Algorithmic Framework for Correlation Between Microclimate Control and Space Usage in Outdoor Public Spaces

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Effects of extreme temperatures are the cause of health-related problems and have an impact on how we go about with our daily lives. This study addresses the critical question on the relationship between architecture and climate. It probes into the correlation between urban environments and microclimate while focusing on the outdoor public spaces. This paper provides a conceptual framework for information processing to enable spatiotemporal design strategies for outdoor public spaces. The flow of information starts with data gathered by sensors, relies on the computational techniques for processing and ends with information as specific as instruction for the behaviour of spray nozzles emitting water vapour. The contribution of this paper is the advancement of the design methodology of public spaces, through the development of dynamic design strategies based on the ability to sense climatic conditions in localised areas and map behaviour of occupants in real-time.

Keywords: *Interactive Architecture, Responsive Environment, Evaporative Cooling, Microclimate, Outdoor Public Space*

INTRODUCTION

The global climate is changing, and heat waves are becoming more frequent. Extreme temperatures are the cause of health-related problems and have an impact on our daily lives. WHO (2019) identifies heat as one of the leading threats to sustainable development. It says that the effect is most pronounced in cities characterised by large expanses of urban paved and concrete structures, which absorb radiant heat, and conversely, a lack of reflective or green spaces to effect cooling. It warns that average centre city temperatures are anywhere from 3-5^0 C above those in the surrounding countryside. A large amount of heat generated from urban structures, as they consume and re-radiate solar radiations, and from the anthropogenic heat are the leading causes of Urban Heat Island (UHI) effect (Memon 2008). The problem of heat accumulation in urban areas drives the sizable body of research (e.g. Dwivedi 2019; Taha 1997). UHI is now recognised as the most evident characteristic of urban climate, with an influence on material and energy flows in cities, and therefore their structure and function (Yang et al. 2016).

Known UHI mitigation techniques include the use of adequate materials, urban vegetation, water and shading as potential solutions to moderate temperatures and increase the adaptive capacity of cities to the warming climate (Osmond and Sharifi 2017). However, the existing body of knowledge on adapting to the UHI effect is not fully assimilated into architecture and urban design (Yow 2007). And, despite the evolving understanding of urban climates changes, the use of innovative technology to augment architectural solutions is still insufficiently integrated in practice (Lally 2012; Yang 2012).

The study reported on in this paper, explores the potentials of dynamic architecture enabled by responsive technologies. In the book "Interactive Architecture" Fox and Kemp (2009, p 27) write that "there is a great potential for dynamic architecture that arises from understanding what space or object is currently doing and how it can aid in promoting or accommodating a specific task. Some of this understanding relates to dynamically changing architectural elements or spatial layouts that address desires to have public or private space, to optimise thermal, visual, lighting, and acoustic conditions, and to promote sharing or collaboration in space. This understanding boils down to examining how architecture can extend the notion of enhancing our every day activities by assisting users in accomplishing specific activities or possibly suggesting new ways to interact with space and other users to complete tasks."

This paper focuses on the role of evaporative cooling, one of the water-based solutions for UHI mitigation. Evaporative cooling removes heat from the atmosphere as water changes phase from liquid to vapour. The ambient air temperature is reduced by forcing water through small nozzles under high pressure, producing clouds of fine mist which absorb ambient heat to be evaporated in the air (Osmond and Sharifi 2017). The system is effective while it has low power demand and thus is responsible for light carbon dioxide emission (Farnham et al. 2017; Frederick and Khosla 2014).

We recognise the potency of evaporative systems to control outside air temperature, but also their potential to improve occupants' engagement with space. Two precedents demonstrate a successful application of evaporative cooling in the architecture of outdoor public spaces. Tanner Fountain at Harvard University, USA (1984) by PWP Landscape Architecture and Le Miroir d'eau, Bordeaux, France (2004) by Michel Corajoud both utilise water emitted from nozzles to alter microlite in public spaces in response to the weather. PWP states that the Tanner fountain invites human participation without suggesting any particular activity and that it is heavily used by people of various ages who sit, read, climb, jump, flirt, converse, and meditate (1984). Same applies to the project in Bordeaux, and both schemes exemplify the potency of evaporative cooling and microclimate control in architectural design.

The conceptual framework presented in this paper focuses on the expanded role of an evaporative cooling system in outdoor public spaces. The study is drawn on the research efforts which integrate science, professional practice, and stakeholder participation to improve the design of public spaces (Ahern et al. 2014); and whereby technology is used to mediate between disciplines and to enable participation of end-users (Felson and Pickett 2005; Hanzl 2007; van Den Berg and van Winden 2017; Yigitcanlar et al. 2008).

Systems affecting thermal comfort are amongst the most studied and developed technologies related to the built environment (e.g. Hatefnia and Ghobad 2015). However, in outdoor spaces, they are seldomly optimised according to measurements which go beyond climatic conditions, such as measurements of occupants' behaviour (Zhe et al. 2019). The similar view is established in earlier research (Nikolopoulou, Baker and Steemers, 2001; Spagnolo and De Dear, 2003) but to date, the issue remains understudied. In the past decades, there has been considerable interest in developing innovative ways of measuring the built environment, covering diverse topics such as those related to bus stop crime (Loukaitou-Sideris 2001) and residential satisfaction in mass housing projects (Dinc 2014). Such measurements offer themselves as a design intelligence and the basis for dynamic (spatiotemporal) conceptions of the built environment. Increasingly, efforts are being made to use remote sensing technology and numerical simulation methods, to study ecological and environmental effects of UHI across different scales (Tsou et al. 2006; Munitxa and Bogosian 2015; Voogt and Oke 2003; Yang et al. 2016) and for the mapping of microclimates (Zellweger et al. 2019). To this end, a wide array of techniques to measure specific aspects of space use has been tested, based on energy consumption, C02 emission, movement detection, sound levels, radio-frequency identification (RFID) and many more (Stojanovic and Vujovic, 2020). However, occupancy data is proved to be elusive and difficult to establish with sufficient accuracy (Sun et al. 2020). A growing number of studies demonstrate that measuring devices of different types should be employed simultaneously to avoid inaccuracies (Hobson et al. 2019). This study examines the use of pressure-based sensors integrated into the floor surface instead of commonly used cameras or PIR sensors. It is assumed that pressure sensors will provide more consistent space coverage, will avoid occlusion between users, and will not intrude privacy. The reliance on tactile sensors for information harvesting leads to the use of less demanding recognition algorithms based on weight or gait. (Bränzel et al. 2013).

OBJECTIVE

This paper provides answers to how responsive technologies can optimise evaporative cooling solutions to mitigate UHI effects in outdoor public areas, as well as support occupants' engagement with space; and how to formulate dynamic design strategies for better correspondence between microclimate control and space usage

The ability to sense climatic conditions in localised areas and map behaviour of occupants in real-time allows designers to employ active strategies. However, current practice shows a lack of coordination between climate control and outdoor space usage. This paper provides a tool for information processing to enable spatiotemporal design strategies for outdoor public spaces. The information flow starts with data gathered by sensory devices, relies on the computational techniques for processing and ends with information as specific as instruction for the behaviour of spray nozzles emitting water vapour.

This study aims to create a conceptual framework for dynamic architecture, which integrates the operation of the evaporative cooling system and occupants' behaviour, with the help of responsive technologies. We assume that technology is not only improving microclimate conditions but also changing the way people interact with space. In response to the topic of the eCAADe 2020 conference, Architecture and Fabrication in the Cognizant Age, this paper presents a novel conceptual framework for correlation between human activities and climatic conditions. The objective is to provide grounding future studies through the implementation of advanced computation methods and make a contribution to the development of the design methodology of outdoor public spaces.

ALGORITHMIC FRAMEWORK

The method presented in the following paragraphs focuses on the algorithmic framework for data harvesting, information processing and actuation of spatial change. The conceptual framework integrates climate control and activities of occupants to enable dynamic design strategies for outdoor public spaces. The concept is based on the ability to sense selected climatic conditions in localised areas and map behaviour of occupants in real-time. The proposed framework offers two critical advantages. Firstly, it provides a way to optimise cooling systems in outdoor areas, by their selective and intelligent application. Secondly, the framework contributes to the design methodology of public spaces by providing designers instantaneously with information otherwise available only through post-occupancy evaluation. The proposed design approach is user-centred and allows for user behaviour to influence the climate conditions in the built environment via operation of a responsive system.

In evaporative cooling, the combined effect of water pressure and restriction delivered by the nozzle affects the size of the droplet issued into the environment. An increase of either pressure or restriction results in the smaller size of the droplet, which evaporates more quickly. However, a study on evaporative cooling (Nunes et al. 2011), points out that numerical fluid analysis (Yamada et al. 2008) show that there is no significant temperature reduction for different particle sizes issued from the nozzles, and suggests that water vapour release periods and distribution patterns may have a more significant impact on the efficiency of the system. Therefore, this study explores how to establish a more accurate control of release periods and distribution patterns with the use of innovative technologies. The output information on release periods is calculated as the duration of action and pause time while information on distribution patterns is delivered as a percentage of active nozzles as well as the angle at the top of spray dispersal cone.

DATA HARVESTING

This paragraph introduces the network of sensors needed to harvest data and a scheme for integrated measuring of parameters related to meteorological conditions and occupants' behaviour (Figure 1). There are two categories of input information, the first one is for climatic conditions and the second one is for occupants' activities. Climate conditions are established through localised measurement of solar irradiance, wind speed and direction, temperature, and humidity. Occupants' activities are observed as presence, movement, and interaction or distance between people. The scope of activities measured is based on the categorisation of activities in outdoor public spaces established by Jan Gehl (1985). In the seminal book "Life Between Buildings: Using Public Space" Gehl writes how outdoor activities are influenced by climatic or physical conditions and how design affects the possibility of meeting, seeing and hearing other people in outdoor public spaces. He identifies essential activities in outdoor public spaces as walking, standing, sitting and places specific importance on the interaction between people.

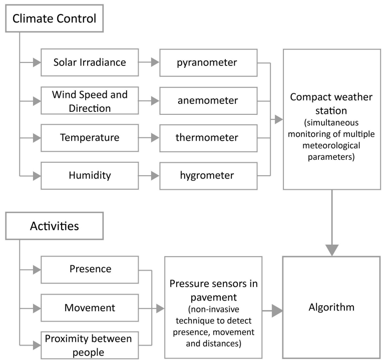

Figure 1
Integrated measuring of climate conditions and occupants' activities

Sensory devices employed for the measurement of climatic conditions are anemometer, thermometer, and hygrometer. Multiple sensors are linked into clusters to form a compact weather monitoring station allowing for simultaneous recording of key meteorological parameters.

Devices for measurement and the subsequent establishment of activity categories according to the method introduced by Gehl (1985) are pressure sensors located on the pavement surface. A vast amount of pressure sensors is employed rather than cameras in order to protect the privacy of occupants. A non-invasive technique is given an advantage over a visual recording to minimise data-privacy concerns and provide easier delivery. A pressure sensor detects the presence of an occupant, upon which the speed of movement and distance between users is established. According to Gehl (1985), the speed of the movement is proportional to the engagement between people and the built environment. If people move more quickly, they are about to commute from one place to another, but if they move more slowly or stop this is because they are attracted to engage with space, and they are willing to interact with other people. Accordingly, presented measuring approach supplies information needed for the evaluation of the existing outdoor public spaces, which is useful for future design. In this study, integrated measurements of climate conditions and occupants' activities are fed to the algorithmic framework and processed to produce output information needed for the autonomous adjustment of climatic conditions.

INFORMATION PROCESSING

This chapter outlines an algorithmic structuring of the information flow. Two categories of information, introduced in the previous chapter, are structured into vertical and horizontal input in the diagram (Figure 2).

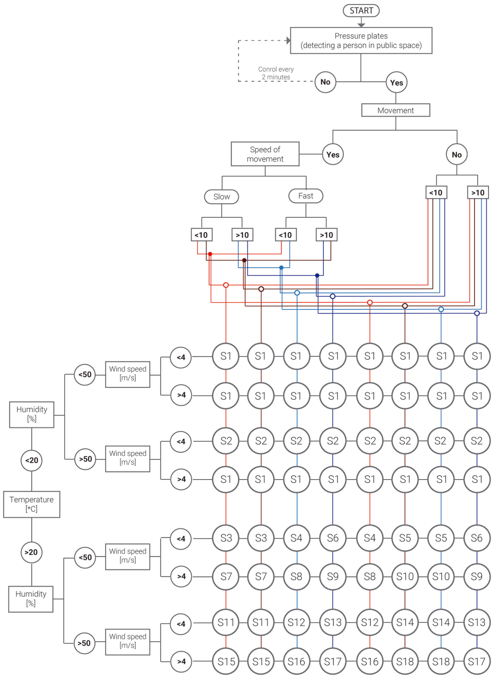

Figure 2
Algorithmic framework

Vertical input is provided by tactile sensors. Pressure plates embedded in the paving surface detect the presence of people in the outdoor public space. Based on this information, the speed of movement and proximity between occupants is established. This reliable and robust system is composed of square tiles, each equipped with a certain number of pressure sensors (usually four strain gauge load cells), processors, and a wired connection to the neighbouring cells (Andries et al. 2015). Depending on the resolution of the slabs, the proposed system can distinguish standing from walking, as well as to measure steps and therefore provide sufficient information on occupant's activities. Simultaneously, horizontal input is provided by the localised weather station. Horizontal input categories are limited for this paper to include temperature, humidity, and wind speed.

The algorithm results in a matrix, showing possible scenarios. Each of 64 possible combinations in that matrix requires activation of the cooling system in a slightly different way. While it is understood that the ability of the system to act with the minimal waste of energy is essential, it is also assumed that insignificant differences between regimes allow for the very similar or identical application of the cooling system. It is, therefore, accepted that a limited number of modes would be sufficient for the operation of the proposed system.

In this study, the microclimate control is delivered through evaporative cooling, an effective and energy-efficient system, composed of the water pump, filter, supply tubing and different nozzles. The evaporative cooling system reduces the ambient air temperature, with the use of water. Through nozzles and under high pressure, water is sprayed into the air to produce clouds of fine mist. The mixing between water and the air stream cools the ambient air from its dry-bulb temperature to its wet-bulb temperature. Evaporative cooling systems are capable of reducing outdoor temperature between 3 and 8 ˚C, depending on the relative humidity. They are most effective if the relative humidity is low.

ACTUATION OF SPATIAL CHANGE

The actuation of the presented framework is based on the performance of nozzles. The proposed cooling system allows for their selective and clustered employment. The cooling water mist is sprayed in selected zones only, where climatic conditions and occupant's presence are requiring so. There are three categories of output information regulating nozzle performance, and they are water vapour release periods, number of active nozzles, and the spray dispersal angle.

The first category, water vapour release periods are expressed in minutes. It defines the duration of nozzle action as well as the pause periods. The second category, the number of active nozzles, is captured as a percentage of nozzles which are active, out of all nozzles belonging to the same system. It is anticipated that the climate of outdoor public space will be controlled by multiple systems, each composed of 10 nozzles and assigned to specific microclimatic zones. Within any one outdoor public space, there could be one or many such systems at work. Finally, the spray dispersal angle is controlled by the intensity of air pressure and is expressed in degrees of the angle at which water mist is dispersed through the nozzle. Nozzles use air to break up the fluid into a spray pattern. The maximum dispersal angle is 70˚, and each source installed at the recommended height of 3m may affect the area measuring up to 5m in diameter (Osmond and Sharifi 2017).

A wide variety of nozzle types are currently available and used in different industries for the emission of both gases and fluids. Different types enable different distribution patterns and provide an opportunity for a responsive application of the cooling system. Two or more nozzles, located at the same spot, may be employed in alternation to optimise the performance of the system. The number of active nozzles and the spray angle definition have a critical impact on the rate at which water mist evaporates and thus influences the efficiency of the cooling system. The effectiveness of the proposed system is improved with its ability to respond to fluctuations in temperature, ambient humidity and wind speed. At the same time, presented the algorithmic framework along with the integrated measuring approach also enables the system's response to occupants' activities. For example, when people congregate in specific areas, more nozzles are activated. If the ambient humidity is low, more nozzles are activated for longer periods of time and at short intervals. If the outside air temperature is low, a smaller percentage of nozzles are activated and for shorter periods with longer pauses. If wind speed picks up, the spray angle is reduced, even if the temperature does not drop. The table below provides descriptive information of the system's response according to 6 representative modes established through the integrated measuring of climatic conditions and occupants' activities (Table 1).

Table 1
Representative input modes and output information

	INPUT: integrated measuring of climatic conditions and occupants' activities	Water vapour release periods (min)	Active nozzles (% of all nozzles)	Spray dispersal angle (°)
Mode 1	any number of people walking slowly, any number of people walking fast, any number of people not moving, temperature lower than 20°C, when humidity is less than 50% with any wind speed	Off	n/a	n/a
Mode 2	any number of people walking slowly, any number of people walking fast, any number of people not moving, temperature lower than 20°C, when humidity is more than 50% and wind speed less than 4m/s	On (1 min, every 30 min)	20%	70°
Mode 3	less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity less than 50%, wind speed less than 4m/s	On (2 min, every 2 min)	50%	70°
Mode 7	less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity less than 50%, wind speed more than 4m/s	On (2 min, every 5 min)	50%	50°
Mode 11	less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity more than 50%, wind speed less than 4m/s	On (1 min, every 10 min)	20%	35°
Mode 15	less than 10 people walking slowly, any number of people walking fast, less than 10 people not moving, temperature higher than 20°C, humidity more than 50%, wind speed more than 4m/s	On (1 min, every 20 min)	20%	15°

DISCUSSION AND CONCLUSIONS

The presented conceptual framework provides grounding for the application of advanced computational techniques and further interdisciplinary collaboration between architecture, computer science and mechatronics. The framework utilises algorithmic logic to allow synchronous measuring of climatic conditions and occupants activities and relies on the use of responsive technologies to establish a two-way relationship between occupants' behaviour and physical conditions of the built environment. In this study, the actuation of spatial changes is delivered by an evaporative cooling system. The release periods and water misting patterns delivered by selectively activated nozzles are brought into relation with meteorological conditions and human behaviour in outdoor public spaces.

The study, motivated by rapidly changing climatic conditions in urban areas, addresses the lack of architectural use of innovative technologies identified in the literature review. The presented approach reflects on the complexities of the relationship between the built environment and the climate and establishes a way to integrate innovative technologies into architecture. The research report shows how the application of responsive technologies could help optimise cooling solutions in public areas, as well as help occupants to engage with space. The algorithmic logic applied provides an open-end structure and a scalable design tool that can be applied in different environments and adjusted to diverse input information.

The presented framework is a generic solution, necessitating adaptation according to specific physical, geographical and seasonal conditions. The adaptation aspect is not included in the scope of this report. Further development of the proposed framework is planned in a laboratory setting through research based on prototyping and iterative testing of the concept. At this stage, the research is presented at the conceptual level to structure further development.

The presented framework is beneficial to architects and urban designers by enabling better correlation between microclimate control and space usage in outdoor public spaces. The benefits are twofold. The proposed framework improves the efficiency of the evaporative cooling system, while also providing means for architects to design space as dynamic and changing according to occupants needs and climatic conditions. An effective outdoor cooling system will improve the user comfort in public spaces, while the responsive change of physical conditions enhances occupants' engagement with space. The approach envisages a dynamic transformation of microclimatic zones within outdoor public spaces and allows the user to take an active role in the process.

The presented framework also enables evidence-based understanding of how public spaces are being used in different weather conditions. It allows for real-time data collection and structuring of data sets according to specific questions raised by designers. In the form of instant and continuing post-occupancy evaluation, such acquisition of information may be a valuable addition to design knowledge. Future study will focus on the actual data capture and creation of useful data sets.

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