Development and prototyping of an integrated 3D-printed façade for thermal regulation in complex geometries

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Abstract

Currently, several research projects investigate Additive Manufacturing (AM) technology as a possible construction method for future buildings. AM methods have some advantages over other production processes, such as great freedom of form, shape complexity, scale, and material use. These characteristics are relevant for façade applications, which demand the integration of several functions. Given the established capacity of AM to generate complex geometries, most existing research focuses on mechanical material properties and mainly in relation to the load-bearing capacity and the construction system. The integration of additional aspects is often achieved with post processing and the use of multiple materials. Research is needed to investigate properties for insulation, thermal storage, and energy harvesting, combined in one component and one production technology.

To this end, the research project "SPONG3D" aimed at developing a 3D-printed façade panel that integrates insulating properties with heat storage in a complex, mono-material geometry. This paper gives an overview of the panel development process, including aspects of material selection, printing process, structural properties, energy performance, and thermal heat storage. The development process was guided by experiments and simulations and resulted in the design and manufacturing of a full-scale façade element prototype using FDM printing with PETG. The project proved the possibility of the integration of functions in 3D-printed façades, but also highlighted the limitations and the need for further developments.

Keywords

additive manufacturing, 3d-printing, PETG, heat storage, thermal insulation, façade module

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1 INTRODUCTION

Additive manufacturing methods provide great freedom of form compared to traditional methods (Strauss & Knaack, 2016). Nowadays, designers and engineers can freely create complex designs in shapes that traditional production processes could not provide. Furthermore, additive processes allow access to the inner part of the product, thus enabling integration of multiple design domains to realise multi-functionalities (Yang & Zhao, 2015), with no additional cost for the increased complexity (Gao et al., 2015). In additive manufacturing, regardless of their degree of complexity, objects are fabricated following the same procedure. This capability provides the design with very large geometric design freedom (Quan et al., 2015).

Complexity in form is observed in the façade, which is one of the most challenging parts of a building. This complexity can be attributed to the multifunctional nature of the component that controls the indoor environment of a building (Strauss & Knaack, 2016). Moreover, the growing demand for low energy consumption and comfort have given the façade an important role in the overall building concept. It must not only be extremely well insulated but also adaptive in order to positively modulate the interior climate. This ultimately has a positive effect on the use of energy. The façade becomes an integral part of the climate concept and building services components can be integrated into it (Klein, 2013). An increasing interest in the application of advanced building envelope solutions can be seen both in research activities and in industrial developments (Favoino, Goia, Perino, & Serra, 2016; Loonen, Trčka, Cóstola, & Hensen, 2013). The potential of 3d printing technology to generate complex geometries for integrating multiple materials and functions should be investigated in this respect.

The potentials of 3d printing technology for façade construction has been investigated by a few studies, such as the one from Peters (2016), Paoletti (2017) and de Witte et al. (2017). However, there is still research to be done to define the performance limits, especially for insulation and building physics to be combined in one component and one production technology. The focus of most research has been on the mechanical material properties, and mainly in the relation to the load-bearing capacity (Labonnote, Rønnquist, Manum, & Rüther, 2016). It is necessary to explore and determine the boundaries of those functions that can be integrated within a façade component.

In this context, the present research focuses on the potential and limits of integrating multiple functions in one façade component with 3d printing production technology. The main objective of this research is to demonstrate that with 3d printing technology it is possible to create mono-material façade components that integrate multiple functions. This hypothesis is tested by creating a façade panel that regulates the temperature inside the building with the use of its thermal insulation and heat storage properties. This paper presents the design and evaluation of the façade panel. Four research phases are presented. In the first one, samples were designed and 3D printed based on symmetrical cellular structures. In the second phase, samples were designed and 3D printed based on elongated and asymmetrical structures; and a broad range of heat flux and temperature measurements were conducted. In the third phase, channels for water circulation were designed, 3D-printed and tested for water tightness. Finally, the most promising design principles were scaled up into larger prototypes.

2 METHODOLOGY

The proposed façade panel has two main functions: thermal insulation and adaptable heat storage. The heat storage consists of the two external layers that are 3D printed: the water based liquid and the water tank. According to the different seasons and time of the day, the water is placed on the inside or outside of the façade to absorb or release heat, as shown in Fig. 1. To circulate the water, two reversible pumps are used, connecting the two external layers with the water tank. The façade thus acts as a cooling device in summer and as a heating device in winter. Along with the heat storage function, the panel needs to provide thermal insulation as part of the external envelope.

A *research through design* methodology was used to test if the above façade concept can be manufactured as a 3D-printed mono-material panel. Research through design is a methodology in which design alternatives, samples and prototypes are being developed in an iterative process, in which evaluations (e.g. simulations and measurements) lead to input for the development of the next generation of design alternatives, samples, and prototypes. The main tools used for these evaluations were theoretical models and literature, physical experiments, heat transfer simulations and structural optimisation. Multiple samples were produced for the different parts of the façade with variation in different parameters such as: layer height, infill percentage, speed, extrusion width, and temperature.

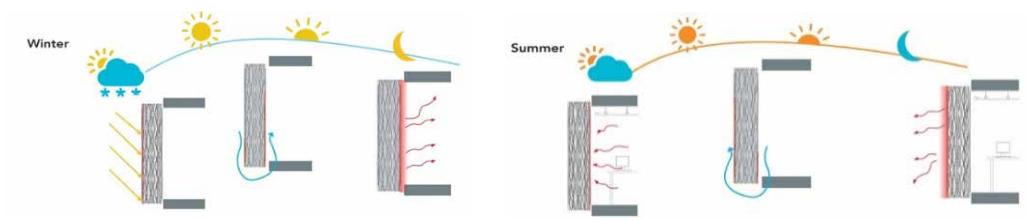
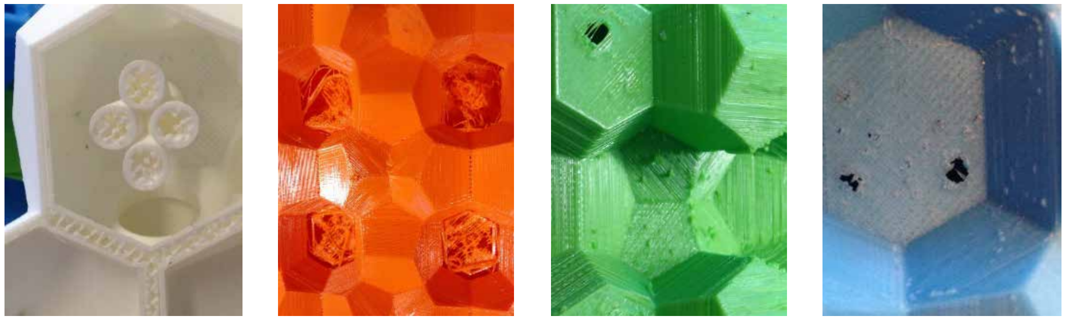


FIG. 1 Façade panel principle: Water circulation in a cooling season (a) in a heating season (b)

The designs of the first samples were created using software called Rhinoceros 3D and Grasshopper, in order to produce the geometry of the thermal insulation and the heat storage system. The 3D printing process that was selected was Fused Deposition Modelling. FDM technology and polymer filament is easily accessible to anyone who wants to 3D print. In addition, thermoplastics are relatively lightweight, have low thermal conductivity, and some of them are recyclable. Transparent PETG was chosen due to its higher solar transmittance for the external layer. Moreover, PETG has higher stiffness and strength than PLA for instance, and it is 100% recyclable.

3 PHASE 1: POLYHEDRA CONFIGURATION

In the first phase, the preliminary research of polyhedra structures and their potentials in thermal insulation were considered. The part that was designed and tested first was the external layer that will integrate water for heat storage. The main parameters used to evaluate the specific configuration were the ability to 3D print this configuration, the 3D printing time, the water tightness, the ability to design and print larger components in short timeframes, and the structural performance.
The material that was used was PLA.



a b c d

FIG. 2 Printing samples of the polyhedral configuration, showing problems of the printed surfaces.

Closed cellular structures are known to have relatively good thermal performance (Ashby, 2006). The cells are designed to have a low surface area, like a foam structure, which creates potential for cellular structures that have a relatively low ratio of solid to gas. Previous investigation into the 10mm cells showed that small panels made with these cells have relatively low effective thermal conductivity, 0.044 W/mK (Sarakinioti, 2016). The limiting factor in reducing the effective thermal conductivity is the minimal wall thickness needed from the manufacturing technique.

The process that followed was to 3D print the first samples of this configuration using FDM production technology. The objective was to test the properties of the 3D printed surface in terms of water tightness and surface quality. The samples were 3D printed with a nozzle of 0.4 mm. The length of time taken for printing was an issue and a solution needed to be investigated to produce the larger components. Furthermore, the specific configuration of polyhedral structures resulted in some surfaces being horizontal and collapsing during the printing process, as shown in Fig. 2.

4 PHASE 2: ELONGATED CELLS CONFIGURATION

Based on the conclusions drawn during Phase 1, the next phase of the research was set, aiming to improve the use of material, printing speed, and total production time. In particular, the approach based on two layers was revised, leading to re-thinking and re-designing the façade panel with different configurations.

4.1 CELLS DESIGN CONSIDERATIONS

The results received from the investigation of the Phase 1 helped to design further configurations that require less material, shorter printing time, and have good thermal performance. Considering the two different functions of the façade component (heat storage and thermal insulation), the two parts of the façade were investigated separately. The inner core needed air cavities to act as insulation, whereas the external layer needed channels that integrate water for heat storage and circulation. The air cavities were stretched in all directions except the direction of the heat transfer which was kept between 10-20mm, while the water channels were re-designed based on structures driven by fluid dynamics, using streams and channels that would circulate the water faster and with lower pressure drop from the bottom of the layer to the top (Fig. 3).

a b

FIG. 3 Cross section of the panels, showing the elongated cells in the insulation core and the channels in the external water layer.

In addition, the cells were initially designed with surfaces that are connected to enclose air inside them. The sides of the cells were regular and created sharp edges at the points at which they are connected. In the final design, the configurations have curved edges and sides. As a result, the extruder follows a continuous path while extruding material, the travelling time of the extruder is reduced, the printing speed could be increased as vibrations were lowered, and, therefore, the total printing time was reduced.

4.2 THERMAL CONDUCTIVITY PROPERTIES

First, the possible options for the insulation layer were designed, 3D printed, and tested for their thermal conductivity. For the thermal tests, a 1 m^3 box made of polystyrene was built and a hole of 20cm X 20cm in which to place the samples was created in one side. A lamp was placed inside the box to heat up the environment. The tests of the heat flux that is transferred from one side of the sample to the other took place during the summer months. In one typical summer day the mean temperature of the office was 28.7°C. On that day the temperature inside the box was 54°C, while outside was 28.7°C. This means that the difference was 25.3°C. A similar difference in temperature was also measured in the temperatures of the surfaces.

The thermal resistance of the sample was determined by measuring the temperature inside the box, on the surface of both sides of the sample, and of the external environment using thermocouples, and by measuring the heat flux through the sample with a heat flux plate (Hukseflux HFP01) on each side of the sample. Only the long-term average results were used once a steady-state situation had been reached.

The results for the different samples, as shown in Table 1, showed a relatively high thermal conductivity. The reason for this is the amount of material needed due to the production process; the porosity of the samples is rather low. The values of the thermal conductivity of the samples were similar and therefore the configuration with the shortest printing time was selected. The selected configuration was flexible and not stiff for a façade panel. Therefore, the configuration was deformed by keeping the main principle of the smooth curves and inserting connection points in some parts of the surfaces to increase the structural stiffness.

DESIGN	1	2	3	4
				
Nozzle size mm	0.4	0.4	0.4	0.4
Wall thickness	1.2mm	0.8 mm	1.2mm	1.2mm
Material	PETG colour	PETG transparent	PETG transparent	PETG transparent
Mass kg	0.533	0.286	0.417	0.693
Volume ratio solid /gas	0.2	0.08	0.23	0.23
thermal conductivity λ	0.101W/mK	0.094W/mK	0.104W/mK	0.109W/mK

TABLE 1 Different configurations that were tested for thermal conductivity

5 PHASE 3: EXTERNAL LAYER CONFIGURATION AND FIRST LARGE-SCALE PRINTING

In the third phase, the focus was on the external layer but also on the design of the large components. The design with the most promising performance, highest printing speed, potentials for uniform water flow, and lowest pressure drop was selected and further 3D printed. Several tests for water tightness were undertaken. Moreover, for the larger component, the two layers were designed in one object and the final design was 3D printed for the first time.

5.1 EXTERNAL LAYER

The configuration of the external layer is inspired by natural configurations that transfer fluids such as blood vessels, veins in leaves, and 3D bionic structures. The external layer, where the liquid flows, requires water-tightness and the channels in this layer require a hydrodynamic shape to allow for minimal pressure drop and uniform flow. Based on this concept, channels of different diameter were incorporated in the external layer (Fig. 4).

FIG. 4 Printed segment of the external layer

a b

FIG. 5 Water circulation test in the external layer

Several samples with different configurations were tested for flow resistance and water tightness, using a water pump and a hose that connects the input of the sample with the output of the pump (Fig. 5). Preliminary testing of the samples showed that the surface had micro-holes between the layers, caused by discontinuities and high speeds in the printing process. An epoxy coating (EpoxAcast 690) was applied both on the inside of the channels and on the external surface of the component to ensure water tightness.

5.2 THERMAL PERFORMANCE

In parallel to the design and manufacturing process, the potential for energy saving was investigated for different climates. The potential in the heating season was assessed by analysing correlations between solar irradiance and ambient temperature in TMY weather files for 14 cities. Similarly, the potential in the cooling season was investigated by comparing the difference between daytime air temperature and night-time sky temperature. From this study, it was found that Spong3D has more potential for cooling than for heating, because there are several warm climates in which the night-time sky temperature drops significantly below the thermal comfort zone, and can thus be used as a heat sink for nocturnal cooling. The added value of Spong3D is most pronounced in composite climates with at least a moderate need for both heating and cooling. Madrid, Los Angeles, and Cape Town are examples of such cities. The climate analysis showed that, in these cities, there is potential for natural heating or cooling with Spong3D on 75% to 80% of the days in a year. In all three climates, Spong3D has potential throughout almost the entire cooling season and for around half of the heating season (sunny days). This result indicates that Spong3D can have a significant impact on reducing heating and cooling energy demand, provided that its operation is tuned to the resources that are available in the ambient climate.

A dynamic simulation study was carried out to further quantify the performance potential of Spong3D. To this end, a Trnsys model of a reference office zone was developed with hydronic systems in the exterior (solar collector) as well as interior (radiant system) layers of the façade. These heat-exchanging surfaces were coupled with a storage tank with controlled fluid flow to represent the daily and seasonal behaviour of Spong3D. The Spong3D system was only modelled on the south facing façade – it was assumed that the office space was part of a bigger building, and that other

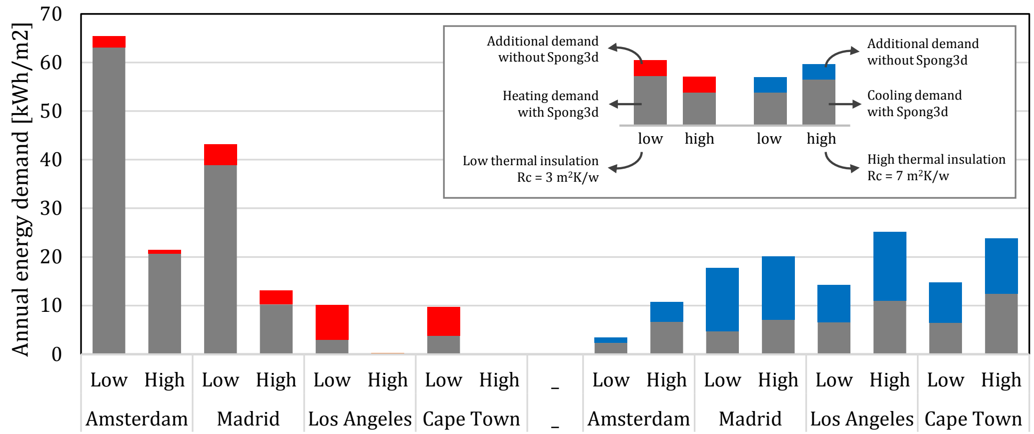


FIG. 6 Predicted energy demand for a reference office space in four different cities.

walls, floor, and ceiling are adjacent to rooms with similar thermal conditions. Among the many design variables that were studied, it turned out that tank volume, solar absorptance, and fluid flow rates have the greatest influence on the resulting performance of Spong3D. The case study results (Fig. 6) show that application of Spong3D can lead to significant reductions in energy demand, particularly for cooling. Percentage-wise, the energy-saving effect is similar for both a moderate and a highly insulated building envelope system. This is an encouraging finding for the viability of the Spong3D concept, as it shows that the thickness of the insulating middle layer can be kept at modest values and still lead to satisfactory performance.

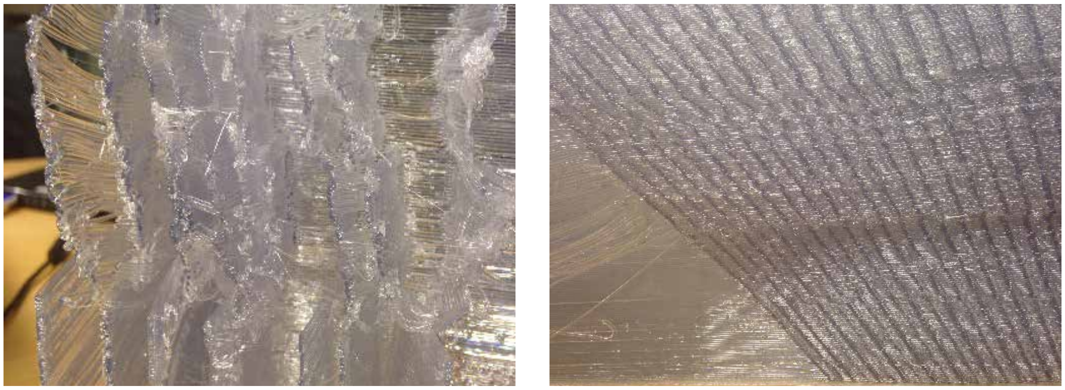
6 PHASE 4: LARGE SCALE PROTOTYPES

The project aimed not only to design the panel but also to produce a 1:1 scale prototype for a proof of concept. Two different prototypes were designed for the final production. The first one was a double-curved panel. The second one was a straight panel. Both prototypes faced several challenges, of which two are the most relevant.

6.1 LARGE SCALE 3D PRINTING

The first challenge regarded the identification of a proper number of layers for the large-scale prototype, based on achieving a balance between printing time and stiffness of the printed surfaces during printing. The second challenge regarded the stabilisation of the prototype during printing, to avoid warping during the cooling process of the extruded material, and to avoid any shifting of the prototype on the print bed. Firstly, a double-curved panel with water channel sizes of 5mm-15mm was prototyped. The printing process stopped at a lower height than expected. The final size of the produced panel was (55x30x30cm). The process of prototyping the double-curved panel allowed for the drastic improvement of the production of the straight panel with regard to both of these main challenges.

Regarding the number of layers, for the double-curved panel, the external channels were designed to be printed with one layer only, to minimise the use of material and time. Because the channels were not stiff and not thick enough, the extruder could put pressure on the channels and therefore could easily cause a displacement of the channels and deformation of those parts. Regarding the



a *b*

FIG. 7 The double-curved prototype, showing the displacement of the printed layers; cross section (a) and frond view (b).

stabilisation of the prototype during printing, every surface adhered to the print bed with a narrow base (a large thin printed surface). The surface that connected the model to the print bed was minimised and each surface would act independently during the printing process causing vibrations of the model and higher possibilities to deform (Figs. 7a and 7b). Based on this experience, decisions were taken to print the straight prototype with multiple layers for the external channels. Moreover, the decision was taken to sufficiently enlarge the surface that connected the model to the print bed.

6.2 FINAL PROTOTYPE

The final product is a large-scale prototype, which basically constitutes the proof of concept.
The design was adjusted to address the problems identified in printing during the previous phase. The diameter of the channels was increased from 5mm to 20mm for the small channels and from 15mm to 40mm for the big channels. Moreover, a second wall in the channels was inserted to make them stiffer. A single base for all the parts of the component was designed. These settings and some irregular parts of the design caused the creation of small surface cavities in the transitional areas between the large and smaller channels. The large panel had a rectangular shape.
The internal layer, which provides the thermal insulation properties, was designed according to the elongated cells principle (Fig. 8a) developed and measured in Phase 2. The thermal conductivity λ was measured to be 0.1 W/(m·K), which means that the panel with a thickness of 33cm insulation, has a thermal transmittance coefficient U value of 0.30W/(m2·K).

The overall prototype dimensions are 1500x500x360mm. Due to limitations of the printed size, the panel was printed as two components. The two models interlocked vertically and consisted of a free-standing component (Fig. 8b). The purpose of this model was to demonstrate the feasibility of printing such a panel, and it is not a fully functioning system. The water circulation system was not incorporated at this stage. Nevertheless, the possibility of water circulation in the 3d-printed channels was tested in the previous development phase, with a working prototype.
The printing process of the large component was successful except for some small cavities in the surface. The total printing time for the panel was 512 hours.

7 DISCUSSION

The manufacturing of the multifunctional façade panel was proven to be feasible, as the production of a 1:1 scale prototype indicates. Such a development, although still experimental, provides a positive outlook of the possibilities of additive manufacturing to integrate functions and improve the energy efficiency of buildings. The steps of the development process provided insights into the issues that may be encountered during the manufacturing of larger building components and how they can be addressed, as well as the opportunities offered by complex geometries, not only for appearance but also for performance of the building.

However, it needs to be clarified that considerable further developments are required to lead it towards a marketable façade system, which are, on the one hand, related to the manufacturing process, the function, and the performance of the system and, on the other hand, to the system implementation. Regarding the manufacturing process, which is the main innovation of the study, a number of issues need to be addressed. Firstly, the water circulation system should be integrated and tested in the panel and the design of the channels should be improved for better water circulation and heat storage. Most importantly, the 3D printing time is long for complex geometries and multiple integration of performances, despite trying to reduce the time through proper design. However, there is a continuous development of larger scale printers/chambers and techniques that can shorten the 3d printing time. Finally, further investigation needs to be done in relation to the feasibility of the production of large scale components in terms of time and costs.

a *b*

FIG. 8 The final full-size prototype: side view of the bottom part (a) and the full, freestanding prototype (b)

Furthermore, an in-depth analysis and testing on the structural behaviour of the 3D printed material are required, especially when considering extreme thermal conditions and durability, as well as long term testing on creep. The testing is also related to the investigation in 3d printed polymers and the selection of the most efficient polymer. 3d printing technology provides the designer with an opportunity to create elements that are tailored to the overall shape of the façade and the placement on the building, which allows the design of the façade to adapt according to customised requirements. Further investigation needs to be done to find the correct direction for implementing this customisation potential. Moreover, the component should be investigated in terms of its potential to be part of a façade that can integrate areas with transparency, translucency, and opacity.

To further develop the proof of concept into a façade product, investigation needs to be done on the potentials for compatibility with existing façade systems and components, such as gaskets sealants, infills, connectors etc., in addition to the 3d printed product's assembly and connection to the main structure and other building components. Finally, compliance with building regulations, such as structural load, building physics, daylight, fire safety etc. needs to be proven and ensured, before the façade panel can be considered as a product.

8 CONCLUSION

This paper discusses the development process of a mono-material, multifunctional, adaptive façade panel, which controls the heat exchange between the indoor and the outdoor environment, while testing the potential of additive manufacturing for its production. The panel concept is based on an inner core with highest possible thermal resistance and two outer layers where water accumulates heat from solar gain or indoor sources, circulates, and releases it on the other side. The intention was to create a component that is relatively lightweight and is recyclable. The plastic filament is a material that can be easily accessible to anyone who wants to 3D print.

The research work was structured in four phases. During the first phase, samples were designed and 3D printed based on symmetrical cellular structures; structural performances were measured on specimens and simulated. In the second phase, samples were designed and 3D printed based on elongated and asymmetrical structures; a broad range of thermal measurements for heat-flux were conducted under different thermal conditions. In the third phase, channels and tanks for water circulation were designed, 3D printed, and tested for water tightness. Finally, in the fourth phase, the most promising design principles were further implemented in the design and manufacturing of a one-to-one scale prototype.

The construction of the prototype constitutes the proof of the concept, as it demonstrated that it is possible to print a façade panel with complex geometry, which incorporates a heat storage system and thermal insulation properties. Moreover, the thermal simulations showed that, even though the system is not capable of replacing conventional heating and cooling systems entirely, it still shows promising predictions in reducing the heating and cooling demand of buildings and thereby reducing the costs for heating and cooling energy as well as associated greenhouse gas emissions, especially when implemented in a location with a composite climate requiring a moderate need for both heating and cooling.

The described façade panel is an experimental approach to prove that integrating functions in additively manufactured building components is possible. Such approaches have the potential to provide the needed energy efficiency, while accommodating design requirements for complex geometries. Nevertheless, several developments, investigations, and tests should be performed in terms of a marketable façade system, including structural, construction, and safety requirements, along with expanding design and performance possibilities. As additive manufacturing technologies rapidly advance, the design and production of integrated products will be, on one hand, facilitated and, on the other hand, will set the requirements for those technologies.

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