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Una nueva estrategia integral para modelar materiales urbanos para ciudades térmicamente habitables. Un caso de estudio en Madrid.
A new integrated strategy for modelling urban materials for thermally liveable cities. A case study in Madrid.

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Resumen-- **Desde el punto de vista térmico, el uso de materiales multifuncionales e innovadores en las superficies urbanas puede proporcionar mejoras radicales y reducir el efecto de Isla de Calor Urbana. En la simulación energética de edificios se ha prestado poca atención a las interacciones, no despreciables, entre la envolvente exterior de los edificios, la demanda energética y su impacto en el microclima urbano. Las herramientas actuales de simulación de edificios tienen una capacidad limitada para evaluar estas interrelaciones. Por estas razones, es necesario crear flujos de trabajo basados en simulaciones ad-hoc capaces de evaluar la influencia de los materiales y sus impactos en ambientes exteriores e interiores. Este artículo muestra la estrategia de simulación que se utilizará en un proyecto de investigación nacional cuyo objetivo es validar la viabilidad del uso de materiales urbanos optimizados, mediante simulación. Para ello se utilizará un innovador flujo de trabajo racionalizado basado en la herramienta Grasshopper.**

Palabras clave— Diseño Paramétrico; Herramienta de Simulación Exterior; Materiales urbanos optimizados; Isla de Calor Urbana; Cambio Climático.

Abstract— **From a thermal point of view, the use of multifunctional and innovative materials in urban surfaces can provide radical improvements and reduce the Urban Heat Island effect. In building energy simulation, little attention has been paid to the non-negligible interactions between the external building envelope, energy demand and its impact on the urban microclimate. Current building simulation tools are limited in their ability to assess these interrelationships. For these reasons, it is necessary to create workflows based on ad-hoc simulations capable of assessing the influence of materials and their impacts on outdoor and indoor environments. This article shows the simulation strategy to be used in a national research project aiming to validate the feasibility of using optimised urban materials through simulation. An innovative streamlined workflow based on the Grasshopper tool will be used for this purpose.**

Index Terms— Parametric Design; Exterior Simulation Tool; Optimised Urban Materials; Urban Heat Island; Climate Change.

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I. INTRODUCTION

I As urbanisation increases around the world, it is critical to understand the links between urbanised environments, the energy demand of buildings and the well-being of citizens. These needs are also reflected in SDG 13 "Climate Action" which identifies the need to reduce energy consumption and SDG 11 "Sustainable Cities and Communities" which calls for improved living standards for citizens. In addition, the built environment is highly responsible for the development of the Urban Heat Island (UHI) phenomenon associated with the overheating of cities and, consequently, with global and local climate change. These phenomena with higher ambient temperatures have a serious impact on the energy consumption of buildings, increase the concentration of air pollutants, negatively influencing thermal comfort and health. (Santamouris et al., 2015). To minimise the impact of urban overheating, several mitigation technologies have been proposed and implemented in full-scale projects (Akbari et al., 2016). As shown in the literature, façade characteristics can influence the absorption, reflection and re-emission of heat and light to the outside. Therefore, the façade is considered a primary element that thermally and visually connects the external and internal environment.

One of the main causes of urban overheating is heat-absorbing building materials, a mitigation strategy would be to replace them with more sunlight-rejecting materials. The correct use of urban materials and their high impact on efficient solutions can be an answer to the transition towards climate-neutral cities. From a thermal point of view, the use of multifunctional and innovative materials in urban surfaces can provide radical improvements (Croce et al., 2021). Opaque building envelopes have a significant impact on energy consumption. The use of highly absorptive building materials contributes greatly to lowering the heating loads of buildings but, at the same time, they also increase the cooling demand (Santamouris et al., 1996). On the other hand, reflective materials developed to decrease the surface temperature contribute to minimise the sensible heat transfer into the building and decrease its cooling demand (Synnefa et al., 2012). Several approaches can be found in the literature for the climatic optimisation of these materials, most of which are aimed at reducing the UHI effect (Santamouris et al., 2020). Recent research has pointed out remarkable interactions between the external building envelope, the energy demand of buildings and the external microclimate perceived by pedestrians (Naboni et al., 2020; Mauree et al., 2018). In fact, the need to simulate and map these microclimates has also increased (Santamouris et al., 2017). However, in building energy simulation, little attention has been paid to the impact on the urban microclimate. Simulation tools have usually dealt with the building or outdoor environment simulation separately, and only recently have these aspects started to be interconnected. The influence of the building envelope on the indoor and outdoor environment can be assessed in different physical domains: thermal, visual and mass flow. Current Building Performance Simulation (BPS) tools are limited in their ability to evaluate these interrelationships (Loonen et al., 2017). For these reasons, it is necessary to create workflows based on customised simulation tools capable of evaluating the influence of traditional and innovative materials in light of their impacts on outdoor and indoor environments. These workflows based on different customised simulation tools can help to achieve the goal of climate-neutral cities with improved liveability and sustainability.

This article shows the simulation strategy that will be used in a recently approved Spanish research project. The strategy will serve to validate, through simulation, the feasibility of using optimised urban and façade materials, such as smart chromogenic materials. Through this strategy, the mutual relationships between relevant urban factors (microclimate, materials, typologies...), building energy performance and external thermal comfort will be evaluated. For this purpose, an innovative streamlined digital workflow based on the Grasshopper (GH) tool (McNeel, 2022) will be used. The project will be carried out in selected vulnerable areas of Madrid, as it is an ideal city to analyse the UHI problem given its size and Mediterranean climate, with significant energy demands for heating in winter and cooling in summer. The results of a very preliminary simulation of a part of the overall digital workflow are shown. In particular, an ad-hoc developed BPS tool is presented that allows to properly simulate the effect of the hysteretic behaviour of a thermochromic (TC) material and its influence on the energy use in a case study for an envelope with thermochromic pigments. These preliminary results are used to test the TC material simulation strategy, and are presented with the perspective of extending the developed BPS tool to make it more generally applicable to other façade technologies as well, and to integrate it more seamlessly into the design process.

II. MATEMAD CONCEPT

The recently approved Spanish coordinated research project, mateMad, is based on the hypothesis that optimised materials, such as smart chromogenic materials for urban surfaces, can provide efficient solutions to the UHI effect.

It is proposed to address the coordinated project under a multidisciplinary approach by combining the activities carried out under three sub-projects (Fig. 1), respectively:

- Sub-project 1, coordinator (SP1). This SP1 will address the characterisation of urban materials in multiple dimensions, the thermo-optical performances that mainly define their impact on the urban environment and the well-being of citizens. This approach is necessary to identify those materials potentially suitable to be considered for optimisation and to obtain reliable results from simulations by the digital model of cities.
- Subproject 2 (SP2). In this SP2 the monitoring of environmental parameters affecting the habitability of public spaces and energy demand will be carried out, as well as the response of citizens to stimuli related to urban materials. This approach is necessary for the validation of the digital model of the city.

- Sub-project 3 (SP3), called URBAN therCOM, which is the subject of this work. SP3 will address the modelling of outdoor thermal comfort and energy demand in urban areas, through a comprehensive digital workflow that implements mutual relationships between these two aspects and relevant urban factors, such as microclimate, materials and typologies. This approach is necessary to test and quantify the effect of urban material substitution on the liveability and sustainability of cities in a digital environment.

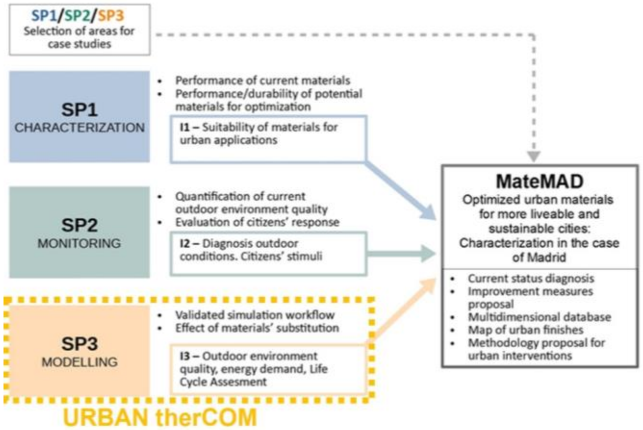

Fig. 1. Schematic overview of the multidisciplinary approach of the mateMad project strategy (Source: Own).

III. METHODOLOGY

The overall project methodology consists of two parts:

The first will define the relevant KPIs, using Grasshopper (GH) scripts, and link various domains. This will be used to determine the energy demand of the building, as well as to simulate building surface temperatures.

The second part will provide a unified approach for real-time assessment of the outdoor performance of the materials evaluated in the project. This will include in-situ physical characterisation of factors affecting the wide range of transient performance.

A. *Simulation approach and workflow*

The digital workflow that will be used to complete the digital twin between the Madrid and simulation areas will be based on Grasshopper (GH). GH is a plug-in running within the Rhinoceros CAD application (Rhinoceros, 2022) that allows the parametric handling of geometric information by providing the user with a graphical interface for scripting in the Python programming language (Python, 2022). In this way, the designer/modeller needs to develop (or import) only one virtual building/urban model, and automatically the developed GH tool links different domains. The first step of the proposed simulation workflow will be to create an appropriate geometric representation of the urban area to be investigated. From it the energy demand of the building will be determined, as well as to simulate the surface temperatures of the building.

At this point, the main focus is on shortwave heat exchanges in the urban building, reducing the current deficiencies in the assessment of outdoor thermal comfort. Therefore, a suitable comfort model can be selected taking into account climatic conditions, urban environment and physical characteristics.

The workflow is based on the interrelation of several GH plug-ins to enable the simulation of the indoor and outdoor thermal field. Dragonfly (Dragonfly, 2022) will run the Urban Weather Generator tool (UWG, n.d.), which estimates the hourly air temperature and relative humidity in the urban area from an existing weather file, and will generate a transformed weather file in ".epw" format, compatible with many building energy simulation tools (Bueno et al., 2013). On the other hand, Honeybee and Ladybug (Ladybug and Honeybee, n.d.) take into account the interaction of the envelope with indoor and outdoor spaces: they calculate the energy demand for space heating and cooling based on the EnergyPlus (Energyplus, n.d.) and Radiance (Radiance, n.d.) engines, and also evaluate the average outdoor radiant temperature. Finally, the workflow will measure the thermal comfort perceived by pedestrians through appropriate metrics, i.e. mean radiant temperature (MRT) and universal thermal

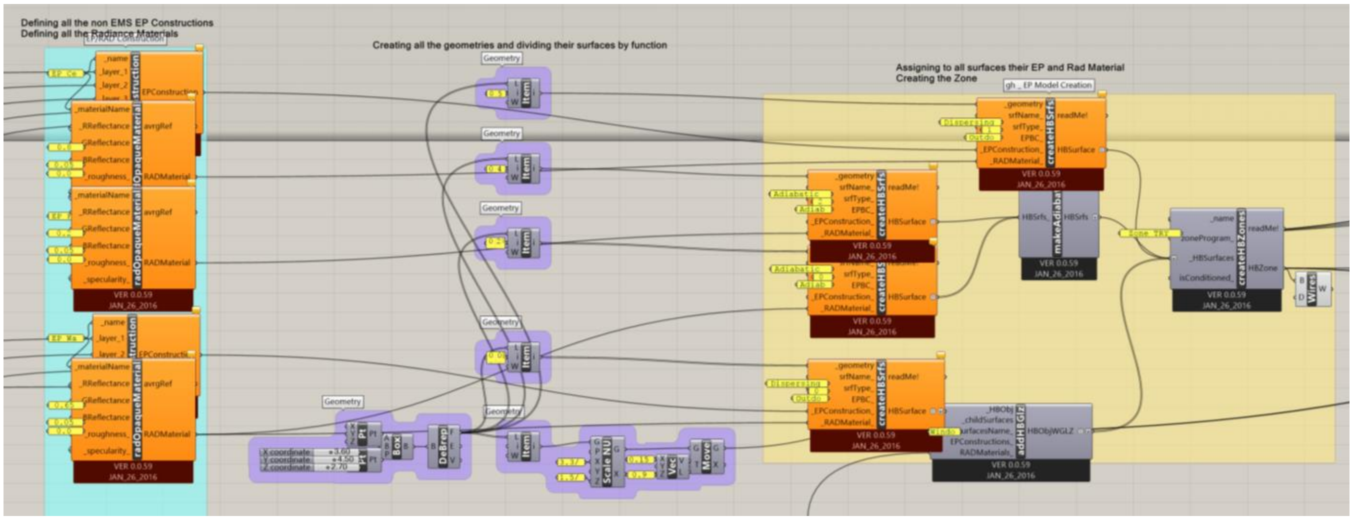

Fig. 1. Grasshopper interface of the new simulation tool (Source: own).

climate index (UTCI). Special attention will be paid to materials whose performance is hardly discussed in the literature.

A part of the general digital workflow described above is presented in this paper. Fig. 2 shows a schematic of the GH-based BPS tool developed ad-hoc to allow the effect of the hysteretic behaviour of a thermochromic (TC) material and its influence on the energy use in buildings with a thermochromic pigmented envelope to be properly simulated. The performance of the CT material and the influence of the hysteresis width on this performance are evaluated through a virtual experiment by simulating a reference office room, in which the CT envelope was integrated, and measuring the annual performance in relation to different domains of interest. Virtual models of the case study in each physical domain are generated through an integrated approach using HoneyBee and LadyBug. In the case of CT, a series of simulations are first run in Radiance to represent all possible effects of CT states in the visual domain. Look-up tables are automatically generated and fed into the EnergyPlus thermal model, which combines the historical-independent visual results according to the simulated temperatures. The control and tuning of the thermo-optical properties of the CT was performed parametrically by integrating the EnergyPlus Energy Management System (EMS) into HoneyBee (via GH).

The presented step-by-step simulation approach allows for the variation of the thermo-optical properties of the TC material at simulation run time. This in turn implies accurate consideration of the thermal inertia of the building and its effects on the energy demands for heating and cooling.

IV. RESULTS

As an example, a first approximation to the simulation environment is presented. For this purpose, the variations of: (a) the hysteresis width and (b) the transition temperature in a simple test room space in Madrid have been considered. This location is characterised by semi-arid climatic conditions and falls within the Csa zone according to the Koppen-Geiger classification. The climatic characteristics of Madrid correspond to mild, cool winters and hot, dry summers, as shown in Fig. 3. Winters reach average minimum values ranging from 1°-3° C and average relative humidities ranging from 69-83%. Summers are hot and drier, with average maximum temperatures between 28°-34° C and relative humidities between 40-52%. The average global solar radiation value over the horizontal is 1617 kWh/m^2, reaching maximum values in summer, ranging between 190 and 230 kWh/m^2, and minimum values in winter, ranging between 45 and 78 kWh/m^2.

The article shows some preliminary results on the annual heating and cooling thermal requirements for the single test room space with and without TC pigments in the south-facing envelope. To evaluate the energy performance of the building models, a TMY provided by the climate database of the Energy Plus website (Energyplus, n.d.), created from real data from the World Meteorological Organization (WMO), has been used.

An enclosed office 3.6 m wide, 4.5 m deep and 2.7 m high was assumed as a case study. In one of the short, south-facing walls, a window 2.26 m wide and 1.5 m high is located, with a Window-to-Wall Ratio (WWR) of 35%. The case study was assumed to be part of an office block, flanked by two identical offices on two sides, on the same floor and on the floor

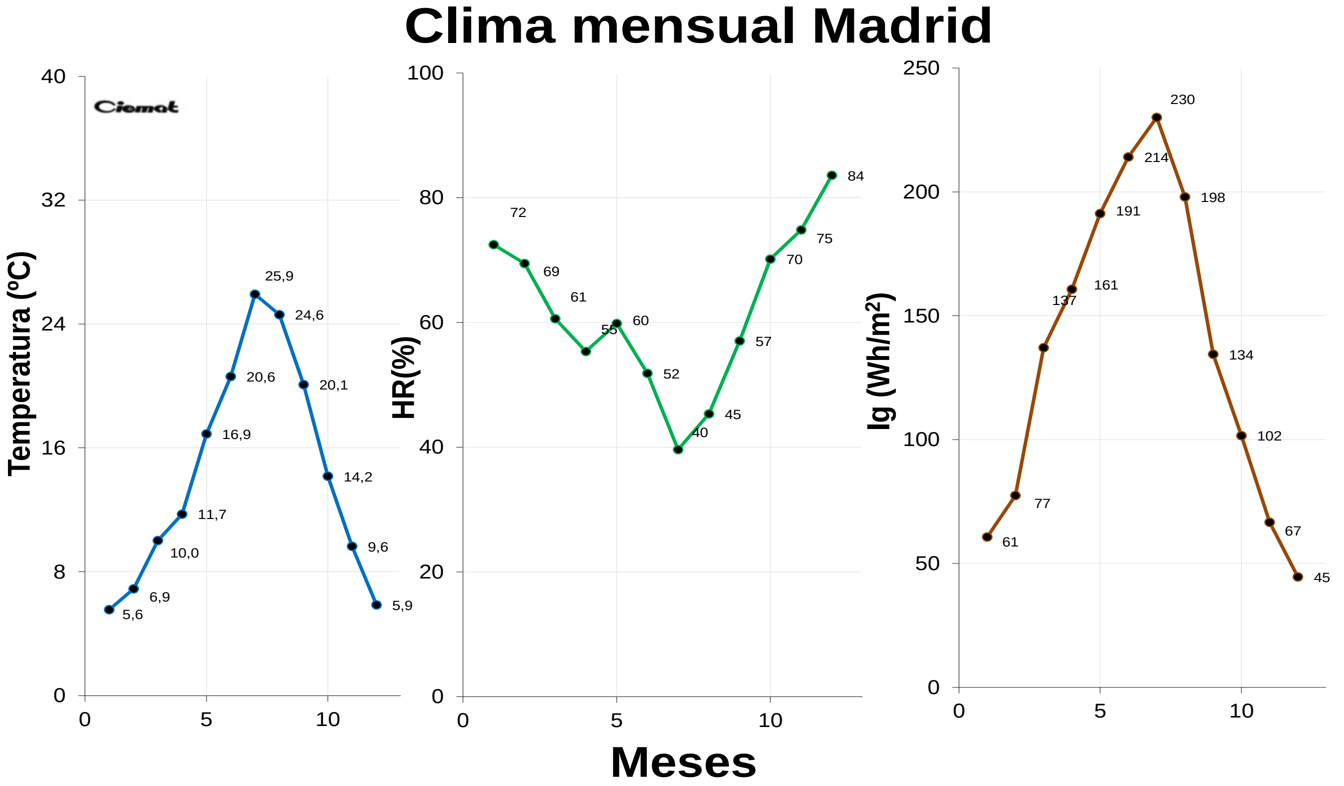

Fig. 2. Monthly climatology data for Madrid from the Energy Plus database (Source: own).

immediately above and below, and by a corridor with the same thermal conditions on the third side on the same floor. All horizontal and vertical internal partitions were therefore considered adiabatic. The opaque external envelope has been modelled considering design values, which meet the minimum construction and performance requirements regulated by the Spanish regulations for the year 2006 (BOE, 2006). The design data established by the regulations for the Madrid climate zone (D3) are shown in Table 1. A commercial TC coating with the following characteristics is used for the numerical model of the TC coating: visible transmittance (τ_{vis}) ranges between 0.68 and 0.06 (cold and warm state respectively); solar transmittance (τ_{sol}) ranges between 0.62 and 0.23; transition temperature range between 26° C and 71° C; hysteresis width equal to 5° C; and hysteresis width equal to 5° C.

TABLE I
OVERALL HEAT TRANSFER COEFFICIENTS LIMITS ESTABLISHED IN THE CTE 2006 STANDARD FOR WINDOWS AND DOORS AND WINDOWS

Constructive Elements	U_{limit} 2006 (W/m^{2}K)
Roof	0.38
Façade	0.66
Floor	0.66
Interior partitions	0.66
U window	1.43
g window	0.61
Window frame	2,20

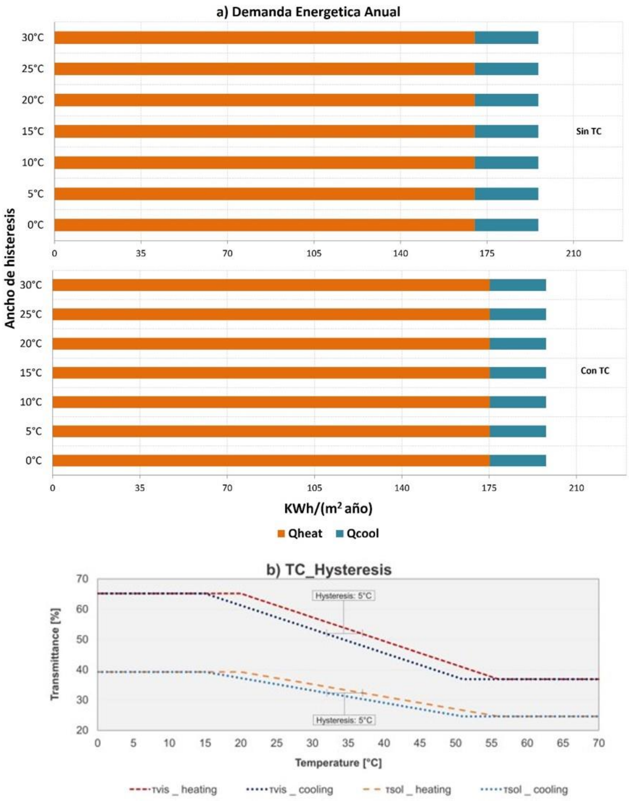

Fig. 4. a) Annual energy demand results for the case study with and without CT pigment. b) Characterisation of CT (with hysteresis) by visible and solar transmittance considered in this study (Source: own).database (Source: own).

Fig. 4 represents the thermal requirements obtained for the case study with and without the CT pigments together with the characteristics of the CT used in the study. Fig. 4 shows that the heating needs are much higher than the cooling needs. This is due to the climatic conditions in Madrid and the higher number of months of the heating period (9 months) compared to the cooling period (3 months). The application of the proposed TC pigments on the south façade leads to an increase of the heating energy demands by 3.1% while the cooling demand has been reduced by 12.7%. It is interesting to note that the hysteresis effect of CT on the energy performance is negligible. There is a clear need for future work to test different CT technologies in different orientations and envelopes.

With this preliminary approach it has been possible to prove that the modelling strategy used reproduces the effect due to the use of the TC material. This last aspect represents a strength of the proposed integrated simulation approach, as a comprehensive assessment of the performance of the TC material would not have been possible using the currently available BPS tools. The latter tools should introduce simplifications in the analysis, with a consequent higher degree of inaccuracy in the final results. Finally, the GH implementation of this simulation strategy allows a high flexibility for its application, since all the actions described in the previous steps are performed in an automated way. The only requirement is to specify the numerical model describing the behaviour of the adaptive component, which allows simulating both the control strategies for the active components and the intrinsic behaviour of the adaptive passive component.

V. CONCLUSIONS

It has been shown that urban surfaces have a strong influence on the quality of the outdoor environment, the energy demand and the well-being of citizens, and that thermo-optical properties are the key factor in defining and controlling this influence. However, there is a gap in knowledge and research focused on outdoor spaces in Europe and especially in climates such as Spain. This paper aims to move forward to fill this gap by developing a methodology for optimising urban materials and validating its feasibility through experimental research, monitoring, and simulation.

As shown in this paper, the use of parametric design tools is a valid strategy to explore solutions for analysing the environmental performance of buildings that integrate new types of adaptable materials in the envelope. Although the methodology has been tested for a specific case study, a similar approach can be used to investigate the variation of different design parameters (i.e., building orientation, building geometry, window-to-wall ratio, thermal resistance of the external envelope, Thermo-optical properties of CTs, etc.) using the developed parametric user interface. Future research will be carried out to test and validate the strategy and the overall digital workflow with real case studies in Madrid, using the information that will be acquired throughout the duration of the project.

The comprehensive simulation workflow will be used to estimate the quality of future energy efficient buildings. Furthermore, this workflow will depend on the performance of each component and the interaction between these components in the whole façade system, and how the façade interacts with the internal/external environment creating specific external microclimates.

In this way, this type of strategy will be useful for planners and designers and will help public administrators and end-users who are faced with the most appropriate decision-making process.

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