Challenges in modelling thermo-optical performance of 3D-printed facades: a cross-domain review

Conference Paper

Author(s):
Piccioni, Valeria; Leschok, Matthias; Borkowski, Esther; Hischier, Illias; Schlueter, Arno

Publication date:
2023-09

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000635325

Originally published in:
Building Simulation Conference Proceedings 18, https://doi.org/10.26868/25222708.2023.1585

Funding acknowledgement:
- NCCR Digital Fabrication ()

Challenges in modelling thermo-optical performance of 3D-printed facades: a cross-domain review

Valeria Piccioni[1], Matthias Leschok[2], Esther Borkowski[1], Illias Hischier[1], Arno Schlueter[1]
[1]Architecture and Building Systems, ITA, ETH Zurich, Switzerland
[2]Digital Building Technologies, ITA, ETH Zurich, Switzerland

Abstract

Thanks to large-scale 3D printing, it is possible to fabricate performance-integrated building facades, contributing to the building sector's decarbonisation. The assessment of thermo-optical performance in 3D-printed facades (3DPF) is still at an early stage. The main challenges are related to the specificity of such components: the geometrical complexity, the interaction of multiple physical effects and the influence of the fabrication process on their properties. This focused review examines the aspects of performance indicators, multiphysics and multiscale modelling by reviewing recent efforts in the fields of advanced facades and process engineering. Learnings from the reviewed studies guided the development of a novel approach for modelling the thermo-optical properties of polymer 3DPF and informing their design.

Highlights

- 3DPF can feature tailored thermo-optical performances to achieve high energy efficiency and low environmental impact.
- Characterisation is challenging due to the geometrical complexity and the multiscale, multiphysics effects occurring from fabrication to operation.
- Relevant modelling efforts from the field of advanced facades and process engineering are reviewed.
- Knowledge transfer informed the creation of a novel framework for assessing and integrating the thermo-optical properties of polymer 3DPF.

Introduction

Recent efforts towards the decarbonisation of the building sector have focused on developing facade solutions that can improve buildings' energy performance and decrease greenhouse gas emissions (Bui et al. (2020); Kim et al. (2018)). 3D-printing, the process of creating physical objects by depositing materials layer by layer based on a digital model, has been identified as a fabrication alternative for new facade technologies. The latest advancements in large-scale 3D printing have shown that it is possible to fabricate building facades from various materials (Leschok et al. (2023); Naboni and Jakica (2022)). Multiple functions can be embedded in one component, and performances can be tuned for specific applications: from thermal insulation and structural properties (Dielemans et al. (2021); Figliola and Battisti (2021)) to season thermal control (Sarakinioti et al. (2017); Tenpierik et al. (2018)) and optical properties (Piccioni et al. (2023); Seshadri et al. (2021)). Complex shapes and geometrical articulations can be controlled using computational design tools. However, the assessment of the environmental performance of 3D-printed components still represents a challenge (Leschok et al. (2023)).

More specifically, referring to standard calculation methodologies is usually impossible when dealing with bespoke, non-standard geometries. Since 3DPF feature articulate geometries with heterogeneous properties, standard and averaged performance indicators are often insufficient for their characterisation as they do not capture their complexity (Briels et al. (2022)). Moreover, 3DPF usually integrate multiple functions, so multiphysics effects need to be accounted for. Due to limited integration into the simulation code, current building performance simulation (BPS) tools may not be flexible enough to model these heterogeneous components and capture their behaviour. A combination of different tools can help overcome this challenge. Most of these challenges are also found in the performance assessment of advanced facade systems (AF) and have been analysed (Borkowski et al. (2022); Taveres-Cachat et al. (2021); Favoino et al. (2018)).

Another set of challenges regards the manufacturing technique. The 3D printing layer deposition affects the material's properties at a millimetre scale and the way a part behaves as a whole. Hence, a new design and simulation resolution comes into play (Carver (2015); Piccioni et al. (2023)). This new dimension needs to be understood in relation to the component and building scale. 3D printing materials may also be new to the building industry and, thus, need extensive characterisation before being implemented in BPS and applied to facade components. Other fields, such as material and process engineering, face the similar challenge of unveiling the relationships between material, fabrication parameters, properties and performances. For this purpose, the field has developed multiscale design and simulation methodologies, which could be transferred to the study of 3DPF.

Scope and Methodology

In a focused literature review, this paper describes the main challenges related to the performance assessment of 3DPF and identifies viable approaches based on knowledge gained from within and outside of the construction industry. After identifying relevant issues in the simulation and characterisation of 3DPF, we performed multiple literature searches on Scopus and Web of Science using keywords such as *”performance assessment”*, *”characterisation”*, *”modelling”*, in combination with *”advanced facade systems”*, *”adaptive facades”*, *”additive manufacturing”* and *”3D printing”*. Given the lack of studies specifically examining 3D-printed facades, two different literature searches were performed addressing facades and 3D-printed components separately. Thematic analysis of the literature led to categorising the reviewed material into three main challenges and approaches to tackle them, reflected in the structure of the paper: performance indicators, multiphysics problems, and multiscale phenomena.

Performance Indicators

Characterising the thermal and optical performance of advanced facade components is key to supporting decision-making and engineering. Conventional performance metrics (e.g. U-value and g-value) are defined following assumptions which are generally valid for conventional facade components. It is assumed that they do not vary due to changing boundary conditions and do not account for transient physical effects (Goia et al. (2014)). They are usually based on geometrical simplifications of the physical problem and boundary conditions and are not made to describe multi-functional systems. Therefore, they are limited in describing the performance of advanced and 3D-printed facades.

In order to avoid inaccuracies in characterisation, alternative methods have been proposed to derive static standard performance indicators for AF. For example, a study used multiple linear regression to identify metrics describing the performance of glazing systems as a function of varying boundary conditions (Goia et al. (2014)). However, these metrics still deviate significantly from the experimental results for advanced glazing systems. Standard indicators can also be expanded for more comprehensive performance characterisation. In the case of components with switchable insulation, the U-value can be defined as a range of possible values or, at least, for two possible states (Fawaier and Bokor (2022)).

A single-number value for the g-value, which is usually calculated at the normal incidence of incoming solar radiation, is an appropriate simplification for standard glazing products. However, it falls short in describing components with angle-dependent properties, often defined as complex fenestration systems (CFS). To avoid gross overestimations of cooling loads, a climate-based g-value can be used, which is calculated for location-specific incoming sun angles as a simpler alternative to bidirectional scattering distribution function (BSDF) descriptions (Wermke (2021)). For advanced facades, novel performance indicators have been derived from numerical and experimental datasets, quantifying the system's objective rather than describing a physical effect. Often, these metrics take the form of dimensionless efficiency (e.g. describing the amount of heat transferred within the component) normalised over boundary conditions and with temporal resolution chosen according to the dynamic of the facade system (Bianco et al. (2018); Juaristi et al. (2022)).

Given the facades' complexity, multiple performance indicators are needed to describe their behaviour comprehensively, and general methodologies should be proposed to derive meaningful metrics beyond project-specific ones. When comparing with traditional facade components or among different AF and 3DPDF, the total environmental impact should also be considered as the facade is not only responsible for carbon dioxide (CO_2) emitted in the use phase of a building but also in the pre-use and post-use phase (Saleem et al. (2018)). To date, facade design and engineering rarely account for aspects other than energy efficiency and user comfort. However, the building sector decarbonisation goal demands adopting a more comprehensive life cycle assessment ~~LCA~~ framework. In this context, it will be crucial to identify the most impactful life cycle phases of AF, quantify the embodied impact of novel materials and account for adaptive behaviours in the operational phase (Crespi and Persiani (2019)).

The following sections present approaches to derive performance indicators for advanced and 3D-printed facades. Such approaches consider the specificity of their behaviour, namely the dependence of performance on interactions of multiple physical phenomena and the influence of the fabrication on their properties across multiple dimensional scales.

Multiphysics problems

The behaviour of advanced facades usually relies on the interaction phenomena happening at different physical domains, the most crucial for energy performance being the thermal, optical and airflow domains. Most BPS tools provide thermal and airflow modelling integration, whereas optical domain integration often relies on the synergistic use of additional software (Loonen et al. (2017)). The challenge in describing the performance of advanced facades is that BPS tools cannot capture the complex phenomena that define their performance. On the other hand, more specific tools, such as finite element methods or computational fluid dynamics (CFD) software, are useful for gathering a detailed understanding of their physical behaviour but fail to quantify the impact of AF technologies as a system applied in a building (Favoino (2015)).

Thermal + Optical

Optical and thermal domains are intrinsically coupled when considering transparent components (Fig.1a). Advanced facades can feature integrated shading layers which selectively admit or block solar radiation and may or may not contribute to thermal insulation. Such elements are defined as CFS (Thanachareonkit and Scartezzini (2010)), and their optical and thermal properties are dependent on the angle of incidence and wavelength of incoming radiation (Demanega et al. (2018)). A comprehensive physical description of their behaviour requires the definition of the angle dependency of thermo-optical properties - such as g-value and visual transmission (Tvis) - and an identification of the long-wave properties (emissivity). The Tvis and g-value can be represented using the BSDF. In this representation discretises the incoming radiation hemisphere according to a chosen resolution. The Klems resolution is the most popular, consisting of 145 input and output directions (Lee et al. (2018)), and was designed to simplify the modelling of solar heat gains in multi-layer CFS.

BSDF data is widespread in research and industry, and many products and materials can be found in the complex glazing database by Lawrence Berkeley National Laboratory. These descriptions can be used to calculate the thermo-optical performance of CFS, featuring a combination of glazing, shadings and films, in the software WINDOW, again in the form of BSDF. Then, the BSDF can be used as an input for BPS tools to calculate the energy performance and the indoor comfort of a building with CFS applied. Michele et al. (2018) reviewed the capabilities of BPS tools to implement BSDF descriptions of advanced facades. Among the most popular tools, EnergyPlus enables BSDF descriptions thanks to the strong coupling with LBNL Window. Moreover, it provides a built-in option to control the state of CFS, e.g. blind down or up, using the Energy Management System (EMS) feature (Ellis and Torcellini (2007)). TRNSYS implements the BSDF representation of thermal properties according to ISO 15099 (Hauer et al. (2019)) and has been enriched with a custom type for daylight prediction to be coupled with the thermal model (Michele et al. (2015)). Finally, the open-source Fener Tool is a BPS tool targeted at innovative CFS and their control (Bueno et al. (2015)). It couples Radiance-based daylighting and single-zone thermal models with BSDF representations of CFS.

When a new CFS is being developed, the BSDF is often unavailable for shading and glazing materials. In this case, raytracing can be used to obtain angular-dependent thermo-optical properties. Physical raytracing can be implemented using a scanning goniophotometer implementing movable light sources and detectors (Geisler-Moroder et al. (2021)). Goniophotometer measurements should be considered the most accurate characterisation method, as they account for manufacturing errors and product imperfections (Molina et al. (2015)). The drawback of this approach is that such experimental setups are rare to find, the experimental characterisation can be a very time-consuming task, and it is only possible to test samples with limited size (McNeil et al. (2013); Molina et al. (2015)). An alternative, validated approach is virtual raytracing (Andersen et al. (2005)), an algorithm implemented in the commercial software TracePro, and in Radiance through the *genBSDF* function. The accuracy of the results depends on the modelling of material properties and the geometrical description of the sample to study (McNeil et al. (2013)). Hybrid BSDF description can be achieved by utilising measurements where possible and simulations where instrumentation cannot provide reliable data (e.g. for certain incident angles), as reported in (Krehel et al. (2016)). Moreover, the two methods can be integrated when new materials and complex geometries are involved. Physical measurements on a material sample can be used to obtain a BSDF description, which can be applied to a geometry in a raytracing model to obtain a BSDF characterisation of the system (Michele et al. (2018)).

Other types of advanced transparent facades rely on the possibility of switching the thermo-optical properties of glass in response to stimuli, such as electricity in electrochromic glass and temperature in thermochromic glass (Fig.1a). With a reduced system complexity, the challenge for simulation models is to describe material properties that change during the simulation timeline. EnergyPlus and ESP-r BPS tools include built-in models for only a few established switchable glazing. Therefore, custom modelling routines must be defined to simulate new switchable glass types (Favoino (2015)). Built-in models for switchable glass often turn out to be conservative, as they do not allow for user behaviour and interaction (Zhang et al. (2022)). Therefore, modelling an appropriate control strategy becomes crucial. When the switch stimulus is extrinsic (e.g. electrochromic glass), adaptation is purely triggered by control strategies and based on the choice of appropriate state variable acting as stimuli. When the switch is intrinsic (e.g. thermochromic glass), adaptation is

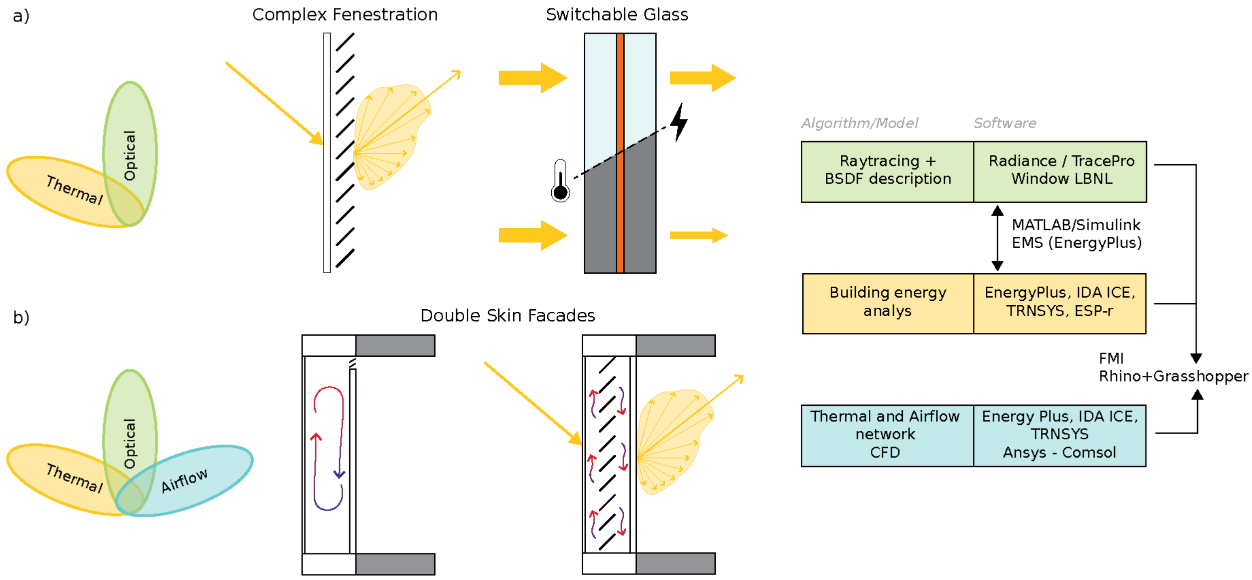

Figure 1: Summary of reviewed multiphysics approaches to advanced facades: domains, technologies and tools.

linked to a change of state in the material itself, and the stimulus needs to be derived during the simulation runtime. EnergyPlus allows expert users to program custom control routines within the EMS feature (Ellis and Torcellini (2007)). Favoino et al. (2015) implemented a modelling approach for thermochromic glass using the EMS feature and validated it against the in-built method in EnergyPlus and experimental data. The thermo-optical characterisation of the glass in the different states was done using experiments. Ganji Kheybari et al. (2021) used TRNSYS and Radiance as thermal and daylight simulation engines to assess electrochromic glass performance. They coupled TRNSYS with MATLAB to achieve a model predictive control of the system. Moreover, they modelled multiple states for the assembly using WINDOW and used Radiance to obtain daylight results for artificial lighting controls. For such systems, the facade control strategy was found to be equally important in the design and operation stages (Zhang et al. (2022)).

Thermal + Optical + Airflow

Double-skin facades (DSF) are relatively well-established fully-glazed facade systems that feature a deep air cavity acting as a thermal buffer within double glazing (Fig.1b). The nature of the cavity, which can be open or closed, with fixed or adjustable inlets and outlets, determines DSF's physical behaviour (Pomponi et al. (2016)). Catto Lucchino et al. (2019) provided an in-depth review of the modelling approaches for DSF, from empirical correlations to detailed computational fluid dynamics models (CFD). The most popular modelling approach of integrated thermal and airflow network models is integrated into the majority of BPS tools and offers a good trade-off between flexibility and accuracy. In this approach, air and energy transport in the air cavity is studied using an RC network, and airflow is mainly modelled as a result of the pressure difference between the two nodes. In-built models for DSF are provided in EnergyPlus and IDA ICE and have been developed for TRNSYS; however, they are very limited when control aspects have to be implemented (Catto Lucchino et al. (2019)). Empirical validation of DSF models in different software tools revealed that simulation results are less accurate during peak loads of solar radiation and for naturally ventilated facades, where re-circulation flows cannot be accounted for. Additional efforts are needed to validate the simulation of DFS with integrated shading (Borkowski et al. (2022). Similar challenges are found in the modelling of opaque DSF and Trombe Walls.

Often, DSFs include a shading layer which affects their thermo-optical properties and adds complexity to the modelling of these systems (Fig.1b). Therefore, they need to be studied across optics, thermo- and fluid dynamics domains. CFD remains the only way to solve details in the design of a DSF, such as flow around Venetian blinds, openings and different shading systems (De Gracia et al. (2013)). Demanega et al. (2018) proposed a CFD-raytracing integrated approach to study the performance of a CFS featuring cavity glass and shading systems. They compared a simplified approach based on ISO 15099, implemented in LBNL Window, and a detailed approach combining Radiance and COMSOL multiphysics for raytracing and CFD, respectively, to retrieve the U-value, g-value, solar and visible transmittance of the system. They concluded that implementing BSDF material description is vital to avoid underestimating the g-value of up to 30%. Moreover, the simplified approach underestimates the U-value by around 8%, and this inaccuracy is even more relevant for wider cavity CFS.

Integrating BPS and CFD tools can provide the most accurate results for DFS (De Gracia et al. (2013)). Colombo et al. (2017) presented an approach for the simulation of DSF where BPS and CFD simulation tools are coupled and run independently to converge to a common solution. Their two-step approach involves a first whole-building simulation with approximate values for cavity convection in order to retrieve surface temperature values. These results are used as boundary conditions for the CFD simulation to retrieve air temperature and heat fluxes within and through the DSF. In the second step, the CFD-calculated fluxes are used as input for the BPS instead of the approximate convection conditions. As the process iterates, increased accuracy is achieved. The coupling of BPS and CFD can improve the accuracy of both methods, provided data exchange between the two simulations is managed. Singh and Sharston (2022) provide an extensive overview of coupling methods for BPS and CFD, focusing on their ability to resolve the main challenges of i) time scale, as as BPS typically run at a coarser resolution than CFD; ii) spatial resolution, as BPS considers averaged values for a zone while CFD analyses spatial distribution within a zone; iii) computational cost, as BPS can run simulation periods of one year in minutes, while CFD simulations take longer than the real timescale of the problem. Such challenges apply to other coupling challenges; therefore, a more general discussion about co-simulation is presented in the next section.

Co-simulation

When a single model cannot handle cross-domain phenomena, there is a need to connect multiple models to resolve distinct parts of a coupled problem. This can be done through co-simulation, where computed data is exchanged across models during the simulation runtime. Different types of co-simulation can be implemented depending on the exchanged data and the coupling frequency. These must be chosen according to the physical variable that needs to be studied and the control action to be implemented (Borkowski (2021); Taveres-Cachat et al. (2021)). Integration platforms have been created to solve the data exchange challenge between different tools and simultaneous simulation. Among those, the Functional Mock-up Interface (FMI) standard is a tool-independent standard widely used in the industry (Junghanns et al. (2021)), which has also been explored for the modelling of adaptive building envelopes (Borkowski et al. (2022)).

Of particular interest is also the visual programming environment of Grasshopper for Rhino, which allows the implementation of simulation scripts (from EnergyPlus, Open Studio, Radiance and Daysim) through the Honeybee and Ladybug plugins, along with the parametric and generative design procedures (Borkowski (2021)). As an interface to different simulation tools, the Grasshopper environment can be used to increase interoperability between engines and thus facilitate co-simulation (Taveres-Cachat and Goia (2020)). Some BPS tools, namely EnergyPlus and Matlab/Simulink, also include built-in connection possibilities to specialised external engines, such as Radiance, OpenFOAM, Window and THERM, thanks to their application programming interfaces (APIs). Coupling simulation engines and programming environments also opens the stage for performance-driven design and optimisation (Bui et al. (2020)). However, in the absence of user-friendly and generalisable coupling platforms, using such methods requires users to have a deep understanding of BPS and specialised simulation tools. Therefore, co-simulation is mostly limited to research studies and has not been uptaken by the facade industry (Singh and Sharston (2022)).

A similar approach can be used when dealing with multiple spatial scales, as we elaborate in the following section. In multi-scale modelling approaches, the coupling of different models relies on the choice of model extents, simulation outputs and physical property descriptions across different resolutions.

Multiscale phenomena

Material design and process engineering often face the challenge of understanding and modelling physics pertaining to multiple time and length scales, which a single set of governing equations and constitutive laws cannot describe. Understanding the macroscale behaviour of a component in relation to microscale features and properties of its constituent material allows the formulation of reverse-engineered problems where microscale features can be designed to achieve a specific macroscale performance. This level of tailoring is particularly relevant to 3D printing, where a vast space of process parameters can be tuned to obtain selected properties over different dimensional scales (Gantenbein et al. (2018); Monaldo and Marfia (2021); Sharafi et al. (2022); Yuk et al. (2020)).

Material Databases

Understanding the process-structure-property (P-S-P) relationships is at the base of material science and engineering. This knowledge has guided the design and tailoring of materials and structures, especially in the field of metallurgy and composite materials (Chung (2017)). In 3D printing, the variety of physics involved at different stages of the fabrication processes and the cyclic thermal history make these relationships more complex and challenging to understand (Wang et al. (2022)). Nano- to micro-scale geometrical indicators such as molecular alignment of the

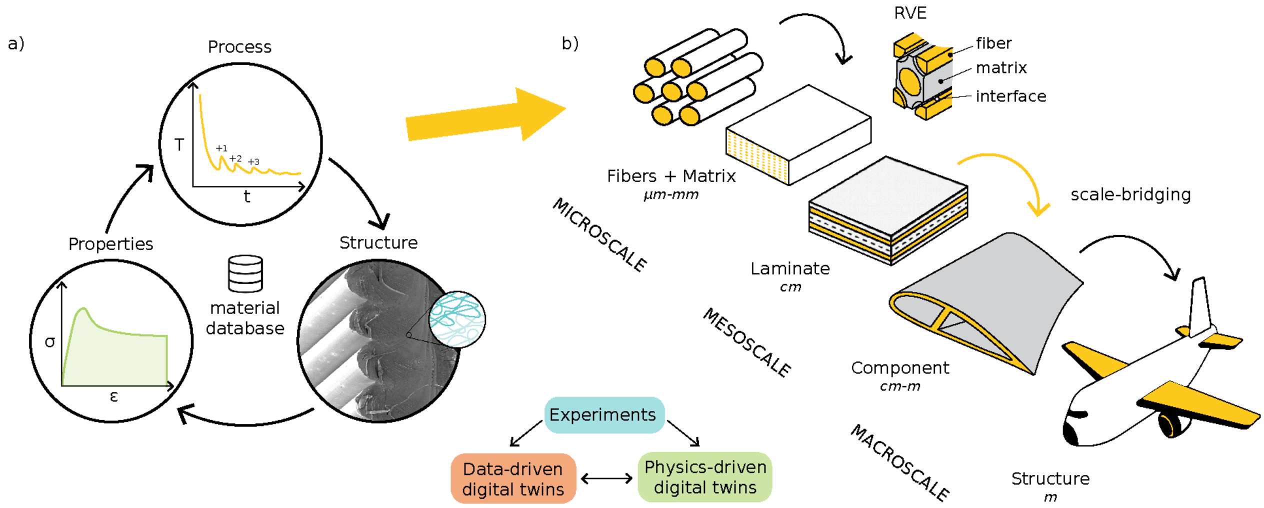

Figure 2: Summary of reviewed multiphysics approaches in material and process engineering. Adapted from Rokvam (2018) and Mageto (2003).

extruded material, presence of voids, cracks or delamination between layers (interfacial bonding quality), surface roughness, and layer width-to-height ratio are crucial to assess and control the properties of printed parts. Depending on their scale, these features can be identified with various techniques: from x-ray diffraction and computed tomography up to scanning electron microscopy and visual inspection. 3DP parts exhibit anisotropic behaviour, which is governed by the microstructure produced during layer deposition (Somireddy and Czekanski (2020)). Anisotropy can be found in mechanical, electrical, thermal and optical properties and mainly depends on inter-layer bonding and the formation of air inclusions between layers (Zohdi and Yang (2021)). Moreover, thermal conditions during processing can cause microstructural heterogeneity, contributing to anisotropic behaviours (Kok et al. (2018)). Anisotropy can be regarded as a drawback of 3D printing but can also be exploited to design parts with tuned functionalities (Chen et al. (2022)).

P-S-P relationships can be encoded in material databases and implemented in the design process (Fig.2a). These efforts are well established in the aerospace engineering field where programmes such as MAPTIS, the Materials And Processes Technical Information System (NASA (2023)), and AGATE, the Advanced General Aviation Transport Experiments (ASAP - Aerospace Safety Advisory Panel (2021)), have been promoted to relate material properties and processing guidelines for metal alloys and composites, respectively. These databases caused a revolution in the way engineers, material manufacturers and material suppliers work, establishing certification standards at different stages of the design process, reducing required testing efforts for the different stakeholders and enabling close control of the material properties and processing parameters. The digitalisation of supply chains and fabrication processes has also reached additive manufacturing, where material informatics is crucial to ensure the reliability and reproducibility of parts, as well as more efficient processing and reduced cost for physical testing (Mies et al. (2016)). Again, additive manufacturing of metals and the aerospace industry are pioneers in creating such data infrastructures (Lu et al. (2017); Prater (2017)). Large-scale 3D-printing, relevant for facade applications, stands at a lower technology readiness level.

The creation of data relies on a combination of numerical modelling and experimental testing. The traditional approach to establishing digital twins of the additive manufacturing processes is based on physical and mathematical modelling of the underlying phenomena (Kouraytem et al. (2021)). An alternative approach relies on data science and machine learning (ML). Data-driven techniques use numerical or experimental data to identify correlations between the inputs and outputs to implicitly model a given phenomenon (Jiang et al. (2022)). Hybrid modelling of the P-S-P relationship through physics-driven ML uses monitoring and experimental data to derive descriptions of the relationships of interest and create predictive models encoding this knowledge (Ko et al. (2023)). Both physics- and data-driven approaches are crucial to leverage the potential of material informatics. The former can provide a high-fidelity understanding of complex physical phenomena for validation. The latter enables predictions at low computational cost and the exploration of large design spaces (Kouraytem et al. (2021)). Recent efforts in the field of large-scale 3D printing of building components have shown a similar approach to link fabrication-related physical phenomena and material behaviour and integrate relationship knowledge into the design process (Ramsgaard Thomsen et al.

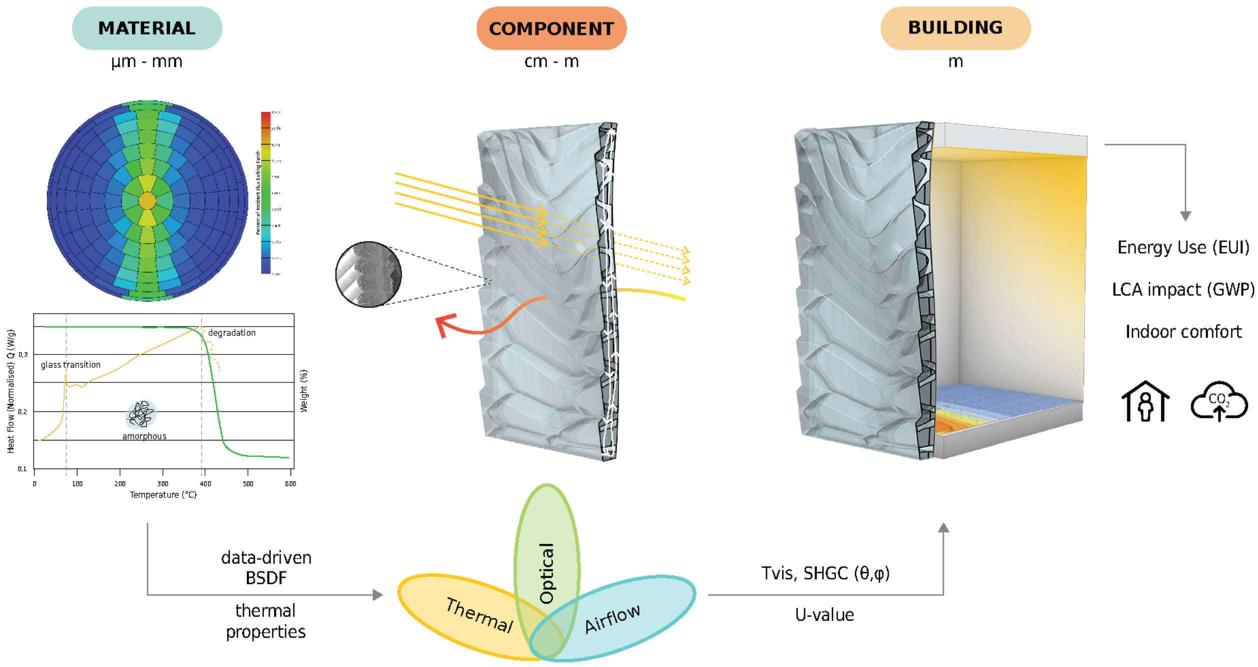

Figure 3: Concept for multiscale multiphysics approach to assess and integrate thermo-optical performance in 3DP facade systems.

(2020); Rossi et al. (2023)).
Overall, data sharing and management in the 3D printing sector is key to pushing the boundaries of this technology and its diffusion by increasing the reliability and performance of parts and reducing risks and costs (Hague et al. (2004); Prater (2017)). These aspects are particularly crucial for the uptake of 3D printing in the building industry, where the slow pace of technological innovation is a structural issue, and cost and risk reduction are driving factors in stakeholders' decision-making.

Multiscale modeling

In additive manufacturing, multiscale modelling approaches have proved capable of capturing P-S-P relationships in metals (Tang et al. (2021); Yan et al. (2018)) and for predicting the performance of end-parts as a low-cost alternative to experimentation (Bayat et al. (2021)). Depending on the combination of material and techniques, multiscale models need to include several multi-domain interactions, such as thermal, mechanical, and fluid dynamics. As mentioned above, high-fidelity multiphysics, multiscale models for 3D-printing processes can be paired with ML to enable real-time solutions (Gunasegaram et al. (2021)).

Multiscale modelling can link processes ranging from molecular dynamics to macroscale continuum mechanics (Fig.2b). The most important challenges are identifying the relevant physics happening at each dimensional scale, the information to be transferred from one scale to another, and the physical conditions to be satisfied within the information transfer (Fish (2009)). Information transfer or scale bridging can use concurrent or hierarchical coupling. In the former, the microscale and the macroscale models are linked together during the computation run. In the latter, a macroscopic model is solved first, and then parameters and functions related to the microscopic scale are separately computed to inform the model (Weinan (2011)). Homogenisation is a commonly used scale bridging technique when modelling the performance of 3D printed parts. It is mostly a hierarchical approach where the behaviour of a heterogeneous material is described by defining an equivalent effective response of a representative volume element (RVE), assumed to be statistically homogeneous (Geers et al. (2017)). RVEs can be used to derive the effective material properties of composite materials used for 3D printing and to describe the effects of the layer-by-layer articulation of the part (Gupta et al. (2022)). When 3DP components feature periodic microstructures, the RVE coincides with the unit cell, the basic geometry, which is periodically repeated to form the structure. Therefore, it can be analysed to retrieve effective properties, which can be input in a full-scale model without having to model its microscale resolution (Carver (2015)).

Examples of multiscale approaches can also be found in architecture and building engineering. Multiscale simulations ranging from urban and building-level models (Miller et al. (2018)) up to the material scale allow the high-fidelity representation of microclimatic effects on buildings and can be used to formulate mitigation strategies (Derome et al. (2019)). Multiscale modelling can also be used to design and characterise innovative building material systems (Liu et al. (2020); Wu et al. (2018)). In relation to advanced fabrication techniques, multiscale modelling strategies can support bi-directional data exchange between manufacturing parameters and global performance of free-form structures (Nicholas et al. (2015); Svilans et al. (2018). Moreover, it can be used to explore how architecture-scale boundary conditions can influence the properties of materials and, hence, structures (Faircloth et al. (2018)).

Summary and Outlook

Simulation and modelling of 3D-printed facades are still in the early development stage. However, knowledge transfer from the fields of advanced facades and process engineering can help the development of specific methodologies and workflows. According to the reviewed studies, such workflows are required to combine different software and modelling approaches. Due to the lack of built examples, literature references and standardised methodologies, computational and experimental techniques are usually coupled for validation and calibration purposes.

Straightforward performance indicators need to be defined to allow their integration into performance-driven design processes and the exploration of the vast design space enabled by 3D printing. Therefore, further research efforts should integrate performance assessments into the design process and relate them to geometrical and fabrication parameters.

The need to understand the performance of 3D-printed facades at multiple dimensions encourages the development of multiscale modelling approaches, which account for fabrication-induced effects over the scale of material, component and building. Moreover, according to the functional requirements of the facade component, these approaches should describe the interaction between multiple physical domains, such as thermal, optical and airflow. Finally, performance indicators related to life-cycle environmental impact should be included within assessment frameworks to allow comparison between 3DPF and traditional components and unveil the potential contribution of 3DPF to the building sector decarbonisation. Building on these guidelines, the authors are developing a modelling approach targeting performance assessment and integration in 3DP polymer facades with bespoke thermo-optical properties (Fig.3).

The modelling framework covers the scale of the material and encodes the influence of the printing process on the optical properties of the part in a material database using experiments and validated raytracing simulations. The data-driven material characterisation is used as an input for component-scale models, which couple finite element analysis and raytracing to study thermal effects in complex geometries and optical interactions of multiple 3D-printed layers, respectively. From the component-scale model, relevant performance indicators are derived, which reflect the physical behaviour of the component and are used as input for building-scale simulations. BPS and life-cycle assessment tools are finally employed to assess the operational and embodied impact of these 3DPF applied to a building. This modelling approach will be discussed in detail in a forthcoming publication.

Acknowledgments

The authors thank I. Cheibas and B. Seshadri (Institute of Technology in Architecture, ETH) for their contributions to the Integrated 3D-Printed Facade project. The National Centre for Competence in Research in Digital Fabrication financially supports this research, funded by the Swiss National Science Foundation (NCCR DFAB Agreement number 51NF40141853).

References

Andersen, M., M. Rubin, R. Powles, and J. L. Scartezzini (2005, February). Bi-directional transmission properties of Venetian blinds: experimental assessment compared to ray-tracing calculations. *Solar Energy 78*(2), 187–198.

ASAP - Aerospace Safety Advisory Panel (2021). AGATE Statistical Analysis Program.

Bayat, M., W. Dong, J. Thorborg, A. C. To, and J. H. Hattel (2021, November). A review of multi-scale and multi-physics simulations of metal additive manufacturing processes with focus on modeling strategies. *Additive Manufacturing 47*, 102278.

Bianco, L., Y. Cascone, S. Avesani, P. Vullo, T. Bejat, S. Koenders, R. C. Loonen, F. Goia, V. Serra, and F. Favoino (2018, November). Towards New Metrics for the Characterisation of the Dynamic Performance of Adaptive Façade Systems. *Journal of Facade Design and Engineering 6*(3), 175–196 Pages.

Borkowski, E. (2021). *Integrated modelling of control and adaptive building envelope: development of a modelling solution using a co-simulation approach.* Ph. D. thesis, Institute For Environmental Design & EngiThe Bartlett School of Environment, Energy and Resources - University College London.

Borkowski, E., A. Luna-Navarro, M. Michael, M. Overend, D. Rovas, and R. Raslan (2022, December). Empirical validation of co-simulation models for adaptive building envelopes. *Journal of Facade Design and Engineering 10*(1), 119–154.

Borkowski, E., D. Rovas, and R. Raslan (2022, March). Adaptive building envelope simulation in current design practice: findings from interviews with practitioners about their understanding of methods, tools and workarounds and implications for future tool developments. *Intelligent Buildings International 14*(2), 172–189.

Briels, D., S. Kollmannsberger, F. Leithner, C. Matthäus, A. S. Nouman, O. Oztoprak, and E. Rank (2022, July). Thermal Optimization of Additively Manufactured Lightweight Concrete Wall Elements with Internal Cellular Structure through Simulations and Measurements. *Buildings 12*(7), 1023.

Bueno, B., J. Wienold, A. Katsifaraki, and T. E. Kuhn (2015, May). Fener: A Radiance-based modelling approach to assess the thermal and daylighting performance of complex fenestration systems in office spaces. *Energy and Buildings 94*, 10–20.

Bui, D.-K., T. N. Nguyen, A. Ghazlan, N.-T. Ngo, and T. D. Ngo (2020, May). Enhancing building energy efficiency by adaptive façade: A computational optimization approach. *Applied Energy 265*, 114797.

TNO Netherlands (2015). *Virtual material design in 3D printing makes headway with multiscale modeling*.

Catto Lucchino, E., F. Goia, G. Lobaccaro, and G. Chaudhary (2019, February). Modelling of double skin facades in whole-building energy simulation tools: A review of current practices and possibilities for future developments. *Building Simulation 12*(1), 3–27.

Chen, J., X. Liu, Y. Tian, W. Zhu, C. Yan, Y. Shi, L. B. Kong, H. J. Qi, and K. Zhou (2022). 3D-Printed Anisotropic Polymer Materials for Functional Applications. *Advanced Materials 34*(5), 2102877.

Chung, D. D. L. (2017, March). Processing-structure-property relationships of continuous carbon fiber polymer-matrix composites. *Materials Science and Engineering: R: Reports 113*, 1–29.

Colombo, E., M. Zwahlen, M. Frey, and J. Loux (2017, September). Design of a glazed double-façade by means of coupled CFD and building performance simulation. *Energy Procedia 122*, 355–360.

Crespi, M. and S. G. L. Persiani (2019). Rethinking Adaptive Building Skins from a Life Cycle Assessment perspective. *Journal of Facade Design and Engineering 7*(2), 21–43.

De Gracia, A., A. Castell, L. Navarro, E. Oró, and L. F. Cabeza (2013, June). Numerical modelling of ventilated facades: A review. *Renewable and Sustainable Energy Reviews 22*, 539–549.

Demanega, I., G. D. Michele, S. Avesani, G. Pernigotto, F. Babich, and A. Gasparella (2018). CFD And Ray Tracing To Evaluate The Thermal Performance Of Complex Fenestration Systems. In *Proceedings of BSO 2018*, Cambridge, UK.

Derome, D., A. Kubilay, J. Allegrini, A. Ferrari, and J. Carmeliet (2019). From Urban Climate to Building and Material Scale: a Multiscale Modelling Approach. In *Proceedings of Building Simulation Conference 2019*, Rome, Italy, pp. 3730–3733.

Dielemans, G., D. Briels, F. Jaugstetter, K. Henke, and K. Dörfler (2021, April). Additive Manufacturing of Thermally Enhanced Lightweight Concrete Wall Elements with Closed Cellular Structures. *Journal of Facade Design and Engineering 9*(1), 59–72.

Ellis, P. G. and P. A. Torcellini (2007). Simulation of Energy Management Systems in EnergyPlus. In *Proceedings Building Simulation Conference 2007*, Beijing, China.

Faircloth, B., R. Welch, M. Tamke, P. Nicholas, P. Ayres, Y. Sinke, B. Cuffy, and M. Ramsgaard Thomsen (2018, June). Multiscale modeling frameworks for architecture: Designing the unseen and invisible with phase change materials. *International Journal of Architectural Computing 16*(2), 104–122.

Favoino, F. (2015, January). Assessing the performance of an advanced integrated facade by means of simulation: The ACTRESS facade case study. *Journal of Facade Design and Engineering 3*(2), 105–127.

Favoino, F., Y. Cascone, L. Bianco, F. Goia, V. Serra, M. Perino, M. Overend, and M. Zinzi (2015, December). Simulating Switchable Glazing with EnergyPlus: An Empirical Validation and Calibration of a Thermotropic Glazing Model. In *Proceedings of BSA Conference 2015*.

Favoino, F., M. Doya, R. Loonen, F. Goia, C. Bedon, and F. Babich (2018). *Building Performance Simulation and Characterisation of Adaptive Facades - Adaptive Facade Network*. Delft: TU Delft Open.

Fawaier, M. and B. Bokor (2022, September). Dynamic insulation systems of building envelopes: A review. *Energy and Buildings 270*, 112268.

Figliola, A. and A. Battisti (2021). Informed Architecture and Clay Materials. Overview of the Main European Research Paths. In A. Figliola and A. Battisti (Eds), *Post-industrial Robotics: Exploring Informed Architecture*, pp. 47–72. Singapore: Springer.

Fish, J. (2009, October). *Multi-scale Methods: Bridging the Scales in Science and Engineering*. Oxford University Press.

Ganji Kheybari, A., T. Steiner, S. Liu, and S. Hoffmann (2021, December). Controlling Switchable Electrochromic Glazing for Energy Savings, Visual Comfort and Thermal Comfort: A Model Predictive Control. *CivilEng 2*(4), 1019–1051.

Gantenbein, S., K. Masania, W. Woigk, J. P. W. Sesseg, T. A. Tervoort, and A. R. Studart (2018, September). Three-dimensional printing of hierarchical liquid-crystal-polymer structures. *Nature 561*(7722), 226–230.

Geers, M. G. D., V. G. Kouznetsova, K. Matouš, and J. Yvonnet (2017). Homogenization Methods and Multiscale Modeling: Nonlinear Problems. In *Encyclopedia of Computational Mechanics Second Edition*, pp. 1–34. John Wiley & Sons, Ltd.

IEA SHC Task 61 (2021, January). *BSDF Generation Procedures for Daylighting Systems*.

Goia, F., L. Bianco, V. Serra, and M. Perino (2014). Energy Performance Assessment of Advanced Integrated Façades by Means of Synthetic Metrics. In A. Li, Y. Zhu, and Y. Li (Eds), *Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning*, Volume 263, pp. 21–28. Berlin, Heidelberg: Springer.

Gunasegaram, D. R., A. B. Murphy, A. Barnard, T. DebRoy, M. J. Matthews, L. Ladani, and D. Gu (2021, October). Towards developing multiscale-multiphysics models and their surrogates for digital twins of metal additive manufacturing. *Additive Manufacturing 46*, 102089.

Gupta, A., S. Hasanov, I. Fidan, and Z. Zhang (2022, February). Homogenized modeling approach for effective property prediction of 3D-printed short fibers reinforced polymer matrix composite material. *The International Journal of Advanced Manufacturing Technology 118*(11), 4161–4178.

Hague, R., S. Mansour, and N. Saleh (2004, November). Material and design considerations for rapid manufacturing. *International Journal of Production Research 42*(22), 4691–4708.

Hauer, M., G. De Michele, F. Babich, D. Plörer, and S. Stefano (2019). Modelling Of Complex Fenestration Systems – Application Of Different Toolchain Approaches On Real Case Scenarios. In *Proceedings of Building Simulation Conference 2019*, Rome, Italy, pp. 4926–4935.

Jiang, J., Y. Xiong, Z. Zhang, and D. W. Rosen (2022, April). Machine learning integrated design for additive manufacturing. *Journal of Intelligent Manufacturing 33*(4), 1073–1086.

Juaristi, M., F. Favoino, T. Gómez-Acebo, and A. Monge-Barrio (2022, March). Adaptive opaque façades and their potential to reduce thermal energy use in residential buildings: A simulation-based evaluation. *Journal of Building Physics 45*(5), 675–720.

Junghanns, A., C. Gomes, C. Schulze, K. Schuch, P. R, M. Blaesken, I. Zacharias, A. Pillekeit, K. Wernersson, T. Sommer, C. Bertsch, T. Blochwitz, and M. Najafi (2021, September). The Functional Mock-up Interface 3.0 - New Features Enabling New Applications. In *Proceeding of Modelica Conference*, pp. 17–26.

Kim, D., S. J. Cox, H. Cho, and J. Yoon (2018, November). Comparative investigation on building energy performance of double skin façade (DSF) with interior or exterior slat blinds. *Journal of Building Engineering 20*, 411–423.

Ko, H., Y. Lu, Z. Yang, N. Y. Ndiaye, and P. Witherell (2023, April). A framework driven by physics-guided machine learning for process-structure-property causal analytics in additive manufacturing. *Journal of Manufacturing Systems 67*, 213–228.

Kok, Y., X. P. Tan, P. Wang, M. L. S. Nai, N. H. Loh, E. Liu, and S. B. Tor (2018, February). Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review. *Materials & Design 139*, 565–586.

Kouraytem, N., X. Li, W. Tan, B. Kappes, and A. D. Spear (2021, April). Modeling process–structure–property relationships in metal additive manufacturing: a review on physics-driven versus data-driven approaches. *Journal of Physics: Materials 4*(3), 032002.

Krehel, M., L. O. Grobe, and S. Wittkopf (2016, January). A hybrid data-driven BSDF model to predict light transmission through complex fenestration systems including high incident directions. *Journal of Facade Design and Engineering 4*(3-4), 79–89.

Lee, E. S., D. Geisler-Moroder, and G. Ward (2018, January). Modeling the direct sun component in buildings using matrix algebraic approaches: Methods and validation. *Solar Energy 160*, 380–395.

Leschok, M., I. Cheibas, V. Piccioni, B. Seshadri, A. Schlüter, F. Gramazio, M. Kohler, and B. Dillenburger (2023, August). 3D printing facades: Design, fabrication, and assessment methods. *Automation in Construction 152*, 104918.

Liu, C., R. Qian, Z. Liu, G. Liu, and Y. Zhang (2020, June). Multi-scale modelling of thermal conductivity of phase change material/recycled cement paste incorporated cement-based composite material. *Materials & Design 191*, 108646.

Loonen, R. C., F. Favoino, J. L. Hensen, and M. Overend (2017, March). Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *Journal of Building Performance Simulation 10*(2), 205–223.

Lu, Y., P. Witherell, and A. Donmez (2017, August). A Collaborative Data Management System for Additive Manufacturing. In *Volume 1: 37th Computers and Information in Engineering Conference*, Cleveland, Ohio, USA, pp. V001T02A036. American Society of Mechanical Engineers.

Mageto, M. (2003, January). *Tem study of microstructure in relation to hardness and ductility in Al-Mg-Si (6xxx) alloys*. Ph. D. thesis, NTNU, Trondheim, Norway.

McNeil, A., C. J. Jonsson, D. Appelfeld, G. Ward, and E. S. Lee (2013, December). A validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems. *Solar Energy 98*, 404–414.

Michele, G. D., R. Loonen, H. Saini, F. Favoino, S. Avesani, L. Papaiz, and A. Gasparella (2018, November). Opportunities and Challenges for Performance Prediction of Dynamic Complex Fenestration Systems (CFS). *Journal of Facade Design and Engineering 6*(3), 101–115.

Michele, G. D., U. F. Oberegger, and L. Baglivo (2015). Coupling dynamic energy and daylighting simulations for complex fenestration systems. In *Proceedings of BSA Conference 2015*, Bolzano, Italy, pp. 289 – 296.

Mies, D., W. Marsden, and S. Warde (2016, December). Overview of Additive Manufacturing Informatics: "A Digital Thread". *Integrating Materials and Manufacturing Innovation 5*(1), 114–142.

Miller, C., D. Thomas, J. Kämpf, and A. Schlueter (2018, May). Urban and building multiscale co-simulation: case study implementations on two university campuses. *Journal of Building Performance Simulation 11*(3), 309–321.

Molina, G., W. Bustamante, J. Rao, P. Fazio, and S. Vera (2015, July). Evaluation of radiance's genBSDF capability to assess solar bidirectional properties of complex fenestration systems. *Journal of Building Performance Simulation 8*(4), 216–225.

Monaldo, E. and S. Marfia (2021, December). Multiscale technique for the analysis of 3D-printed materials. *International Journal of Solids and Structures 232*, 111173.

Naboni, R. and N. Jakica (2022, January). 17 - Additive manufacturing in skin systems: trends and future perspectives. In E. Gasparri, A. Brambilla, G. Lobaccaro, F. Goia, A. Andaloro, and A. Sangiorgio (Eds), *Rethinking Building Skins*, Woodhead Publishing Series in Civil and Structural Engineering, pp. 425–451. Woodhead Publishing.

NASA (2023). MAPTIS - Materials And Processes Technical Information System.

Nicholas, P., D. Stasiuk, E. Nørgaard, C. Hutchinson, and M. Thomsen (2015, October). A Multiscale Adaptive Mesh Refinement Approach to Architectured Steel Specification in the Design of a Frameless Stressed Skin Structure. In *Modelling Behaviour*, pp. 17–34. Springer Cham.

Piccioni, V., M. Leschok, L. O. Grobe, S. Wasilewski, B. Seshadri, I. Hischier, and A. Schlüter (2023, March). Tuning the Solar Performance of Building Facades through Polymer 3D Printing: Toward Bespoke Thermo-Optical Properties. *Advanced Materials Technologies 8*(6), 2201200.

Pomponi, F., P. A. E. Piroozfar, R. Southall, P. Ashton, and E. R. P. Farr (2016, February). Energy performance of Double-Skin Façades in temperate climates: A systematic review and meta-analysis. *Renewable and Sustainable Energy Reviews 54*, 1525–1536.

Prater, T. (2017, June). Database development for additive manufacturing. *Progress in Additive Manufacturing 2*(1), 11–18.

Ramsgaard Thomsen, M., P. Nicholas, M. Tamke, S. Gatz, Y. Sinke, and G. Rossi (2020, December). Towards machine learning for architectural fabrication in the age of industry 4.0. *International Journal of Architectural Computing 18*(4), 335–352.

Rokvam, S. (2018). *Multiscale modelling of fiber composites - Investigating micromechanics of constituents' interaction*. Ph. D. thesis, NTNU, Trondheim, Norway.

Rossi, G., R.-S. Chiujdea, L. Hochegger, A. Lharchi, J. Harding, P. Nicholas, M. Tamke, and M. R. Thomsen (2023). Statistically Modelling the Curing of Cellulose-Based 3d Printed Components: Methods for Material Dataset Composition, Augmentation and Encoding. In C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M. R. Thomsen, and J. Wurm (Eds), *Towards Radical Regeneration*, Cham, pp. 487–500. Springer International Publishing.

Saleem, M., G. Chhipi-Shrestha, M. Túlio Barbosa Andrade, R. Dyck, R. Ruparathna, K. Hewage, and R. Sadiq (2018, December). Life Cycle Thinking–Based Selection of Building Facades. *Journal of Architectural Engineering 24*(4), 04018029.

Sarakinioti, M. V., M. Turrin, M. Teeling, P. de Ruiter, M. van Erk, M. Tenpierik, T. Konstantinou, U. Knaack, E. Dolkemade, M. de Klijn, Loonen, J. Hensen, and D. Vlasblom (2017). Spong3d: 3D printed facade system enabling movable fluid heat storage. *Journal of Architecture and the Built Environment 4*(2), 57–60.

Seshadri, B., I. Cheibas, M. Leschok, V. Piccioni, I. Hischier, and A. Schlüter (2021, November). Parametric design of an additively manufactured building facade for bespoke response to solar radiation. *Journal of Physics: Conference Series 2042*(1), 012180.

Sharafi, S., M. H. Santare, J. Gerdes, and S. G. Advani (2022, March). A multiscale modeling approach of the Fused Filament Fabrication process to predict the mechanical response of 3D printed parts. *Additive Manufacturing 51*, 102597.

Singh, M. and R. Sharston (2022, January). A literature review of building energy simulation and computational fluid dynamics co-simulation strategies and its implications on the accuracy of energy predictions. *Building Services Engineering Research and Technology 43*(1), 113–138.

Somireddy, M. and A. Czekanski (2020, October). Anisotropic material behavior of 3D printed composite structures – Material extrusion additive manufacturing. *Materials & Design 195*, 108953.

Svilans, T., P. Poinet, M. Tamke, and M. Ramsgaard Thomsen (2018). A Multi-scalar Approach for the Modelling and Fabrication of Free-Form Glue-Laminated Timber Structures. In K. De Rycke, C. Gengnagel, O. Baverel, J. Burry, C. Mueller, M. M. Nguyen, P. Rahm, and M. R. Thomsen (Eds), *Humanizing Digital Reality: Design Modelling Symposium Paris 2017*, pp. 247–257. Singapore: Springer.

Tang, H., H. Huang, C. Liu, Z. Liu, and W. Yan (2021, March). Multi-Scale modelling of structure-property relationship in additively manufactured metallic materials. *International Journal of Mechanical Sciences 194*, 106185.

Taveres-Cachat, E., F. Favoino, R. Loonen, and F. Goia (2021, March). Ten questions concerning co-simulation for performance prediction of advanced building envelopes. *Building and Environment 191*, 107570.

Taveres-Cachat, E. and F. Goia (2020, September). Co-simulation and validation of the performance of a highly flexible parametric model of an external shading system. *Building and Environment 182*, 107111.

Tenpierik, M., M. Turrin, Y. Wattez, T. Cosmatu, and S. Tsafou (2018). Double Face 2.0: A lightweight translucent adaptable Trombe wall. *Spool. Journal of Architecture and the Built Environment 5*(2).

Thanachareonkit, A. and J.-L. Scartezzini (2010, April). Modelling Complex Fenestration Systems using physical and virtual models. *Solar Energy 84*(4), 563–586.

Wang, Z., W. Yang, Q. Liu, Y. Zhao, P. Liu, D. Wu, M. Banu, and L. Chen (2022, May). Data-driven modeling of process, structure and property in additive manufacturing: A review and future directions. *Journal of Manufacturing Processes 77*, 13–31.

Weinan, E. (2011). *Principles of multiscale modeling*. Cambridge ; New York: Cambridge University Press. OCLC: ocn721888752.

Wermke, C. (2021, April). Simple versus Complex: Comparing the accuracy of cooling energy demands for complex fenestration systems using BSDF and SHGC (solar heat gain coefficient). In *Proceedings of Powerskin Conference*, Munich, Germany.

Wu, L., P. Liu, Z. Zhang, D. Zhu, and H. Wang (2018). Multi-scale modeling for High Performance Concrete: A Review. *International Journal for Multiscale Computational Engineering 16*(3), 267–283.

Yan, W., S. Lin, O. L. Kafka, C. Yu, Z. Liu, Y. Lian, S. Wolff, J. Cao, G. J. Wagner, and W. K. Liu (2018, December). Modeling process-structure-property relationships for additive manufacturing. *Frontiers of Mechanical Engineering 13*(4), 482–492.

Yuk, H., B. Lu, S. Lin, K. Qu, J. Xu, J. Luo, and X. Zhao (2020, March). 3D printing of conducting polymers. *Nature Communications 11*(1), 1604.

Zhang, X., H. Zhang, Y. Wang, and X. Shi (2022, December). Adaptive Façades: Review of Designs, Performance Evaluation, and Control Systems. *Buildings 12*(12), 2112. Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

Zohdi, N. and R. C. Yang (2021, September). Material Anisotropy in Additively Manufactured Polymers and Polymer Composites: A Review. *Polymers 13*(19), 3368.