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Integrating technical performances within design exploration. The case of an innovative Trombe wall.

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ABSTRACT

The Double Face 2.0 research project aims at developing a novel type of an adaptive translucent Trombe wall. The novelty of the proposed system is based on the integration of new lightweight and translucent materials, used both for latent heat storage and insulation, advanced computational design processes, used to identify the relationship between variations in geometry and their effect in terms of overall performance, as well as proposed fabrication methods based on Fused Deposition Modelling. Various concepts and geometric configurations are explored and improved via a computational design workflow. The exploration is deeply rooted in performance simulations manufacturing constraints and measurements of prototypes. The paper presents the workflow of the overall on-going research project, with specific emphasis on the incorporation of a computational assessment and optimization process. Moreover, it presents the preliminary set of measurements and simulations for thermal performances, their results and related conclusions.

Author Keywords

Simulation-based design; data driven design; building comfort and energy performance.

1 INTRODUCTION

The presented research through design project consists of two sequential stages: the Double Face 1.0 (DF 1.0), which produced a preliminary demonstrator and the DF 2.0, a currently on-going further development and refinement stage. The overall project tackles the integration of technical requirements into the architectural language. In architectural designs, technical requirements are often perceived as limiting constraints rather than inspiring design principles. At contrary, the project develops a workflow for incorporating technical aspects from building physics and from the fabrication process, to support the integration of the engineering performances into the design of the product through an iterative form-finding approach. It does so by focusing on the case of an innovative Trombe wall, conceived as an interior adaptive translucent system. The workflow is being used for multiple design concepts, some of which will be prototyped, and eventually validated via 1:1 demonstrators.

Trombe walls have been implemented as means of passively storing solar heat for more than a century, constantly evolving from the first patent filed by Edward Sylvester Morse in 1881, to the one popularized by the French engineer Felix Trombe in the late 1960's [1]. It generally comprises of a system oriented towards the winter sun composed of an opaque wall (thermal mass), glazing and an air cavity in-between. Through adjustable vents located in the upper and lower part of the wall, air movement can be encouraged creating a convective loop. This allows the heated cavity air to flow towards the interior and the cold air from the interior to be pulled in the cavity.

The proposed Trombe wall is different from traditional Trombe walls for two main reasons: it has the ability to adjust itself towards the heat source or sink and therefore to direct heat absorption and its release where and when needed and it allows daylight transmittance. To achieve these goals, both geometry and innovative materials are investigated. Geometric investigations aim at form-finding as an integral system incorporating multiple design or performance criteria. When complex geometry emerges, fabrication methods such as Fused Deposition Modelling and robotic Fused Deposition Modelling are used. Focusing on the innovative materials, the solid thermal mass of a typical Trombe wall is replaced by phase-change materials (PCM) while the insulation layer consists of translucent aerogel.

PCMs are substances with a high heat of fusion. By changing phase (solid to liquid or liquid to solid) the material can serve as a heat storage [2]. Using PCM as heat storage has a great potential of reducing the energy consumption of buildings [2]. One of the first documented usage of PCM in the construction sector, dates back to 1948 when one of the pioneers of solar energy usage, Dr. Maria Telkes, designed the Dover House [3]. Drums filled with Glauber's salt were housed between the main rooms. Ventilation was used to deliver warm air in winter and cool air in summer. While this system could deliver heat for up to 11 sunless days the target of the DF 2.0 Trombe wall is a daily cycle. More recent projects such as the Wilo headquarters in the Netherlands by Benthem Crouwel Architects make use of the heat-storage capacity of PCM

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doubling the thermal mass of the lightweight building to prevent the interior from overheating. In the case of the Floating Pavilion, by Public Domain Architects and Deltasync, PCMs are used in order to pre-cool or pre-heat the fresh air supply. The recharging of the PCM is controlled by air conditioning units. Several researchers have investigated the use of phase change materials in facades [4, 5, 6, 7]. However, all of these researchers considered static non-adjustable systems.

The starting assumption regarding the composition of the layers for our proposed system places the PCM on one side followed by the insulating aerogel layer, protecting it from the opposite side. The elements composing the wall can be oriented making it possible to face the PCM towards the interior or exterior, depending on the climate conditions and daily cycle. During summer days, the PCM will face the interior, charging itself with heat generated by the users while releasing the heat towards the exterior at night. In winter it will face the sun during the day and release the heat towards the interior at night. The ability of the system to be oriented towards the interior or exterior allows for directed and controlled heat transfer.

The design of the system is under development. The process started with an extensive set of measurements and simulations, to understand the basic parameters of the system and to be able to setup a set of form-finding and optimization loops.

2 OVERALL DIGITAL PROCESS

In the DF 2.0 project, advanced computational means (evolutionary algorithms and clustering techniques) and advanced digital manufacturing techniques (customized additive manufacturing) are applied in order to explore complex geometries and their relationship to performance. The computational process of the research project is meant to facilitate the designer to identify the relations between variations in geometry and the resultant performance oscillations and to integrate the engineering performances within the proposed designs. Specifically, the process aims to integrate hard parameters, such as technical performances for thermal behavior and daylight transmittance, and soft parameters, such as aesthetic values and overall appearance.

The hard parameters rely on approximated material properties up to the point where physical experiments as well as simulations produce implementable results. They include material properties of PCM, material distribution and concentration, controlled by geometrical means, and local surface orientation. They need to target conditions regarding necessary volume for best performance of the PCM, translucency or light permeability, surface morphology as well as adaptability of the proposed systems. In combination with design parameters such as visual connection, they are being included in multi-objective optimization loops to identify their influence over the necessary design objectives allowing sufficient space for unexpected design alternatives.

Additionally, the soft parameters are included and assessed through multiple periodic user interviews. While past interviews were based on common representation techniques, future interviews are planned with the support of virtual reality (VR) to facilitate the users in assessing the soft properties of the proposed system while being able to visualize and understand performance aspects

Figure 1 showcases the workflow for the entire research as well as for the current point in the research process. It highlights the integration between the digital design workflow and the inputs from designers and users. The

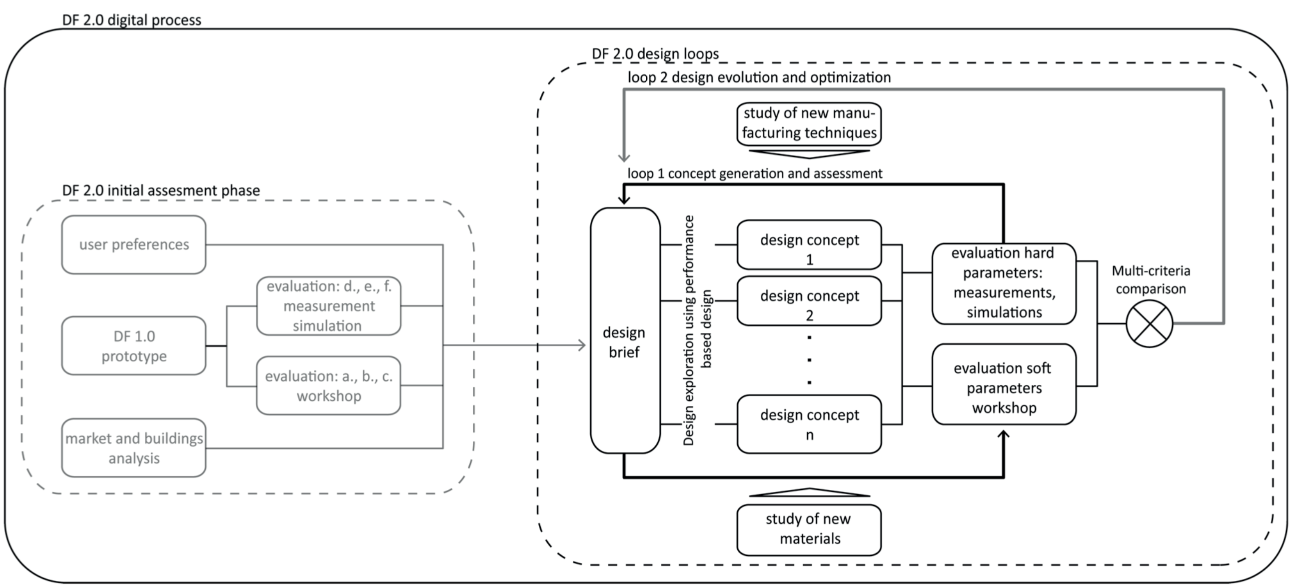

Figure 1. Research process and computational workflow

Figure 2. Demonstrator developed during DF 1.0

overall workflow of the research is divided in two interconnected parts.

The preliminary measurements and simulations were performed during DF 1.0. This phase is represented by the cumulus of user preference studies, market and building analysis and the evaluation through simulation and measurements based on the DF 1.0 demonstrator (Figure 2). This forms a solid base as well as a catalyst for a first concept development phase of DF 2.0 as well as a knowledge pool for informing and enhancing simulation routines to be implemented during DF 2.0.

Secondly DF 2.0 is arranged along 2 design loops: loop 1, concept generation and assessment phase; and loop 2, design evolution and optimization phase. User workshops are introduced within each loop to further asses and fine-tune the concepts, judging design as well as performance related aspects. At the end of each loop a multi-criteria assessment is carried out.

3 PRELIMINARY MEASUREMENTS & SIMULATIONS

This section presents the initial measurements and simulations from DF 1.0 and a second set of simulations from DF 2.0. Several measurements were carried out during DF 1.0 in order to fine-tune assumed material thicknesses as well as establish the specific type of PCM which would allow for an overall better light transmittance to performance ratio.

In parallel simulations using Design Builder v3.4 pointed out that the best tradeoff between unobstructed views and heat storage capacity would lead to a ratio of approximatively 10% opening in the system's overall surface. In order to be able to perform more advanced simulations which would allow for the incorporation of other factors such as movement of the components of the wall, a simulation routine was setup in Matlab/Simulink. The relevant settings are presented in Table 1. For this purpose a small room corresponding to the cardinal orientations in the following order N, E, S, W has been used. The ceiling and floor of the room have been assumed to be adiabatic surfaces. The model takes the use of sun blinds,

calculated time (one winter)	1oct - 30 apr
orientation Trombe wall	south
size of room w*d*h	3.6*5.4*2.7
size window south	80%
size of window north	40%
U-glass	1.65 [W/m2.K]
solar heat gain no sunblind	0.6
people present (7 days a week)	18.00-8.00 h
if PCM panel present	
PCM solid	> 23 Celsius
PCM liquid	> 26 Celsius
% closed wall (no holes)	0,9
thickness of PCM	different per setup
thickness of insulation	0.01 [m]
PCM_c	2000 [J/(kg K)]
PCM_rho	1450 [kg/m3]
PCM_la	0.6 [W/(m K)]
PCM_h	1.8e5 [J/kg]
INS_c	1440 [J/(kg K]
INS_rho	75 [kg/m3]
INS_la	0.012 [W/(m K)]

Table 1. Settings used for the simulations in Matlab

the presence of users, as well as the existence of ventilation into account. As such the model is a full energy performance model including solar gains, internal heat gains, ventilation and infiltration losses, transmission losses through the facades, heat storage in walls, temperature set-points, schedules, etc.

The results are shown in Figure 3. The results give an overview of the amount of energy needed to heat a room. This is 4,78 GJ per winter period. When a Trombe wall of 4 cm concrete is added, the needed energy reduces to 3,71 GJ. When the concrete is replaced by PCM, the needed energy drops to 3,18 GJ. This is a reduction of 33%. The optimum though, lies at a thickness of 1-2 cm of PCM. Here a decrease of 30-32% is achieved.

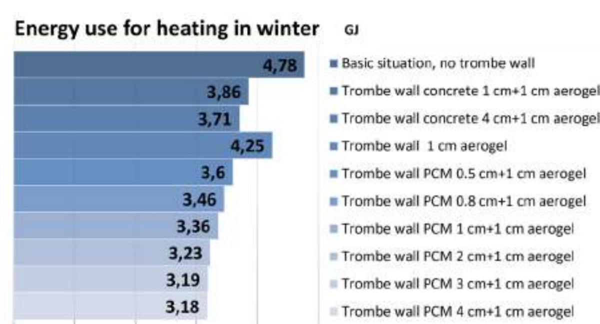

Figure 3. Results regarding the energy use

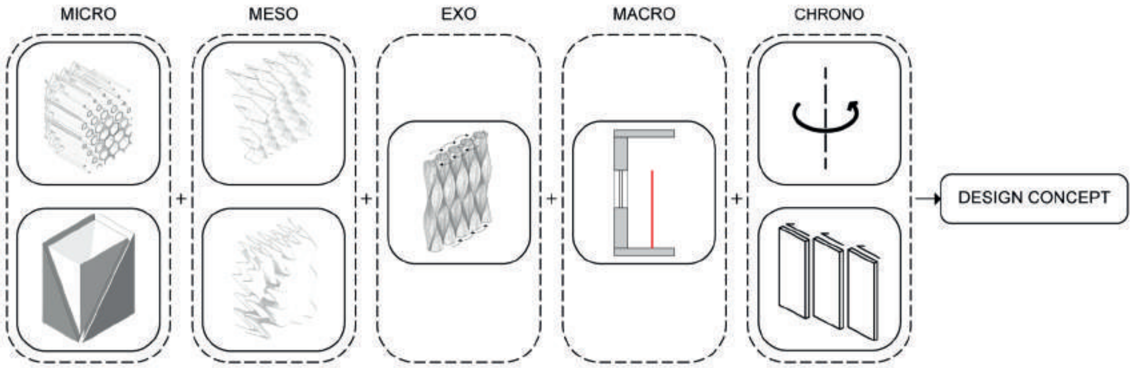

Figure 4. Design concept generation

4 DESIGN WORK

Together with observations from the fabrication spectrum, the preliminary results from simulations and measurements have helped identify multiple levels of design decisions. To make these levels explicit, a mind-map consisting of five categories has been developed. The five categories are: *Micro* referring to the geometrical intricacies at a sectional level; *Meso* regarding the level of detail at the surface level; *Exo* defining a design principle; *Macro* categorizing the possible position within the section of a room; and *Chrono* referring to the type of movement used for adjustment of the wall. The map collects and organizes a broad range of geometric alternative options. For simplicity, Figure 4 summarizes the main principles regarding multiple design scales as well as the concept generation process. Combination of multiple elements per category is possible; nevertheless some of the principles have a certain set of prerequisites embedded in them, acting as constraints for the overall design concept.

User workshops complement the design loops regarding criteria such as: identity, whether the intended use is visible through the chosen design and overall composition; usefulness, whether technical performances are met; and applicability, whether a home or office environment are better suitable for a particular design (Figure 1).

5 FUTURE DEVELOPMENT

Based on the results of the first workshop, the highest scoring concepts are being further analyzed in order to extract either information which might be applicable to other concepts or which will inform the evolution of the existing concepts. The individual concepts will be optimized towards visibility, structural performance, light transmittance and thermal performance. Currently, additional simulations, measurements and further implementation of geometric features within the mind-map are being developed. These will be studied in a layered simulation loop. Simulations regarding airflow and temperature changes within a simplified 2D representation of a room caused by the proposed systems will be investigated with the use of Comsol Multiphysics. Simulations regarding sunlight exposure, radiation values as well as desired transparency percentages will be carried out on a simplified geometrical assembly corresponding to the Macro level (Figure 4) with the use of Grasshopper and relevant plugins such as Ladybug and Honeybee. Resulting simulation data will be visualized and examined within ModeFrontier through the Grasshopper integration node allowing a multi-objective optimization and evaluation loop. Further more detailed CFD simulations will be developed and performed on selected designs in order to validate and improve micro level design decisions in respect to material behavior caused by the proposed geometries. The results of these simulations will be quantified and applied on the designs in an iterative manner.

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