Parametric design of an additively manufactured building façade for bespoke response to solar radiation

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Abstract. The building construction industry is adapting Additive Manufacturing (AM) and robotic fabrication techniques to, among other efficiency and cost benefits, reduce the lifecycle Green House Gas (GHG) emissions of new buildings. This research aims to fabricate a low-GHG emission façade by encoding environmental performance using a combination of material selection, AM techniques, and bespoke geometry. This paper presents the design methodology, specifically the response to solar radiation (i.e. shading and daylight transmission). The key contribution of this publication is establishing the digital fabrication process of AM facades: beginning with performative parametric design, using empirical Bi-directional Scattering Distribution Function (BSDF) data of AM thermoplastic elements for daylight simulation to assess performance, and finally optimising the topology for a specific context (location and orientation).

1. Introduction

1.1. Background

Buildings and building construction sectors account for more than 30\% of the global energy consumption, and 40\% of greenhouse gas (GHG) emissions [1]. Reducing the life-cycle energy and emissions of buildings is vital towards mitigating the climate crisis. Research in architecture and building engineering domains has produced design and construction tools to reduce life-cycle GHG emissions. One such research stream focuses on using Additive Manufacturing (AM) techniques to create building structures using low-GHG materials and processes. The corresponding digital workflow begins with Computer Aided Design as an input into the robotic tool-path planning, followed by AM and ending with post-processing for robustness. Early-stage research and first transfer into practice demonstrated building elements with single performance characteristics, such as structural stability and efficient material usage. However, state-of-the-art research has introduced multi-functional, high-performance building structures aimed at meeting (and exceeding) performance requirements targeted at (i) reducing both operational- (HVAC and lighting) and embodied- (construction, maintenance and deconstruction) GHG emissions, and (ii) improving thermal and visual comfort of the occupants. Advances in this research could realize architectural concepts, which could not be realized using conventional design and...
construction techniques. AM and robotic fabrication could potentially integrate mechanisms such as active heat exchange, harnessing renewable energy, light re-direction, data- and power-distribution, and acoustic customization in architecture [2] [3]. To this effect, it is possible to embed performance within the AM component’s material properties rather than integrating mechanical systems. However, the impact of material-, aggregation- and fabrication- specific properties or parameters on the AM element’s performance are not yet clearly known.

Current research successfully demonstrates the digital workflow from computational design, simulation of integrated performance, and fabrication using AM technology. The demonstrated prototypes support the efficacy of AM processes to fabricate building structures with inherent structural and environmental performance. In addition to the structural integrity, successful prototypes have demonstrated solar shading, insulation, ventilation, moisture-, and thermal mass regulation. A majority of the research utilising AM processes for building structures use robotic extrusion of either ceramics or thermoplastics [4] [5] [6] [7] [8] [9]

1.2. Outline

This paper describes the initial explorations of a longer-term research project which aims to fabricate a low GHG emission, mono-material AM facade with integrated environmental performance, namely solar shading, daylight transmission, ventilation, weather and fire resistance. This publication will only present the design methodology in response to solar radiation (i.e. shading and daylight transmission), customised for the geographical location and facade orientation. The paper demonstrates the use of empirical optical measurements to simulate an AM facade’s performance and tune the facade topology to respond to annual solar radiation patterns. The paper comprises of the following sections: (i) a description of the design objectives, material usage, and AM process, (ii) empirical procedure and measurements of optical properties of the AM facade element, (iv) simulation of the AM facade using the empirical data, and finally (v) topology optimization of the simulated facade.
2. Design objectives, material usage and AM process

This section describes the first iteration of the design of the AM facade. The design objective is to reduce operational GHG emissions and maximise visual comfort. This is done by maximising the transmission of solar radiation during colder periods of the year and reflecting solar radiation during hotter periods of the year. The two key design parameters are (i) the overall topology of the facade, and (ii) the light scattering characteristics of AM elements.

The facade is designed to selectively reflect and transmit solar radiation. The facade topology comprises of several 'units', and each unit comprises of four surfaces which are either reflective or translucent. Each unit of the facade contains both surface types. The topology of the facade is described using simple geometric terms (Figure 1), namely (i) inclination - in response to the geographical solar azimuth, (ii) orientation - in relation to the geographical solar zenith, (iii) translation - describing the intrusion of the facade into the indoor space or protrusion towards the outdoors, and (iii) scale - the spatial distribution of each unit. The four geometric parameters affect the seasonal solar irradiation (hence, solar heat gain), and the daylight autonomy of the indoor space.

Polymeric extrusion AM technique, commonly referred to as Fused Deposition Modelling (FDM), using an industrial robotic setup was chosen to fabricate the facade. Important fabrication parameters including layer dimensions, extrusion -speed and -temperature, and cooling rate can be controlled in this process. As summarised in Section 1.1, ceramics and thermoplastics are identified as materials most compatible with this process. Critical selection criteria include low material- and fabrication- related GHG emissions, cost-effectiveness, mechanical strength, reuse-/recycle- ability, ease of fabrication, fire certification, weather- and thermal- resistance. Since the research aims to demonstrate daylight transmission and reflection properties, the optical properties are essential. Hence, reflective and translucent thermoplastic, Polyethylene Terephthalate (PETG), was chosen as the fabrication material.

3. Optical characteristics of AM thermoplastics

It is necessary to characterise the AM element’s light-scattering properties to design and simulate the facade’s light-transmittance. Literature about the optical properties of AM elements are not well known and only beginning to be explored [10]. The light-scattering properties of the element is defined by its Bi-directional Scattering Distribution Function (BSDF) i.e. the light intensity relation between any two directions of incidence and scattering (reflection or transmission).

One approach uses analytical models generated by ray-tracing techniques based on underlying geometrical optics. However, this is a computationally intensive process especially for complex AM geometries. Instead, the light scattering properties were experimentally measured and implicitly used as a surface property within lighting simulations. This method also captures the surface geometry, micro-patterns, and crystallinity of the element. Other benefits, limitations, and challenges of using this technique have been well documented [11].

3.1. Experimental setup

The BSDF of the element and the measured irradiance of the scattered light are defined by the following equations [12] [13]:

\[
BSDF(\theta_i, \phi_i; \theta_s, \phi_s) = \frac{E(\theta_i, \phi_i; \theta_s, \phi_s)}{P_i \cdot \cos(\theta_s)}
\]  

(1)

\[
L_s(\theta_s, \phi_s) = \int_{\omega=4\pi}^{\omega} BSDF(\theta_i, \phi_i; \theta_s, \phi_s) \cdot L_i(\theta_i, \phi_i) \cdot \cos(\theta_i) d\omega_i
\]

(2)
Figure 2: (a) Workflow for modelling and designing using the spectral characteristics of an AM element; (b) sample translucent AM thermoplastic element; (c) front-to-back Distribution Scattering Function (DSF) for $\Theta, \Phi = 30, 90$; (d) hemispherical integrals of transmission in relation to $\Theta$ and $\Phi$; (e) photo-realistic render taken at Nov 21 1400hrs under uniform sky-conditions.

The directions are defined by spherical coordinates, i.e. zenith angle ($\theta$) and azimuth angle ($\phi$) relative to the orientation of the sample, and the subscripts $i$ and $s$ represent the incident and scattered values. $E$ is the measured illuminance; $P_i$ is the unobstructed light source’s intensity; $L$ is the measured radiance; and $\omega_i$ is the solid angle of the incident source. A scanning goniophotometer was used to generate the light scattering properties of the AM sample.

A commercially available 3D printer was used to fabricate small-scale prototypes (< 0.30 x 0.30m) to measure the BSDFs. For a set of incident directions, the goniophotometer captures scattered light for different outgoing directions. The setup uses collimated light from a halogen lamp (with a bandpass filter to block NIR wavelengths). The incident beam is focused over an aperture (approx. 7mm) which sufficiently covers a representative area of the sample. The BSDF is averaged over this surface area.

3.2. Measured BSDFs

Two thermoplastic AM samples were measured independently. The two samples were ‘reflective’, and ‘translucent’ thermoplastics, and represent the reflective and translucent surfaces of the facade described in Section 2. The incident angles $\theta_i, \phi_i$ were limited between (0, 0) and (90, 90), and a total of 45 measurements for each sample was made. For each set of incident angles, the front-front reflection ($r_{ff}$) and front-back transmission ($t_{fb}$) were measured. The reflective sample followed an inverse relation between hemispherical integrals for $r_{ff}$ (0.78 and 0.83) and $\theta_i$ (10$^0$ and 80$^0$). The hemispherical integral of the translucent sample $t_{fb}$ did not have a clear correlation. The maximum measured value was 0.9 for ($\Theta, \Phi$) = (0$^0$, 90$^0$) and the minimum value was 0.34 for ($\Theta, \Phi$) = (30$^0$, 0$^0$). The interpolated hemispherical integrals of transmission for translucent AM PETG sample is shown in 2(c).
3.3. Optical simulation using BSDF data

The empirical light scattering data was used to calculate the BSDF for each of the two sample AM thermoplastic surface typologies using Radiance. Radiance accepts user-supplied geometry, material properties, and sky conditions for daylight simulations to generate spectral illuminance, color, and glare values. The software can solve for light transmission within complex geometries', and calculates illuminance and glare values, and generates photo-realistic renders using backward ray tracing or photon-mapping techniques. Radiance also contains a workflow to compile empirical BSDF measurements to generate data-driven models. The measured data describes the light scattering functions for the discrete incident angles used in the measurement process. However, the model should simulate the scattering over a wider range of incident light from the sun position, sky hemisphere, and contextual reflections. The data-driven approach to model BSDF is implemented in Radiance to interpolate the measured data to provide angles not measured by the goniophotometer. Gaussian Radial Basis Functions (RBFs), defined for each incident direction, replace the measured data. The RBFs are generated for (i) $\alpha_{RB}$ and (ii) $\beta_{RB}$ using the `pabopto2bsdf` Radiance command. The interpolated BSDF is discretised and compressed using the `bsdf2klems` Radiance command. Figure 2 summarises the workflow beginning with empirical measurements, interpolating between discrete data and simulating the samples.

4. Facade topology optimization

The facade’s geometric features, described in Section 2, are parametrized and modeled in the Rhino-Grasshopper environment. The inclination, orientation, protrusion and scale were bound between 10° and 80°, 10° and 170°, 0 and 1 m, and 1 and 3, respectively. The location was chosen to be Zurich, Switzerland (47.3769° N, 8.5417° E), and the facade orientation was chosen as south-facing. The Ladybug-Honeybee plugin was used to simulate the sun-path and climate. A BSDF (*.xml) surface property was generated from empirical data described in Section 3.3. Based on the performance objectives described in Section 2, four simulated outputs were measured: (i) total solar irradiance (kWh/m²) on the translucent sections of the facade during (i) the summer months (May-August); (ii) the winter months (November to February), (iii) average daylight level (lux) within a 2 m indoor daylit zone during the winter months, and (iv) variance of the illuminance in the daylit zone during the winter months. The performance objectives could also be extended to other indoor comfort parameters (e.g., temperature, and glare index).

To optimize the facade’s topology for the performance objectives, an evolutionary multi-objective optimization engine, Wallacei, was chosen. For the evolutionary algorithm (EA), the Fitness Objectives (FOs) comprised the four performance objectives, and the genes were the four geometric parameters. The total population size of the EA was 900 (generation size and count were 30), crossover probability was 0.9, crossover and mutation distribution indices were 20, and the random seed was set to 1.

Each FO of every individual was ranked from worst (899) to best (0), meaning each individual was labeled with four ranks. A parallel coordinate plot was used to visualize each individual’s performance and compare it against the others. Since the FOs were not given weights, individuals can be shortlisted based on selected FO rankings, average ranks, or least difference in FO ranks. Figure 3 shows the comparison between two shortlisted individuals using a diamond plot to visualize their FO rankings and values. The diamond plot is a useful visualisation technique to (i) compare the relative performances of the different FOs for multiple individuals/generations, (ii) identify individuals which have low relative differences in competing FOs, hence achieving a balanced annual environmental performance.
5. Summary and Conclusions

The paper describes an experimental methodology to measure and simulate the optical properties of an AM facade, to optimise its topology for reduced operational energy consumption. Using a sample topology comprising of reflective and transmissive components, the process from (i) design, (ii) fabrication, (iii) measurement, (iv) simulation and (v) optimisation is demonstrated. The location- and orientation- specific optimisation of the topology for seasonal solar gains and daylight quality highlights the benefit of this workflow.

The following shortcomings should be addressed in future iterations of this workflow: (i) the effect of higher resolution optical measurements is not known; (ii) annual whole building energy simulations, including visual comfort analyses, and material-embodied GHG emissions should be simulated to understand the effect of this workflow on the entire lifecycle GHG emissions; and (iv) the effect of increasing the EA parameters, specifically generation size and population, should be addressed.

This workflow could be applied to more complex micro- and macro- scale AM geometries for building facades. Tuning the optical properties of AM components using material and fabrication
parameters is of interest and could lead to a mono-material fabrication of AM facades with spatially variable optical properties.

Acknowledgments
The authors would like to acknowledge the research funding from the National Centre for Competence in Research (NCCR) in Digital Fabrication from the Swiss National Science Foundation. The authors would also like to thank Dr Lars Grobe and (Dr-Ing) Susanne Gostonyi from the Hochschule Lucerne (School of Engineering and Architecture) for performing the optical measurements, and for feedback on building facade engineering, respectively.

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