Environmental Ceramics

Merging the digital and the physical in the design of a performance -based facade system

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Environmental comfort and space occupancy are essential considerations in architectural design process. Façade systems deeply impact both aspects but are usually standardized. However, performance-based facade systems tackle these issues through computational design to devise non-homogeneous elements. This work proposes a ceramic facade system designed according to a performance-based process grounded on environmental analysis and parametric design to allow adaptation and geometric variation according to specific building demands on environmental comfort and functionality. In this process, the Design Science Research method guided the exploration of both design and evaluation, bridging the gap between theory and practice. Positive facade environmental performance were found from digital and physical models assessment in terms of radiation, illuminance, dampness (with ventilation) and temperature. Computational processes minimized radiation inside the building while maximized illuminance. Their association influenced on operative temperature, which dropped according to local dampness and material absorption. Accordingly, this design process associates not only environmental comfort and functionality concepts but also adaptability, flexibility, mass customization, personal fabrication, additive manufacturing concepts, being an example architectural design changes in the 4th Industrial Revolution.

Keywords: *sustainable design, facade system, computational design, environmental analysis, evolutionary algorithm*

INTRODUCTION

Space demands of current office buildings differ from modernist ones, and space occupancy of contemporary offices vary significantly. For instance, Danielsson and Theorell (2018) describe seven possibilities of workspace organization: cell-office, shared-room office (2-3 people/room), small open plan office (4-9 people share workspace), medium-sized open plan office (10-24 people share workspace), large open plan office (>24 people share workspace), combi-office - teamwork, sharing workspace and facilities, hot-desking office - non personal workstations, no access to back-up environment. At times, the same floor includes more than one type of occupancy. These diverse features are in general associated with different environmental needs based on different categories of activities.

Studies on office design and its influence on employees' well-being have different approaches: architectural and functional, furniture and layout, lighting, air quality, and temperature, amongst others (Gero et al. 2015; Danielsson and Theorell 2018; Pantazis and Gerber 2018; Sun et al. 2018). Environmental comfort is, however, an increasing demand associated with the call of decreasing energy consumption (Shahbazi et al. 2019) especially for the office building typology. Therefore, contemporary office design must contemplate new space and activities requirements, along with specific comfort criteria (which can also be related to tasks) and energy saving.

One way to control the complexity of environmental comfort aspects and stringent sustainable requirements, while also considering space occupancy, is by using the facade as an environmental mediator (Ekwevugbe et al. 2015, Pantazis and Gerber 2018; Shahbazi et al. 2019). Computational design advances have been playing an important role in providing answers to this complexity by managing architectural solutions to the conflicting inter-domain objectives of building design. In this context, parametric and performance-based design emerged as an integrated approach and grant architects the possibility to explore multiple design solutions and strate-

gies, predict model's behavior and rapidly generate alternatives (Pantazis and Gerber 2018).

This paper presents the design research process of a performance-based facade system for contemporary office buildings and was developed in a Brazilian graduate course during the second semester of 2018. Pantazis and Gerber (2018) highlight that facade panels are a complex component due to the combination of structural, environmental, functional and aesthetic parameters. Facade systems can also be analysed in terms of conceptual layers: building and design selected performance criteria. This consideration leverages the need and importance of some performance aspects and is a reminder of the aspects that should have in-depth development (Emmit et al. 2004). Differently from usual facade systems, in which the components are morphologically homogeneous and the solution is standardized, performance-based facade systems commonly take computational design to devise non-homogeneous elements that meet environmental comfort criteria and also relate to building internal functions.

Other essential criteria associated with industrialization aspects are embedded in the design process, such as adaptability, flexibility, and mass customization (Kolarevic 2003). These characteristics are included in the use of additive manufacturing, which was considered in this design exercise. Aiming at a system performance from those design criteria, this study embraced specific aspects and methods, such as material properties, environmental analyses and computational optimization. A parametric process was deployed to synthesize all the constraints and conditions, assuring a personal, customized and replicable facade system.

Material choice in architectural, engineering and construction (AEC) scenario points to ecological choices focusing on sustainable-oriented design approaches. The sustainability aspect of material concern should also consider another stage of the life cycle: post-occupancy evaluation on environmental comfort, which was taken into account in this research from the model analysis. As in the new

structuralism (Oxman and Oxman 2010) the material choice in this study is considered at the beginning of the design process, then deriving structure and form. This choice must take into consideration local features, such as climate, which impact temperature, ventilation, and dampness values.

Eight bioclimatic zones are defined for the Brazilian territory. They differ from each other in terms of relative humidity, temperature and moisture ratio. The Brazilian Association for Technical Standards (ABNT NBR:15220 2003) presents both the zones and their location, and construction guidelines (size of ventilation openings, opening protection and external cladding - walls and roofs) associated with passive thermal conditioning strategies. This research took place in the city of Campinas, Brazil, located in-between bioclimatic zones 3 and 4.

The guidelines for these zones are evaporative cooling, cooling thermal mass and cross ventilation as summer comfort strategies, and solar heating and thermal mass during the winter time. For this study, summer strategies were selected for closer analysis and a ceramic material was chosen due to its properties of thermal transmittance, thermal capacity and density. Besides, passive evaporative cooling techniques employing ceramics were also considered. This passive strategy can be used in contemporary architecture to reduce the dependence on conditioning equipment, and therefore energy consumption (Faggal 2015).

The aim of this research was to design a ceramic facade system through a performance-based process in order to rationalize design alternatives that would output a range of solutions based on mass customization principles. The study focused on designing a static facade system based on parameters that allow adaptation and geometric variation, associated with environmental comfort criteria and space occupancy, according to specific building demands in which the facade system will be applied.

METHODOLOGY

The Design Science Research (DSR) methodology was applied in this study due to its characteristic of encompassing several methodological procedures with the potential to bridge the gap between theory and practice. DSR emphasizes both the design and the evaluation of the artefact and its methodological procedures aim to obtain a solution to be generalized and replicated in similar situations (Dresch et al. 2015). In comparison to traditional methods, the authors demonstrate that while these mainly describe and explore a research problem, DSR focuses on designing and creating systems that do not exist yet. The facade system proposed in this short-period research undertook this method, using design as a research process.

As a premise from the sustainable-oriented design approach, the facade system had a demand to be specifically responsive to Brazil's Bioclimatic Zones 3 and 4. Within the guidelines for these zones, the evaporative cooling requirement was chosen as the main environmental design condition and its implementation was carried out by considering the use of a porous material with high water absorption. The ceramic material was selected due to its high responsiveness and applicability to environmental criteria and the possibility of using large scale 3D printing industrial fabrication in the production process of the elements. The facade system design was proposed based on four essential design aspects, especially for this case and context: radiation, dampness associated with ventilation, inner temperature, and natural lighting.

On one hand, flexible space layout would require a dynamic facade system. On the other hand, the maintenance cost of such a system would be much higher than a static one, especially with the use of relatively heavy ceramic elements. For this reason, our design proposal considered a static facade with density variations that create different environmental qualities and thus allow the distribution of different functions along with it.

Embedding the Physical and the Digital

Both digital simulations and physical experiments were used during the design process in order to analyse and synthesize the aspects and constraints regarding the four conceptual layers of the system: radiation, temperature, daylight illuminance (digital model) and dampness with ventilation (physical model). In the digital approach, parametric tools and techniques in Grasshopper, an algorithmic modelling plugin for Rhinoceros 3D, were used to design a computational process in which an initial shape was optimized to attend the required environmental criteria of minimum radiation and maximum daylight inside floors of a conceptual office building. The design optimization was achieved by the integrated use of environmental analysis tools (Ladybug and Honeybee suite) and an evolutionary design solver (Octopus, a multi-criteria optimization and search tool). Daylight results were analysed according to ABNT NBR/ISO/CIE:8995-1 (2013).

In the physical approach, a generic small-scale shoebox model was built in order to analyse the facade material properties by simulating the performance of a ceramic component grid as an evaporative cooling device by using a wind tunnel test. Hence, the physical experiment evaluated the design benefits of deploying ceramics for the cladding subsystem of the facade under a saturated condition, ventilation and its potential to improve thermal comfort inside the building.

As a result, digital simulation outputs were the association of optimized radiation and illuminance, along with operative temperature inside the building considering the facade system. The wind tunnel experiment put together two variables, analysing the influence of facade saturation, thus environmental dampness, in reducing the temperature. Finally, temperature data crossing was necessary to generate final temperature values, which means inputting the temperature variation from the physical model in the digital results. General considerations of the conceptual layers, how they were analysed in digital and physical models, and their relation to each other to generate final results are presented in Figure 1.
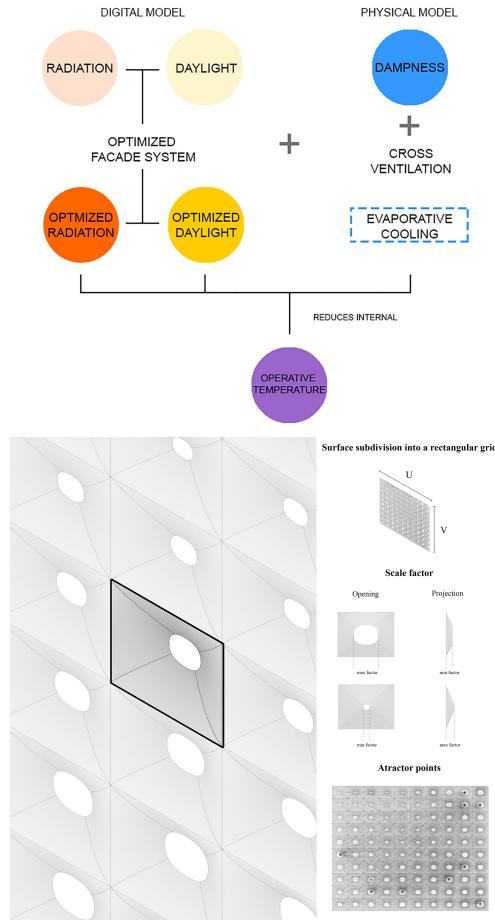

Figure 1
Framework of models and design layers. Font: Authors, 2019.

Figure 2
Parametric definition of the facade system's components setting. Font: Authors, 2019.

Digital Workflow: Performance-based Design

The digital design workflow consisted of four computational processes phases. Firstly, the facade geometry (Figure 2) was built upon the UV subdivision of a surface into a grid of rectangular subsurfaces in order to have boundaries for the system's com-

ponents. Each set of subsurface vertices were interpolated three times to define the curves for lofting the component's funnel-like shape, whose internal and external openings were controlled by parametric scale and projection factors. The opening's factors were calculated by the direct proportion to the sum of proximity distances of ten attractor points randomly placed at the center of each subsurface of the rectangular grid.

The second algorithmic process encompassed environmental analysis by radiation and daylight simulations. In order to assess the facade system performance, a generic four-storey building virtually located at the Bioclimatic Zone 4 was used in the simulations that undertook environmental aspects such as orientation, site context, time of the year and sky matrix. For the radiation analysis, the period between December 12th and March 20th was taken for being the most critical for the specific Bioclimatic Zones, during which heat waves arise and cause impact on building comfort during summer time. Using Ladybug tools, a weather file for São Paulo state was

employed to preset the cumulative sky matrix to be used along with the analysis period and define a specific sky matrix for the computation of the radiation values.

For the Daylight simulation with Honeybee tools, diffuse reflectance values for concrete and ceramics were associated with the corresponding geometries in order to generate Radiance Opaque Materials to be analysed during the simulation. A grid of test points was generated from the four analysed slabs as well as a sky file from the weather file and a specific date in the radiation analysis period. These values were preset as a recipe for grid-based analysis and used to compute the illuminance data.

The simulation results of the facade system achieved concerning radiation and illuminance levels that demanded to be optimized in terms of environmental performance. In the third algorithmic process, a strategy to reach the performance of the facade was defined by creating two criteria: minimization of the total sum of radiation levels and, concurrently, maximization of the total sum of daylight

Figure 3
Digital workflow.
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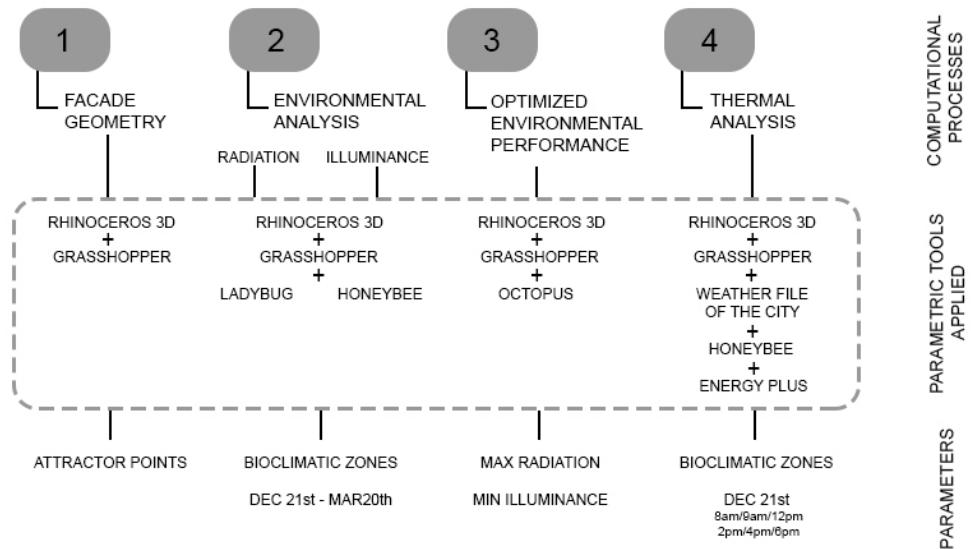
values. The multi-objective optimization and search solver Octopus was used in the design process to implement the optimization strategy by finding the geometric iteration with the best relation among parameters that control the morphological variation of the system components and, hence, the global shape in order to meet the defined performance criteria.

The fourth and last algorithmic process encompassed thermal analysis by energy simulation with the objective to measure the operative temperature inside the generic building. The whole digital model was taken as a zone mass and set as an open office. The glazing panel between the ceramic components and the slabs were taken into account to set a glazing ratio list. These parameters were merged with a weather file for Campinas region in a Honeybee component that exported the data to open studio and ran a simulation in EnergyPlus. The outputs of the simulation were expressed as air temperature, air flow volume, air heat gain rate and surface indoor and outdoor temperatures. These values were assembled in an adaptive comfort analysis recipe for an extremely hot week in the analysis period, resulting in the operative temperature for six periods of December 21st (8am/10am/12pm/2pm/4pm/6pm). It was also important to calculate the average operative temperature for each day period. Figure 3 presents the digital workflow.

Physical Model: Wind Tunnel Simulation

In order to evaluate the potential of the ceramic material for an evaporative cooling system, a physical model simulation was realized at LaCAF (Environmental Comfort and Applied Physics Laboratory), at the Faculty of Civil Engineering, Architecture and Urbanism, State University of Campinas (FEC/UNICAMP). This experiment allowed the measurement of the influence of facade dampness - associated with ventilation - on internal temperature. A 1:50 scale shoebox model was designed with a 30x30cm front opening made of a grid of porous ceramics pieces that are analogue to the components of the proposed facade (Figure 4). Each piece is a hollow cylin-

der with 1.5cm diameter, 2.0cm length, 143.4 kg/m^3 density and water retention capacity of 25% of its mass. These pieces are normally used as filter rings in aquariums and were used in the experiment due to material properties. In order to allow cross ventilation tests, a wind tunnel experiment was undertaken. The back of the model was closed with a cardboard funnel. Two variables were considered in the experiment: dampness and temperature, in and outside the model. Ventilation flow was set constant during the assessment of 68 minutes in which both dampness and temperature were measured every minute. The facade elements were saturated with water after half of the proposed time.

Figure 4
Physical model's front opening with ceramic components representing the proposed facade. Font: Authors, 2019.

RESULTS
Digital Simulations

The first computational process involved the parametric setting of the facade system and the calculation of the opening factors according to attactor points in order to generate the facade's components arrangement, with areas of higher and lower opening densities. In the second phase of the computational process, the environmental aspects of radiation, illuminance and temperature could be assessed. For the radiation assessment (Figure 5), diagrams' color scale varied from 0 to 100 kWh/m2 and a comparison was

rendered considering two situations: with any sunlight projection and with the proposed system. The results show radiation levels without the facade varying from 10kWh/m² up to 100 kWh/m² (in the area closest to the edges). With the facade, the values are lower, with a maximum level of 50 kWh/m² for the same environmental conditions.

Figure 5
Radiation
simulation of the
four slabs of the
generic building
without the facade
system (left) and
considering the
designed system
(right). Font:
Authors, 2019.
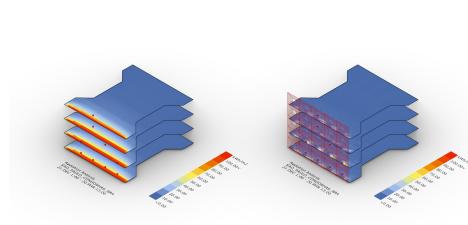
Figure 6
Daylight simulation
of the four slabs of
the generic
building without
the facade system
(left) and
considering the
designed system
(right). Font:
Authors, 2019.
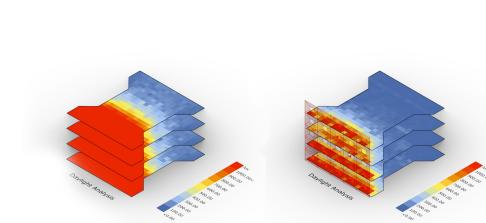
Figure 7
Octopus' graph
displaying the
facade iterations by
daylight and
radiation values.
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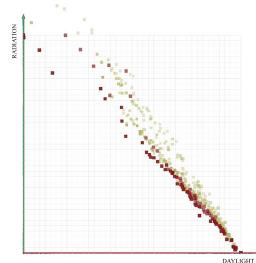
Regarding the illuminance assessment (Figure 6), the results are shown as color scale going from 0 to 100 lux in the same two situations described above. Without the facade, values were up to 1000 lux, which provided daylight depth almost to the center of each slab, whereas with the facade system higher values limited daylight only on the edges, not reaching internal areas.

At the third stage of the computational process, optimized values for radiation and illuminance were achieved. Figure 7 shows the multi-criteria evolutionary solver component, in which a cartesian graph displays the facade iterations by illuminance (axis 1) and radiation (axis 2) values. A population of 100 iterations was created by randomly modifying parameters related to shape that were linked to performance aspects. The population was optimized in 10 generations of offsprings from which one iteration was selected for its well-fitness to the established criteria and, hence, its performance by minimized radiation and maximized daylight values.

The optimization process resulted in a variety of morphological instances for the facade from which one was selected for attending the established performance criteria. The shape of the selected instance is set by parameters related to UV subdivision (28,27), the domain of projection from the plane (12cm - 56cm), the random position of the attractor points and the domain of the components openings (12cm - 44cm). Altogether, these optimized shape parameters performed a minimized sum of radiation levels as 1495.29 kWh/m2 for the four storeys. Simultaneously, the instance performed a maximized sum of daylight levels as 42953.81 lux for the same number of storeys. Figure 8 graph displays the system's optimization in which lower radiation levels were ensured (10 to 20 kWh/m²) along with higher illuminance levels, however still comfortable (100 to 300 lux). Figure 8 shows the selection of an instance with these performance characteristics.

The last computational process encompassed the assessment of operative temperature of the chosen instance with optimized radiation and illumi-

OPTIMIZATION

PERFORMANCE-BASED SELECTION
OF MORPHOLOGICAL INSTANCE

MINIMIZED SUM OF RADIATION LEVELS

MAXMIZED SUM OF DAYLIGHT LEVELS
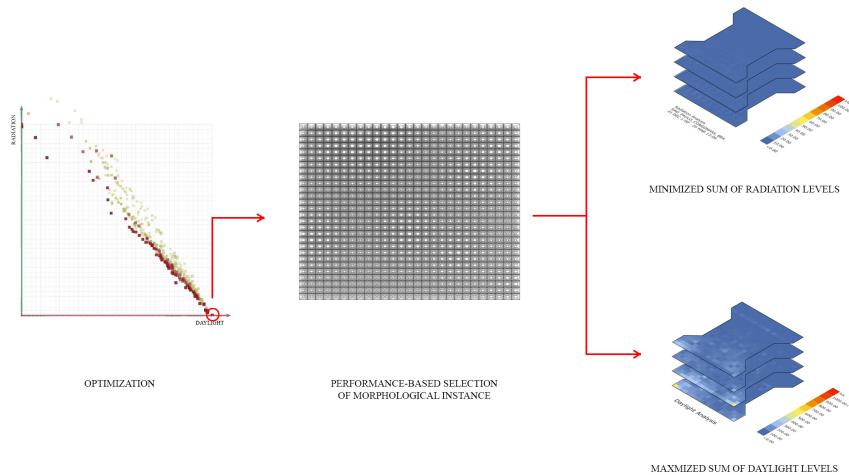
Figure 8
Performance-based
selection of
optimized
morphological
instance in which
radiation levels are
minimized and
daylight levels are
maximized
simultaneously.
Font: Authors, 2019.

8am	10am	12pm
ã = 25.34 °C	ã = 27.43 °C	ã = 28.32 °C

2pm	4pm	6pm
ã = 28.79 °C	ã = 28.39 °C	ã = 27.83 °C
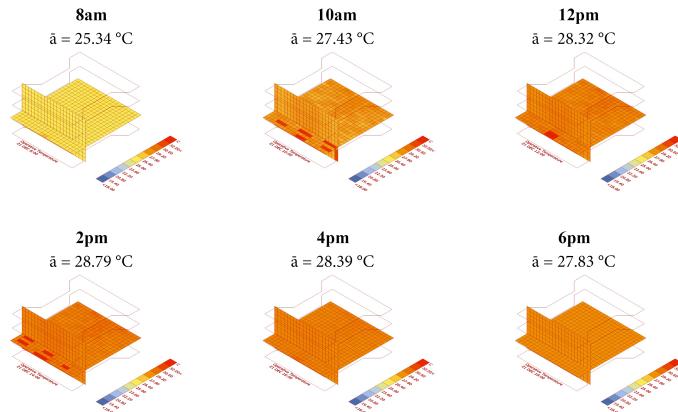
Figure 9
Operative
temperature for
December 21st at
8am, 10am, 12pm,
2pm, 4pm and 6pm.
Font: Authors, 2019.

nance levels. Figure 9 displays six graphs with a temperature range from 0 to 32°C. The analysed aspects of the energy simulation are computed to output the internal operative temperature quantified by hour steps. The average internal operative temperature ranges from about 25.3°C to 28.79°C. Besides the analysed aspects, one must note that the aspects of dampness and wind flow could not be taken into account due to software limitations and were analysed with the physical model. Both data were then interrelated.

Physical Experiment

The experiment involving dampness and temperature under the influence of cross ventilation has its values presented in Figure 10. The graph indicates inside temperature, in blue, outside temperature, in grey, inside dampness, in orange, and outside dampness, in yellow. Outside dampness and temperature were considered as comparison parameters, once variations on the inside were the focus. As noticed, when the dampness increased in the inside, the temperature dropped significantly. Initial inside dampness was 52% going up to 68%, which influenced the temperature going from 23°C to 20,6ºC.
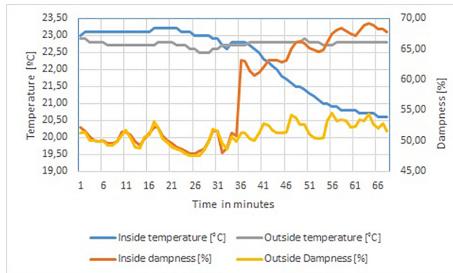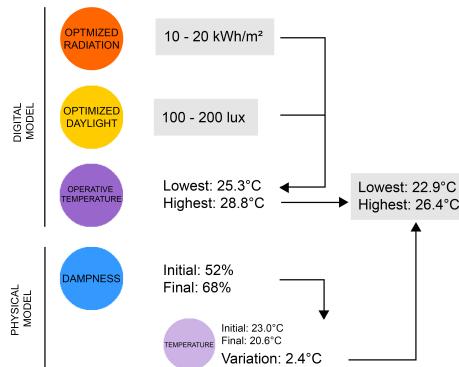
DISCUSSION

The performance-based facade system proposed considered four evaluation criteria: radiation, daylight (illuminance), temperature and dampness. The first two criteria were analysed into the digital, the temperature was comprehended both by digital and physical methods. Regarding the analogical method, the assessment was based on an evaporative cooling technique, therefore dampness and cross ventilation were associated using a ceramic component material for the cladding. Figure 11 shows the final levels for the four criteria, however, dampness was considered only in terms of its influence on temperature reduction.

Direct radiation impacts on temperature, therefore, low levels inside a building imply on temperature reduction, which is connected to thermal comfort and the amount of mechanical cooling needed (and also energy expenditure). However, blocking all radiation might impact natural daylight entering spaces, and this aspect is essential for developing activities and, the same way, the less daylight, the more artificial lights are necessary, increasing energy consumption. The results of this study show that it was possible to achieve low levels of radiation, still guaranteeing necessary levels of lighting. According to NBR/ISO 8995, in office environments, the minimum illuminance requirement for general areas are around 100 and 200 lux, which were the values achieved. For specific activities, such as writing and using the computer, artificial lighting can be added to reach the necessary illuminance values.

On the temperature values, digital outputs were still high, but evaporative cooling was not assessed in the digital simulations., but by the physical experiment. Compared to the dry facades, the saturated wall of the physical model had an increase of 30.8% of the internal dampness, followed by a 2.4ºC decrease. Linking the digital and the physical outputs, it is possible to infer that once the inner temperature has an average domain from 25.3ºC to 28.8ºC with a dry facade, when it is humidified the temperature drops down to 22.9ºC to 26.4ºC, approximately.

The evaporative cooling strategy proposed must be used especially during spring, when temperatures and radiation levels are high, but air moisture is low. Despite this passive cooling strategy is also applicable for summer, as indicated on ABNT NBR:15220

requirements, this must be weighted because air dampness is higher during this time of the year at the considered city (Campinas). To attend this variation of dampness requirement over temperature decrease, general solutions can be thought for controlled water collection system and facade irrigation. The proposal could be based on ensuring dampness flows in cases of dry weather, which is performed by small water ducts integrated into the facade ceramic components to be 3D printed.

The preliminary results suggest the possibility of applying the proposed design system instead of using a standardized design solution along all the building facade. Nevertheless, further development is necessary to fully functional industrial application, such as embedding ceramic material properties in digital simulation, incorporating complementary environmental analysis on wind flow by making use of computational fluid dynamics (CFD) tools into the design process, and analysing the individual pavements regarding internal function and its relation to facade components openings.

CONCLUSION

The foregoing discussion has attempted to bring into light one of the many possibilities of aligning design technology and architectural theory and practice. The presented design research on performance-based facade systems was developed with DSR methodology to create, asses, study, modify and finally propose an optimal solution in terms of building comfort and industrial fabrication. This design process associates the concepts of adaptability, flexibility, mass customization, and additive manufacturing, and can be considered an example of the new architectural design process in the 4th Industrial Revolution. The aspects discussed and included to develop the facade system are the reason this study has a strong innovative approach: material choice prior to structure and form, DSR methodology for the architectural design process, digital models used as a way to achieve mass customization with additive manufacturing, and also environmental simulation based

on different criteria. Altogether, this research is part of a bigger debate in which it is crucial for architects to understand and adapt to new circumstances, improving the solutions they deliver to society.

ACKNOWLEDGEMENTS

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