Simulation in Support of the Design Process for an Outdoor Space

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Abstract

This paper presents a case study of outdoor thermal comfort simulation to support the design of an outdoor space. The outdoor space studied is a courtyard located in a hot arid climate that is expected to be too warm for a portion of the year. A pipeline of tools is presented to predict the thermal stress of occupants in the courtyard using simulated environmental variables and the Universal Thermal Climate Index (UTCI). This pipeline is then deployed systematically to provide guidance for the design team to design a more comfortable courtyard space.

Through this case study, we provide a model for the integration of simulation in the design process that serves to support rather than to diminish the role of the designer. The analytical approach is based on a decision tree with multiple design paths, with each node of the tree relating to a design decision. In this way, the analysis systematically walks through a series of design decisions engaging the designer in potential trade-offs rather than simulating all potential combination of parameter values to determine a single mathematically optimal solution.

Introduction

Architects balance many factors throughout the design process. Charged with the task of designing a useful outdoor space, many considerations arise beyond comfort, including aesthetics, program requirements, and construction costs. Detailed analysis of any one factor such as comfort helps inform design decisions, but only to the extent it can respond to variation in other factors. The case study presented in this paper illustrates the potential for harnessing the power of simulation to support the design process with the flexibility to be useful.

The project is located in a hot arid climate, characterized by hot summers and mild winters. Precipitation is limited and concentrated in the winter. Wind is moderate and does not exhibit a strong seasonal pattern; the most common wind direction is northwest. Initial climate analysis suggested comfortable outdoor conditions exist throughout the winter and that the summer brings weather that is uncomfortably hot.

The project consists of the design of an outdoor courtyard space with openings oriented east and west (see Figure 1). The intent of the project was to identify and prioritize strategies that could make the space more comfortable. While the hot conditions of summer were not likely to be comfortable no matter what strategy was used, the client wanted to extend the use of the space through as much of the year as possible.

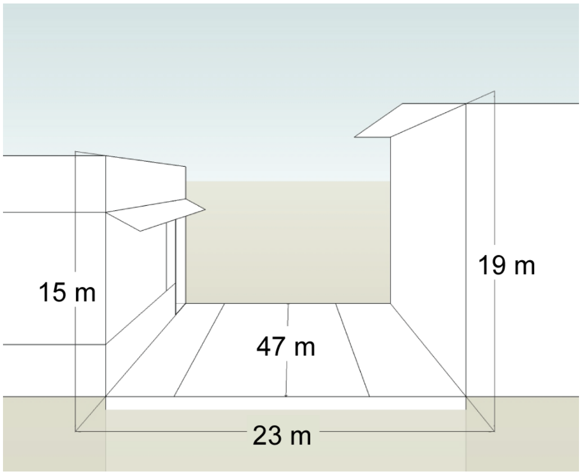

Figure 1: View looking east

A number of strategies were already being discussed, the primary being the use of active and/or passive downdraft evaporative cooling. Strategies also included shading and increased air movement. While we knew that each of the strategies being discussed had the potential to increase comfort, we did not yet know how these strategies should be prioritized or combined.

Methodology

We used simulation as a tool to guide the design team in selecting and prioritizing these thermal comfort strategies. In this early stage of the design process, we were focused on the question of *how can* a design work, rather than *how will* it work. For instance, rather than studying the effectiveness of a specific overhang, we studied the effectiveness of full shade. This approach helped the team explore possibilities and to set goals for the project. With an understanding of the environmental conditions that would help the courtyard work, the team was then able to go about designing and testing strategies to achieve these conditions. The team still needed to use simulation as a tool to test to see if particular design alternative would work, but this is a separate and later consideration.

For further perspective on this approach of bringing simulation into the design process, we took as a precedent the development of automatic machine tool control, as described by Noble (1984). After the Second World War there developed at least two competing approaches for automating control of manufacturing machines such as metal lathes or milling machines. One approach favored numeric control, a technology that effectively replaced the intelligence of the machinist with encoded algorithms, shifting control of the process to the code and to technicians who primarily understood automation technology rather than the milling process. Another approach was developed for the Specialmatic. This machine automated routines for the machinist, allowing the operators to apply their expertise more effectively and to remain in charge of the overall process. The latter approach produced better results since the final process was informed by operators' creativity and full experience, including inputs such as sound and smell that could not be included in code-driven automation.

In building simulation, there are multiple examples of parametric analyses that seek to automate the process of selecting an optimized design. For instance, Chen, Ooka, and Kato (2008) describe an application of a genetic algorithm to select an optimal placement of trees in an outdoor space. This approach is helpful when the objective can be described as a quantitative function and all constraints are known in advance. However, the typical design process guarantees neither of these conditions. For this reason, guidance from this kind of simulation optimization too easily becomes reductive and divorced from the process of design.

Our focus on open-endedness and flexibility acknowledges the multifaceted nature of the design process as mediated and controlled by the designer, similar to the machinists on the *Specialmatic*. We sought not to deliver only an optimized comfort solution, since this in effect would circumvent the other considerations of the designer. Rather, we sought to provide the designer intelligent feedback and guidance throughout the design process. In short, this paper presents simulation as augmentation of the design process.

Simulation Methods

We initially searched for a simulation approach that could assess strategies to improve thermal comfort in the outdoor courtyard space. Studies such as Jeong and Yoon (2012) or Echave and Cuchi (2004) calculated comfort for outdoor spaces, however the studies used custom heat balance calculation methods that were not suited to our project timeline or budget. Since the design goal was to extend the use of this space into the shoulder seasons, we needed a tool that can assess hour-by-hour annual performance. One publically available tool used in similar projects is ENVI-met. Perini and Magliocco (2014) and Taleb and Taleb (2014) used ENVI-met to simulate thermal comfort in an exterior space for selected days of the year. While the software takes into account the necessary variables to determine thermal comfort (air temperature, relative humidity, mean radiant temperature and wind speed), it does so at a relatively fine spatial resolution that is appropriate to simulating 1-2 days of performance and not well suited to calculation of comfort on a yearly basis.

We looked for a comfort metric appropriate to the context of an outdoor space. While some outdoor thermal comfort analyses have used Predictive Mean Vote (PMV) as a comfort metric, Fanger (1970) developed the PMV metric in the context of indoor comfort. Alternatively, Jendritzky, de Dear and Havenith (2012) describe the development the Universal Thermal Climate Index (UTCI). This is a metric designed for outdoor comfort assessment, appropriate for this study.

UTCI indicates varying levels of thermal comfort by specifying an equivalent temperature that correlates to thermal stress (see Table 1). UTCI is calculated from dry bulb temperature (DBT), mean radiant temperature (MRT), relative humidity (RH), and wind speed. Colloquially, UTCI may be given as a "feels like" temperature. For the purposes of this project, we considered any amount of thermal stress to be uncomfortable.

Table 1. UTCI heat stress

Level	UTCI Range	Description
0	9–26°C	No thermal stress
+1	26–28°C	Slight heat stress
+2	28–32°C	Moderate heat stress
+3	32–38°C	Strong heat stress
+4	>38°C	Very strong to extreme heat stress

Based on design strategies affecting outdoor thermal comfort, we developed a list of approaches to test:

- Evaporative cooling for the air
- Shade surfaces
- Shade the occupant's body
- Evaporative cooling for surfaces
- Elevated air speed on skin
- Physical and psychological effects of introducing green plants and other landscaping measures

In order to test which strategies were the most promising, we collected and linked a set of tools and data sources to model the UTCI. (see Figure 2 on the following page for a diagram showing the procedure).

To calculate UTCI, we used the Outdoor Comfort Calculator module in the Grasshopper Ladybug library (Roudsari, 2013). For the inputs to this script, we began with data from a nearby weather station compiled as a Typical Meteorological Year (TMY) weather file. We used these data in the UTCI calculation, modifying specific values as described below to represent the potential for each strategy.

We used the weather file values for air temperature and relative humidity for most of the strategies, with the exception of evaporative cooling. The mechanical engineer had estimated that the evaporative cooling system could be designed to supply air at 75% RH. This represented the maximum potential, since we knew that the humidified air would mix with ambient air, thus lowering the humidity a certain amount. We tested different values of RH from ambient levels up to 75%, and adjusted DBT to maintain the psychrometric relationships.

MRT was more complicated to model, since surface characteristics and solar radiation are essential factors to consider beyond data in a modified weather file. We determined MRT in two steps. First, we built a thermal simulation using EnergyPlus to model surface temperatures (Figure 1 is a screen shot of the model). We ran this model with material properties of surfaces and for the weather conditions in the weather file. We then calculated MRT based on hourly surface temperatures and calculated view factors for three locations in the courtyard. Second, we modified this MRT using the Outdoor Solar Temperature Adjustor module in Ladybug, This factored in the effect of sun on the body based on exposure to direct solar radiation for each courtyard location and for each hour of the year.

Finally, wind speed was the most complicated variable due to the chaotic nature of wind and the inherent difficulties of making accurate predictions for one point in time, much less for each hour of the year. We thus used a range of wind speeds, from minimal air movement up to a speed of 3 m/s, which was an upper limit on what would typically be acceptable in a courtyard.

Decision Tree

With the range of stragegies defined, we developed a traditional matrix of all potential scenarios. We then began to simulate the scenarios represented by cells in the matrix. For each simulation completed, we calculated the portion of all hours in a year likely to produce heat stress and visualized the diurnal and seasonal patterns of heat stress using a heat map. The baseline scenario showed heat stress during 53% of hours throughout the year, with significant heat stress beginning around February and March (see Figure 3).

After simulating the baseline, we selected subsequent scenarios to test. Instead of using optimization methods to find the cluster of "best possible" strategy combinations, we began to study the performance of scenarios sequentially. With each subsequent application of a strategy, a distinct scenario was created; these scenarios can be mapped as nodes in a tree-like structure

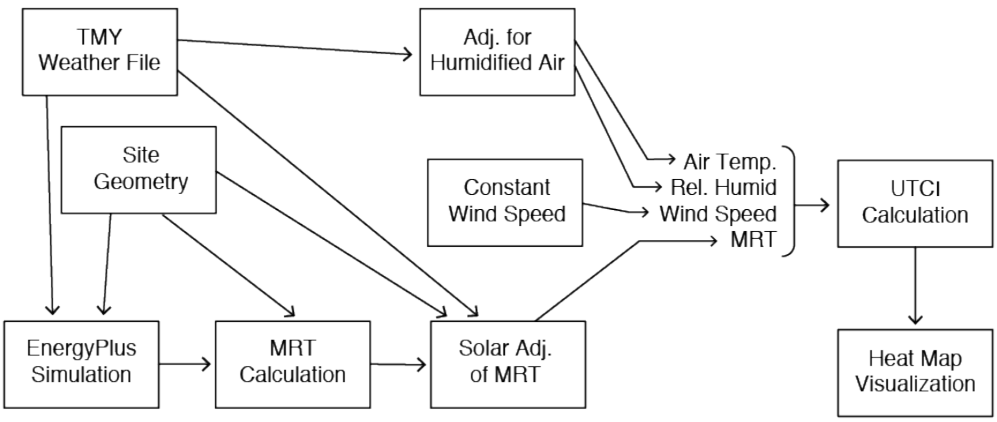

Figure 2 Pipeline of tools used to calculate UTCI and visualize thermal stress.

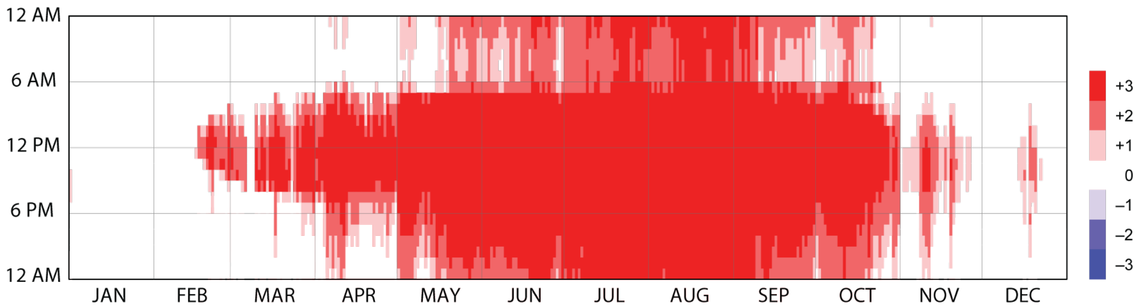

Figure 3 Hourly heat stress, base condition: thermal stress during 53% of the year.

that shows the paths of discovery as we explored courtyard performance.

The goals of this exploration were not only to find scenarios that performed best, but also more importantly for the designers to develop intuition regarding which strategies and combinations of strategies might be the most promising. For this reason, judgment as designers was used to select which decision tree branches were to be explored.

Building the nodes manually rather than automatically allowed us to gain an intuitive understanding of the sensitivity of the design solutions to the various inputs. It also allowed us to map out the scenarios in terms of what interventions might or might not be possible. The decision tree showing how each simulation further developed a previous simulation was presented as a diagram (see Figure 4). The diagram allowed us and the client to understand how incremental design decisions affect the comfort in the space. Since this conditional logic was built into the decision tree, we and our client were well prepared to consider various scenarios.

For instance, we knew that adding shade to the body would be effective and was also easier relative to other strategies. So we largely saved adding shade to the body (labelled “umbrella” in the decision tree below) for the last strategy added in order to more clearly see which of the other strategies were more effective.

In the first pathway, we studied the effect of changing location of study within the courtyard and discovered it had little impact (see Path 1 in Figure 4). The second pathway showed the effects of changing the humidity (and thus also the temperature) on the skin, then near surfaces in the courtyard (see Path 2).

Indeed, many of these approaches were interdependent; some combinations of strategies would work better together, while other combinations had the potential to perform worse together. For instance, we noted that higher wind speeds would present a trade-off with evaporative cooling since evaporative cooling would require air to be calm to be contained in the courtyard space.

Another pathway through the nodes (see Path 3 in Figure 4) yielded the best performance possible, employing all strategies, while limiting the wind speed due to the feasibility of using elevated air speed and humidification simultaneously (see the description of the scenario in Table 2). In this scenario, we found that the total number of hours of heat stress could be reduced to 23% of the year.

Table 2. Path 3 strategies

Strategy			
75% RH on person and surface	X	X	X
Shade surfaces	X	X	X
wind of 1m/s		X	X
Shade person			X
% discomfort	33%	32%	23%

We felt it would also be helpful to study a pathway with less aggressive humidification of the courtyard air to account for the potential difficulty of fully containing humidified air. This scenario assumes that humidity

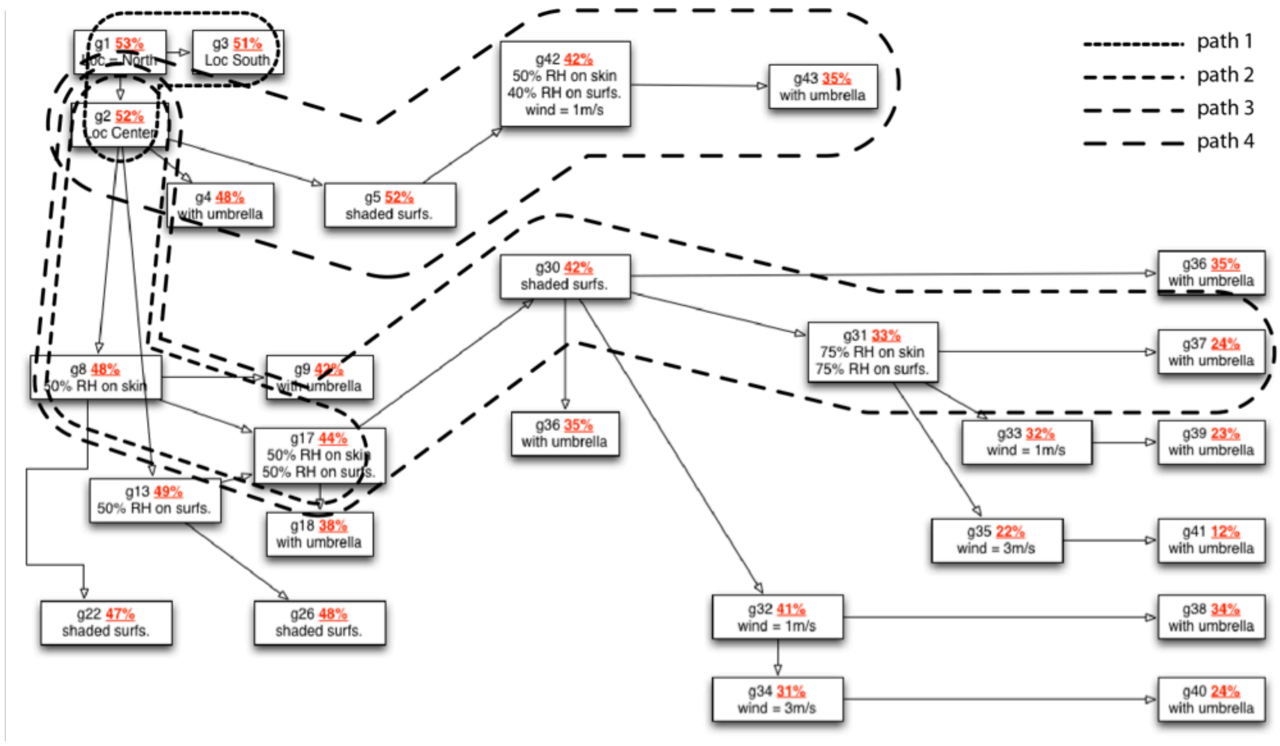

Figure 4 Design decision tree showing process of testing

could be maintained at 50% near occupants and at 40% on average near surfaces (see Path 4 in Figure 4). We maintained other strategies identified, including shading surfaces, shading occupants, and a small amount of air movement (see the description of the scenario in Table 3). We found that with this set of realistic targets, the hours of heat stress could be reduced to 35% (see Figure 5). This heat map visualization helped reveal that the intensity of heat stress was also reduced, so that the space would be more inhabitable even during times that are not free of heat stress. The visualization also shows that these strategies have the potential to extend the inhabitable season through April or early May.

Table 3. Path 4 strategies

	Strategy		
1	50% RH on person	Yes	No
2	40% RH on surfaces	Yes	No
3	Shade surfaces	Yes	No
4	wind of 1m/s	Yes	No
5	Shade person	Yes	No
	% discomfort	35%	52%

Results

Reviewing the most successful paths through the decision tree, the approaches to outdoor comfort yielded a set of performance goals for the space:

- Occupants need access to shade
- Surfaces of courtyard should be shaded
- Courtyard must be able to contain humidified air

We were then able to take these strategies and test design alternatives to see if specific design alternatives could satisfy the goals. Since we laid out the parameters one at a time and explored performance showing the conditional logic in the decision tree map, we and our client had an intuitive understanding of performance that prepared us to consider various scenarios.

Finally, the analysis also gave us the performance requirements that we used for further testing. For instance, the question of containment of air for humidification was tested in a series of wind tunnel tests.

Discussion

It is important to observe that the approach presented in this paper is very different than what may be called parametric optimization. Parametric optimization in simulation is a means of arriving at the best solution or a set of best solutions. This kind of simulation tends not to fit well into the design process. In a sense the simulation is giving the "correct" answer to the designer and asking them to use it in their design; the optimization has effectively replaced the designer in this step of the design process.

Here we have presented an approach that "augments" the designer's capabilities through simulation. The salient features of this approach are the use of particular paths along a decision tree to build understanding of performance and the selection of strategies defined by broad ranges of parameter values rather than by the performance of specific design alternatives. As a result, this helps the designer understand how a space *can work*, as opposed to whether a space *will work*. For example, we did not test to see if a wind velocity of 1 m/s was possible. Rather, we tested to see what wind velocity was desirable, and in what relationship to other thermal comfort strategies. With this understanding of how various strategies can combine to achieve good performance, the strategies were in effect translated to design specifications that the team then attempted to meet using specific design alternatives.

Looking back at the process we note the following steps:

1. Identify and list the strategies that could affect thermal comfort in the courtyard, defining the strategies in such a way that they are decoupled from specific design alternatives. There should be different way of implementing any one of the strategies. For example, a comfort strategy to shade the body from direct sunlight could be achieved using free-standing umbrellas, a retractable canopy, building shade or trees.
2. Develop a decision tree that shows how sequential design decisions affect comfort. The mapping in the decision tree will provide multiple alternate design pathways. This will result in more than one viable design solution.

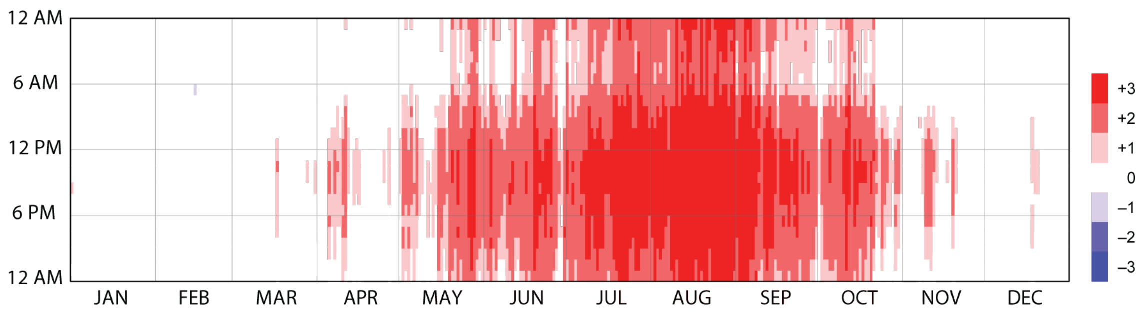

Figure 5 Hourly heat stress, target: thermal stress during 35% of the year.

3. The designer works through the decision tree while considering all factors and arrives at an acceptable comfort condition. It is important to note this comfort condition may not be the most optimized solution. Using a decision tree in this manner allows the designer work with all the other aspects of the design, such as cost, constructability, architectural impact, and other client requirements.

Conclusion

In addition to applying a design decision tree framework, we also supported the design process by balancing the need for accuracy with the need for quick analysis. We used site and project-specific information (weather, geometry, material definitions) to ensure simulation results were sufficiently accurate and precise, while we also made more generic assumptions that helped us test alternative performance specifications (e.g., that the system could maintain the relative humidity at a certain level, or that the courtyard could provide a specific amount of shade or a specific range of wind speeds).

This approach satisfies two needs for simulation in support of a design process:

- The need to accurately and precisely model performance so that the simulation results predict actual impacts of design decisions.
- The need for simulation results to be relevant to the design process in that they are produced quickly and are open ended so they can be used to guide the design process.

While these are sometimes contradictory considerations, it is important to recognize that complexity is inherent in any design process. Given the right balance, simulation has the potential to make projects better by supporting rather than constraining the design process.

Acknowledgement

This work was developed during a project in consulting practice. The client and project are confidential.

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