located at the northeast of Singapore.

1. Introduction
Heat stress could cause discomfort and illness as well as an impact in the economic sector [1-3]. Therefore, Outdoor Thermal Comfort (OTC) of an urban space is an important topic for environmental policy makers and urban designers, especially in a country with a tropical climate like Singapore. Different heat mitigation strategies are required for different climates [4] and it is challenging for urban designers to identify the impact on OTC without using climatological analysis which is provided by a domain expert. To address this challenge, a climate-responsive design tool is paramount in order to evaluate the optimal design and communicate the decision process to the policy makers [5].

Nouri et al. tackled this complex problem via an interdisciplinary approach of climatic adaptation and urban design through various case studies [6]. Chatzidimitriou et al. presented microclimatic interventions which could improve pedestrians’ comfort in urban design [7–9]. Tapias et al. proposed an automated tool to assess OTC, the microclimate conditions and building geometries during the exploration of urban forms [10]. Irzmańska et al. conducted microclimatic simulations using ENVI-met 4 in the tropical city Dhaka and compared the simulated Physiological Equivalent Temperature (PET) [12] against Actual Thermal Sensation Votes (ASV) through a thermal comfort survey in the case-study areas. They found that the results are strongly aligned for simple urban geometry in the formal areas.
Theoretical comfort models can be applicable for the general understanding of comfort situations at urban outdoors even though different thermal sensations of the citizens may have an impact on their accuracy.

Sustainable urban renewal tools should be integrative (provide holistic and systematic analysis), dynamic (be able to show various alternatives according to the interest of the stakeholders), interactive, transparent, flexible, reusable, fast, easy to use, communicative, educational, and authoritative (capable of meeting political standards) [13]. Kapelan et al. developed criteria for integrated urban Decision-Support Tools (DSTs) and pointed out that the use of ranking and optimisation technology is an important part of modern DST [14], as it may assist the user to make more informed decisions. Tools such as SimCity and ESRI’s CityEngine focus on visualization and data reporting, while their quantitative analysis capability is lacking. Mostafavi et al. presented a framework which takes spatial data, demographic dynamics and economic dynamics calibrated with user inputs to model urban dynamics [15]. Pettit et al. presented a decision-making tool dedicated to planners with spatial analysis [16]. The weighting of data according to its environmental, social and economic impact reflects the relative importance of the factors in the conceptual redevelopment options, and new information technologies aim at closing the knowledge gap of non-domain experts and allow for a participatory planning process [17].

In this paper, we aim to formulate the urban design problem in a climate sensitive framework. To better communicate the factors that influence the quality of various urban design for the case study set, this tool is built on top of a 3D interactive presentation platform called Singapore Views [18].

2. Methodology

Urban design is a complex process that requires assessment of economic, social, and environmental aspects. Current simulation tools address these aspects separately and are not intuitive for urban designers and decision makers regarding the quality of the proposed design. We propose an interactive tool for urban designers to incorporate the spatial-temporal OTC evaluation based on a rigorous mathematical framework which utilises ideas from mathematical disciplines such as decision theory [19] and risk theory [20]. In this framework, the urban design problem is formulated using the concept of weather types, exposure map, and scenarios selection as urban factors. Damage function is introduced to benchmark these urban factors according to the decision making guideline.

In the spatial-temporal assessment, we denote $x$ as the position and $t$ as the time of the assessment.

2.1. Urban factors

We now present the components which will be the core of our decision-making methodology. We denote by $x \in \mathbb{R}^2$ the spatial location and by $t \in \mathbb{R}^+$ the time index.

2.1.1. Weather types

The evaluation of thermal comfort depends on various microclimate parameters. Due to computational costs and memory storage limitations, an hourly OTC analysis of annual data is impractical. [21] proposed a weather clustering method to describe typical daily patterns – called weather types. The weather types are defined based on features such as wind direction, wind speed, temperature and humidity. Data from each weather type is used as a representative data in order to simulate the impact of each weather type. During the planning process, according to the design guideline, the planner may opt to plan based on the most frequent weather conditions, or alternatively, based on extreme cases. The clustered weather types allow the user to assess the environmental impact of each design option under different weather conditions. The OTC index is calculated based on climate numerical simulation using ENVI-met model. Weather types are denoted as $W = [W_1, \ldots, W_K]$ where $K$ is the number of weather types. The probability of each weather type is given by $Pr (W_k = w)$, which is estimated based on clustering algorithms, such as k-means.
2.1.2. Damage function
The damage function represents the "damages" stemming from an environmental event. The term "damages" should be understood as a notion of a negative effect that the particular value of the TCI has on society (e.g., people, the environment). This damage could be related to limitation of performing outdoor activities, degradation of health, economic loss due to increased hospitalization of the population due to heat-stress and other. In general, the damage function reflects the welfare degradation effect to the public due to thermal conditions and is denoted as \( D(\alpha) \).

2.1.3. Exposure map
The planner would typically like to allocate more resources to improving OTC in locations where people mostly carry out their outdoor activities. To this end we introduce the notion of exposure map. The exposure map aims at evaluating the importance of each location in the study area. For example, a playground is given the highest weight as it is the place that the residence exercise. The exposure map is denoted by \( E(x, t) \).

2.1.4. Scenario selection
The baseline of this case study is the current urban layout. We defined 14 mitigation strategies as scenarios. These scenarios include removal of car parks, application of green facades, change of tree coverage in courtyard, application of void decks, and application of an urban canopy over a courtyard. The scenarios aim at improving the OTC by increasing urban ventilation, reducing solar radiation and lowering the surface albedo. The ENVI-met simulation results for the 15 scenarios constructed the spatial-temporal process which is defined as Thermal Comfort Index (TCI). The OTC index of a particular position at a given hour for each scenario differs and is denoted by \( Z(x, t; A) \), where \( A \) is the i-th scenario out of the 15. Our goal is to find the optimal design \( \hat{A} \) according to an objective function which incorporates all the aforementioned aspects.

![Diagram](https://via.placeholder.com/150)

**Figure 1.** Urban design decision making framework

2.2. Decision making framework
The conceptual framework is presented in Figure 1. To factor in the exposure and the damage of each point at given point, Loss Process is introduced. The loss of a point is defined as a pointwise product of the damage function and exposure function, denoted as \( \Omega(x, t; A) := D(Z(x, t; A)) \times E(x, t) \). To produce a score of a given scenario, the loss of all the points are aggregated as an overall score. The overall quality is could be calculated as \( L(W; A, X, T) := \int \Omega(x, t; A)dx \, dt \). We note that \( L(W; A, X, T) \) is a random variable due to the weather type variable \( W \).

Now that the loss variable is defined, we express the objective function as follows:

\[
\hat{A} = \arg\min_A E[L(W; A, X, T)].
\]
where $E[L(W;A,X,T)]$ is the statistical expectation (mean) of the random variable $L(W;A,X,T)$. To illustrate our framework, two damage functions are used: indicator function $D(\alpha; A,X,T) = 1 (\alpha > \lambda)$, $\lambda \in \mathbb{R}$, and staircase function. Other damage functions can also be used and should be tailored to the requirements of the problem.

3. Implementation

3.1. Post-processing on Physiological Equivalent Temperature (PET) simulations

The ENVI-met outputs the simulation results in a EDT file format. A single EDT file contains the binary data (in single-precision floating-point format) of the simulation area for one hour. For each weather type in each scenario, EDT files for 24 hours of the day are processed to extract the PET at 1-meter height, in the study area to a CSV file. The Singapore Views [18] platform takes csv files with time and location reference. The study area has 19×63 simulated points. The simulation results for 24 hours are aggregated in one csv file. In our case, there were k=9 weather types, and in total, 10 csv files are generated per scenario: 9 for the weather types and one for the average of all the weather types.

3.2. 3D visualization as a communication tool

As defined above, to qualify a set of urban design, the framework requires weather types, scenarios, damage function, and an exposure map as inputs from the user. These elements are reflected as interactive panels on the GUI. The tool is based on the Unity3D real-time engine.

To simplify the choices, the average weather type over the year was set as a default choice. The performance was assessed as an aggregated score based on the exposure, the OTC index of the area (PET), of the location and the frequency of weather type through the year. The score is a relative one compared within the scenarios and normalized to 100%. The higher the score is, the better the performance the scenario achieves. The scores are ranked in real time every time the user defines a damage function. For example, we have chosen the stair-case function as the damage function. If the user changes the lower bound and higher bound of the stair function, the score will be recalculated. The scores of each scenario are plotted in a line chart toggle group (see Figure 3). A preview of the model is displayed on top of the toggle to help the user to understand the urban design scenario. The tool also gives an overview of the risk distribution during the day. For example, the performance of the baseline scenario is good in the early morning (around 7am to 9am) and the night (12am to 7am), as shown in the image under Environmental Performance Assessment in 24h. To simplify the decision maker’s understanding of how the performance is calculated, it is planned to further develop options for the users, where they can see the raw PET (see Figure 2), the PET after applying the acceptability criteria and the PET after applying the acceptability criteria multiplied by the exposure index (see Figure 3) in the main visualization view.

4. Conclusion

A visual tool has been developed and implemented to assist urban designers in making informed decisions. The framework integrates design considerations from the urban designer, climate science as well as social and economic perspectives. A novel decision-theoretic framework was developed for optimal urban design from an outdoor thermal comfort perspective. In particular, the decision theoretic framework integrates important urban components in a holistic way and considers important design criteria. The framework combines those criteria into a spatial-temporal risk measure to assess the performance of various urban design options. This is used as the basis for our optimal design problem formulation which is formulated as an optimisation problem that is easy to solve and has a clear interpretation. To illustrate how the framework can be used in practice we present a real-world study, which is based on a set of urban design strategies that aim to improve the OTC of a specific site in Singapore. The ENVI-met microclimate model is used to calculate the spatial-temporal OTC process. The proposed framework is demonstrated to be able to assist decision-makers make more informed and interpretable choices on how to select the optimal design option and where to allocate best their investment and resources. A 3D interactive tool is developed to communicate the idea to a broader audience.
Future work could expand the dimension of the urban design components such as citizens feedback and various economic factors. The framework could also be extended to incorporate multistage decision making problems as well as be formulated as a designer-in-the-loop process.

![Decision support tool showing raw PET](image1)

**Figure 2.** Decision support tool showing raw PET

![Decision support tool showing PET post damage function and exposure](image2)

**Figure 3.** Decision support tool showing PET post damage function and exposure

**Acknowledgments**
The research was conducted under the Cooling Singapore project, funded by Singapore’s National Research Foundation (NRF) under its Virtual Singapore programme. Cooling Singapore is a collaborative project led by the Singapore-ETH Centre (SEC), with the Singapore-MIT Alliance for Research and Technology (SMART), TUMCREATE (established by the Technical University of Munich), the National University of Singapore (NUS), and the Agency for Science, Technology and Research (A*STAR).
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