REFRONT

Towards Sustainable Façade Retrofitting using End-to-End Architectural Products

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ABSTRACT
Achieving global sustainability goals requires allocating more resources to research, innovative products, and new services that prioritize building retrofitting as a primary approach. The lack of a unified and standardized solution for enhancing the energy efficiency of building envelopes in the AEC industry affects stakeholders ranging from homeowners to designers and contractors and extends throughout the operational life of buildings. This paper proposes an end-to-end methodology for the design, configuration, and manufacturing of a 3D-printed façade system that addresses contemporary retrofitting requirements in an automated, streamlined, and sustainable manner. The system integrates computational design techniques to capture data from the contextual environment alongside user preferences, leveraging Conditional GANs and advanced analysis engines to reconstruct and evaluate building performance in simulated environments. Its generative algorithm produces a personalized, hyper-customized 3D-printed façade system supported by a flexible lattice and moving joints, enabling the creation of a dynamic building skin, with configuration and key metrics controlled via a web application. The methodology is validated through case studies that document performance gains over traditional methods, adoption of advanced technologies, aesthetic improvements, and additional benefits, such as promoting biodiversity.

1. INTRODUCTION

In the near future, it will be imperative that our cities steer towards sustainability in accordance with agenda 11 (Sustainable Cities and Communities) of the UNSDG 2030 goals (United Nations, 2015). To achieve this, we should limit new construction efforts and focus on retrofitting existing ones to control embodied carbon in the urban environment. The Global Buildings Climate Tracker indicates that the building and construction sector remains off-track in achieving decarbonisation by 2050. As an example, the UK exceeded its emissions by 10 million metric tons of CO2 equivalent in 2021. Given the UK's mature building stock consists of 5% new constructions, retrofitting is vital to meet the country's net-zero agenda. (UKGBC, n.d.) Operational carbon in buildings is a key metric to assess and meet sustainability objectives. Specifically, buildings (residential and non-residential) account for 34% of overall energy use, half of which is attributed to heating and cooling systems (GOV.UK, 2021). A more radical and integrated retrofitting strategy to enhance building performance can facilitate this task and mitigate risks. (GOV.UK, n.d.) However, current building systems and specifically façade solutions and their design and installation cycle are also falling short.

Targeting a net-zero agenda this research tries to address the above shortcoming of building systems by proposing an integrated pipeline for building analysis and building envelope generation using state-of-the-art computational design techniques, leading to a customizable, modular, and easily assembled 3D-printed façade system. This approach upgrades building performance at a granular level, treating architectural design as a product. It enables wider accessibility to efficient retrofitting, thus pacing towards a net-zero future.

In assessing the effectiveness of the suggested method, we will virtually implement it on real-world case studies and conduct performance simulations pre and post retrofitting. We will also attempt to forecast operational energy and cost savings by referring to standard values specific to building typology and wall sections. Additionally, we will document various material combinations and their respective effects, while reflecting on the aesthetic considerations from the point of view of a designer.

2. RELATED WORK

Since 54 BCE, the Roman Empire repurposed old temples as a means of conserving resources. These early attempts at sustainability and managed change are observed in the principles of the modern arts and crafts movement (Hunt and Boyd, 2017). In recent years, the idea of retrofitting has come to the forefront due to growing concerns about global warming, as highlighted in the Montreal and Kyoto Protocols (UK Research and Innovation, 2021).

2.1. PROCEDURALLY GENERATED FACADES

There are numerous tools are available for facade generation. Plugins for existing CAD packages such as Skin Designer (Garay, n.d.) are driven by user customization and informed by Ladybug tools analysis. There are also simplified tools such FacadeGenius (FacadeGenius, n.d.) that feature a user-friendly interface. These tools make features, such as carbon analysis and facade energy improvements, easily accessible to facade designers. Similarly, others can understand the components of a building through point-cloud scans. However, they are currently restricted to comprehending building styles and are not utilized to design retrofits on top of them. (Hussein et al., 2024). The potential exists for the development of a tool that can automate facade reconstruction and design alternative skin systems to improve building performance.

2.2. 3D PRINTED FAÇADE SYSTEMS

The explorations with Ceramic Tectonics to create clay cut extrusions of inter-lockable blocks through tessellations helps create expansive strong flexible surfaces and can be used to create flexible building skins. (Ugarte-Urzúa et al., 2020) There have been attempts to integrate nature and host plants on 3D printed facades through hydroponics that regulate the urban climate and attenuate urban noises while becoming a habitat for flora and fauna in cities. (Šuklje, T. et al., 2013) These interventions though relatively simple, can be combined with computational design and 3D printing of clay to create hyper functional facades as demonstrated in “Brick by Bit”. (Roznowski, 2024). Some of these approaches can be bound by principles of circularity and delivered to the site for installation through modular prefabricated structures to create sustainable interventions that are the need of the hour. (Alivojvodic, 2024) There has not yet been a building skin system that successfully creates a skin integrating all these features.

2.3. SETUP AND METHODOLOGY

We argue on establishing a holistic pipeline to deliver a seamless end-to-end workflow enabling the users of the system to generate a variety façade options for their building envelope, while targeting efficient yet flexible assembly on site. ReFront aims to replace the conventional process of Design and Execution for retrofitting with a circular and therefore more sustainable approach.

As this is an end-to-end workflow, we can identify three distinct parts in our proposal. Inputs, such as data capture, processing as in the translation of data and user preference into design recommendations and finally outputs, that can be both digital and physical. The data capturing process starts with the user using a mobile application to scan a building by a photograph of the façade as seen in figure 1. In the processing part, this input image is run through the back-end system which analyses, evaluates, recommends, hyper-customizes and finally generates the façade modules and overall topology of elements. Once the user has validated the proposal, the system proceeds to on-demand manufacturing of the cladding modules and joining elements, that when completed, are shipped on-site for modular assembly.

3.1. SYSTEM INPUTS

The system uses the minimum number of inputs for the generative process for ease of use. These include:

- The location of the building captured from the mobile device geolocation.
- The captured image or images of the building adhering to guidelines that can make it capable of processing using Machine Learning (ML) for elements segmentation.
- Verification of the scale of the case study by dimensioning one of the tectonic elements of the building. For instance, a window or an entrance door.

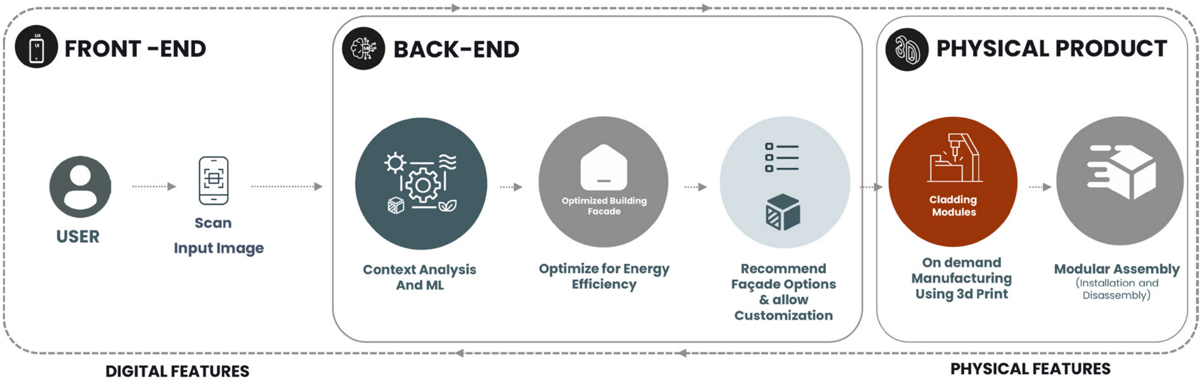


Figure 1:
The high-level overview of the [Project Name] workflow

3.2. BACK-END AND DATA PROCESSING

Our system's back-end system operations begin with the building analysis process. The goal is to come-up a global pattern that dictates the geometric parameters and typology of our system's modules, which will be further documented in the following chapter. This creates a table of parameters that dictate the form of the components to be manufactured for every unique position on the building envelope.
We identify the prevailing tectonic characteristics of the façade using Image Segmentation (IS) using pix2pix. (Isola et al., 2017)

This process assigns different colours to different physical elements of the facade like doors, windows, balconies, overhangs etc as demonstrated in figure 2. This model can be trained on a detailed dataset to identify different types of windows doors and balconies more accurately.

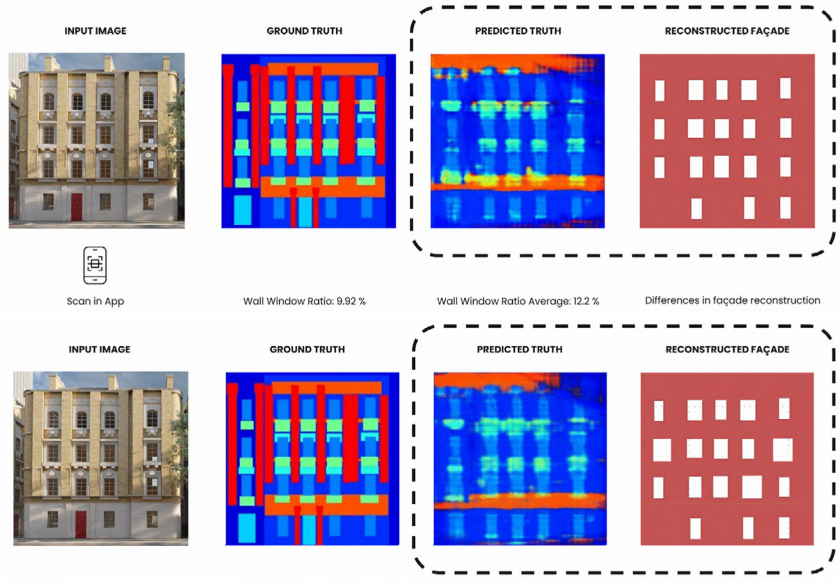


Figure 2:
An overview of results from pix2pix image segmentation.

The reconstructed image representation can be then used to deduct key metrics, such as wall-window-ratio (WWR), materiality and different façade features etc. The reason why this identification of elements is important is because it enables the translation of a 2-dimensional image to 3D mesh representation of the façade, hence allowing us to run analytical processes, such as solar radiation and wind simulations, as documented in existing literature (Sadeghipour Roudsari et al, 2013) (Sadeghipour Roudsari et al, 2019). All these metrics and topology can be traced back to the size of the building facade to predict the embodied carbon of recommended by our system retrofitting façade as per figure 3. But also, to calculate the embodied carbon if a conventional retrofitting process were to be implemented, which consequently assists with the assessment of our assumptions.

ReFront uses Google Earth Imagery to retrieve the contextual environment essential for running said analytical processes. (Baldurk,2023) This is scaled to the actual dimensions of our analysis sandbox and works as a simplified digital twin (fig. 4), necessary for the computing efficiency of the various simulations run. (Micheal, 2024) The ReFront back-end produces a series of maps. These are annual average radiation maps, average daylight hours maps, wind velocity analysis maps, wind pressure maps and building program-use maps as seen in figure 5. A linear Combination algorithm is used to generate the combinations with coefficients generated from Taguchi's Design of Experiments to identify all statistically significant solutions and consequently provide the user with equally good solutions as per their initial requirements (Taguchi, 1987). This linear combination of the parameters can be described by the following formula:

$$Sg = \frac{a.x + b.y + c.z + d.u + e.v}{w} + f$$

where Sg the Geometry Score for each location of the map and parameters can be seen below.

x = Function Map Values	a = Weight of Function map
y = Radiation Map Values	b = Weight of Radiation map
z = Sunlight hours Map Values	c = Weight of Sunlight hours map
u = Wind Pressure Map Values	d = Weight of Wind Pressure map
v = Wind Velocity Map Values	e = Weight of Wind Velocity

And f= A bias addition for user preference.

The values used for Taguchi's Design of Experiments can be seen in the Table 1:

	Function	**Insulation**	**Plantation**	**Ventilation**	**CC/ Outdoor**
Run 1	1	1	1	1	1
Run 2	1	2	2	2	2
Run 3	1	3	3	3	3
Run 4	1	4	4	4	4
Run 5	1	5	5	5	5
Run 6	2	1	2	3	4
Run 7	2	2	3	4	5
Run 8	2	3	4	5	1
Run 9	2	4	5	1	2
Run 10	2	5	1	2	3
Run 11	3	1	3	5	2
Run 12	3	2	4	1	3
Run 13	3	3	5	2	4
Run 14	3	4	1	3	5
Run 15	3	5	2	4	1
Run 16	4	1	4	2	5
Run 17	4	2	5	3	1
Run 18	4	3	1	4	2
Run 19	4	4	2	5	3
Run 20	4	5	3	1	4
Run 21	5	1	5	4	3
Run 22	5	2	1	5	4
Run 23	5	3	2	1	5
Run 24	5	4	3	2	1
Run 25	5	5	4	3	2

Table 1:
Map Combinations weights as per Taguchi's Design of Experiments

These are then superimposed and combined into a new metric mapping, that dictates and influences a particular function of the proposed facade at the specific location. These key metrics are also used to build an energy model in HoneyBee. (Sadeghipour Roudsari et al, 2016) Similarly, EnergyPlus can be used to calculate a baseline energy simulation on the current performance of the building, useful when comparing to the argued improvements by the proposed system. (Ahmad, 2017) (Crawley et al., 2000)

Figure 3:
Manual location selection by the user and reconstructed context map from Google Earth Data

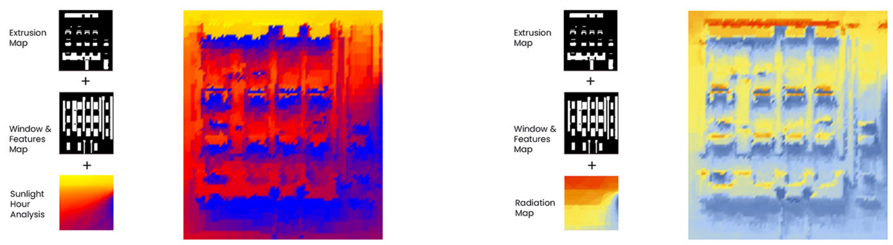
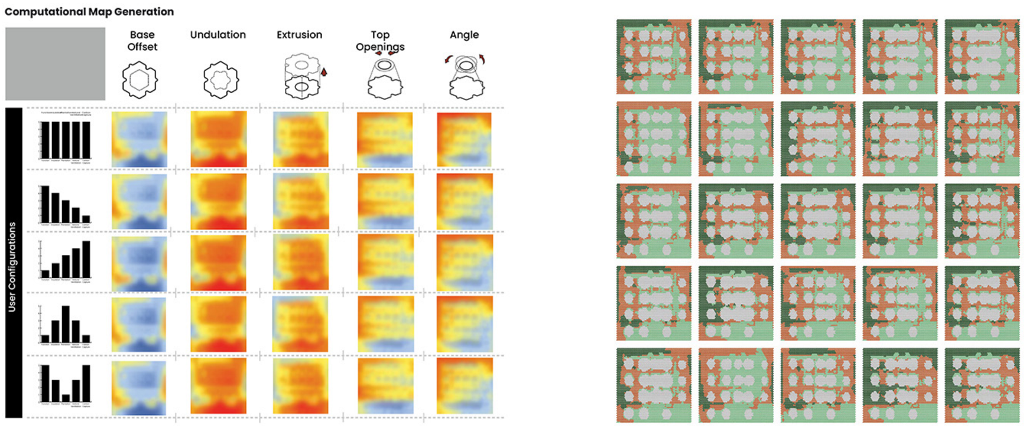


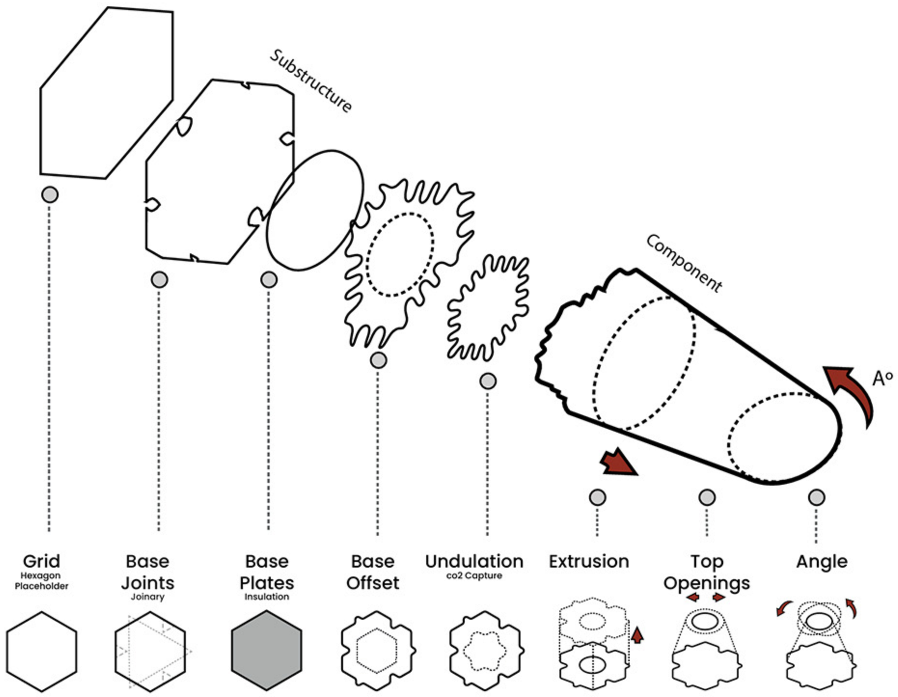
Figure 4:
Solar and Radiation Analysis maps merge with the reconstructed facade mesh which are crucial inputs to combination maps.



3.3. MODULE DESIGN AND MANUFACTURING

Using a typical London Georgian façade as our case study, the ReFront façade was generated on 3600 sampling points obtained from 250mm hexagonal grid. These points are key in both the analysis and generation of the modules' geometric parameters. The geometric output is designed in such a that promotes high performance aimed at mitigating unwanted radiation on the facades, boosting natural ventilation inside the building, and guarding against the harsh street winds, thereby ensuring the comfort of the urban public areas surrounding the building. Within the scope of this project, four distinct component types and three different types of materials were explored. The module types are following as seen in figure 6 while their properties can be review in detail in Table 2:

- Planters
- Carbon Capture module
- Moss hosting modules
- Privacy modules



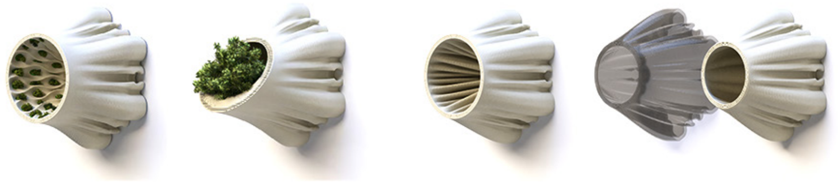


Figure 5:
Controllable parameters to affect the geometry of facade module on left and module types on right.

Aspect	Module Type/ Feature	Description	Purpose	Materials Used	Unique Features
Carbon Capture Module		Module designed with undulated surfaces to maximize carbon adsorption using Purifier PLA.	Captures atmospheric CO2 and reduces wind velocity around facades.	Purifier PLA	High surface area for carbon adsorption; strategic placement for wind deflection.
Privacy Module	HEX-WINDOW	Transparent components for window privacy without sacrificing natural light.	Ensures privacy while maintaining daylight and views.	Translucent PLA	Gradient-controlled openings using Galapagos Genetic Algorithm.
Plantation Module	HEX-PLANT	Structural module to hold and grow plants with angled top openings for biodiversity.	Promotes biodiversity and provides shading for the building.	Hempcrete and Purifier PLA	Heavy-duty design to support soil and plant weight; integrated watering system.
Moss Growth Module	HEX-MOSS	Modules with undulated surfaces optimized for moss growth in shaded regions.	Encourages biodiversity in shaded facade areas and retains humidity for moss growth.	Hempcrete and Purifier PLA	Inner shell designed to hold moss and maintain humidity; automatic placement on shaded areas.
Lattice Joinery	Lattice Joinery (Type A)	Open lattice system placed in front of balconies using the "shortest walk" algorithm for optimized positioning.	Provides structural integrity and enhances openness and ventilation.	PLA	Flexible design catering to open areas; integrates seamlessly with hexagonal grid patterns.
Wall Cladding Joinery	Type B Joinery	Joinery system affixed to building walls for structural support of facade cladding.	Provides rigid structural support for facade systems.	PLA and Steel Screws	Designed for ease of assembly with M8 screws, ensuring strong connections.

Table 2:
Summary of Different Modules used in ReFront and their properties

Each type of module is allocated in such a way in order to ensure an acceptable performance efficiency of the newly proposed façade (fig 7).

The materials explored are for the fabrication of these 3D-printed modules are:

- Purifier PLA- to adsorb atmospheric CO2 over its life, (Meduri et al., 2024)
- Transparent PLA- to counter indoor glare and boost privacy (Ashutosh et al., 2023)
- Clay-to work as a carbon negative substance that has evaporative cooling capabilities. (Mittal et al., 2006)

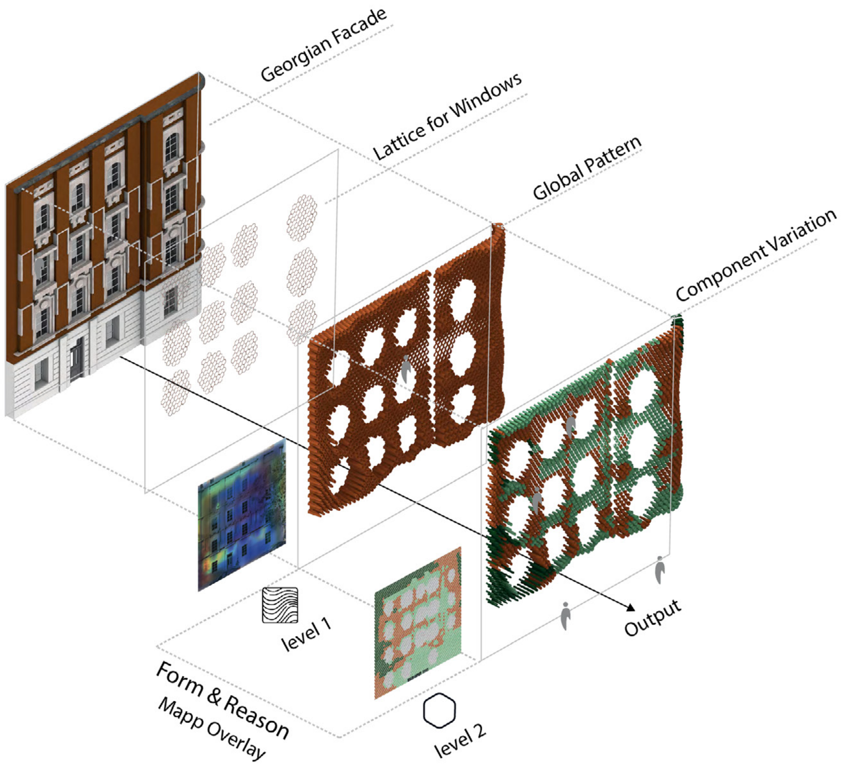


Figure 6:
Controllable parameters to affect the geometry of facade module on left and module types on right.

Further explorations were carried out in large format 3d printing to reduce print times and optimise tool paths for strength and acceptable print times. To add to the adaptability of the facade system on different types of facades in London, explorations were carried out to implement a 2D-lattice system with a certain degree of freedom to warp around the facades. The system evolved to be a non-intrusive deployable system as documented in figure 8. New types of joinery and facade mounting methods were introduced and tested for their adaptability and mechanical integrity.

Figure 7:
Experimentations with tool paths optimisation for large format printing.

The process outputs a CSV File with the serial number of each component on the building façade alongside the parameters to reconstruct the geometry of the model through the grasshopper model. Furthermore, a rhino document of mesh representations that can be saved as STL files for slicing and printing the modules using large format printing is also provided as the system's output.

4. RESULTS

The back-end process of the product was evaluated on various building facades across London. The test set was diverse and included the following: a standard Georgian building furnished only with doors and windows, a Georgian building equipped with accessible balconies to facilitate non-planar facade generation, an office building, an educational structure, and a contemporary high-performance building (Fig. 9).

The digital backend was utilized to generate facades that graced all four cardinal directions; this was done to comprehensively understand the system's adaptability to divergent insolation conditions. The behaviour of the product's backend was observed and recorded as follows in table 3.

Building Type	Georgian Residential Buildings	Bartlett School of Architecture	Georgian Houses with Balconies	Victorian Houses with Balconies	North-facing Office Buildings	Brutalist Building (Chemistry Dept., UCL)
Geographic Context	Urban areas with significant historical architecture	London, focusing on energy-intensive south-west facades	Residential areas with functional balcony needs	Residential areas with structural balcony features	Office spaces requiring natural light and privacy	Concrete buildings with minimal windows
Orientation of Façade	West	South-West	East and South	East and South	North-facing	East
Design Features	Automated context capture, 3D modeling, modular façade forms adapted to environmental needs	Seamless integration with building edges, heat reduction for sun-facing	Double wall systems integrating daylight and ventilation	Double wall systems enhancing functionality while preserving aesthetics	Translucent modules allowing daylight while reducing glare and wind	Moss modules promoting biodiversity and reducing wind impact
Simulation Focus	3D geometry adjusted for surrounding vegetation	Warping forms for enhanced aesthetics	Access to daylight and ventilation in balconies	Preservation of visual harmony while providing functionality	Urban wind counteraction, energy efficiency	Wind velocity simulations to reduce street-level wind effects
Key Components	Modular components customized for Georgian aesthetics	Lattice forms optimized with Kangaroo plugins	Planar embedded modules for flexibility	Double wall and lattice systems	Translucent and carbon-saving materials	Moss-retaining and transparent modules
Outcome	Significant adaptation for historical coherence while improving performance	Unique seamless façade for heat management	Increased liveability and energy efficiency	Improved interaction of façade and aesthetics	Balanced natural lighting and glare reduction	Respect for cultural heritage and environmental adaptations

Table 3:
Comparative adaptiveness of the ReFront algorithms and its response to different building type inputs.

A performance analysis was run on the Standard Georgian residential building model. The analysis was conducted by assuming certain parameters listed below:

1. The building program was assumed to be "Midrise Apartment".
2. The building section in the base case was with
    - One brick thick wall (230mm) and no external plaster,
    - One brick thick wall (230mm) with external plaster.
    - Aluminium section was a half brick thick wall (115mm) with glass wool insulation (75mm) aluminium plates (15mm) on the outside
    - ReFront modules with minimum depth on a half brick thick wall,
3. The glass transmittance was assumed to be 0.55
4. The climatic zone was assumed to be Cfb as per Koppen classification.(Köppen, 1884)
5. Standard thermal resistance values were assumed and the value for ReFront modules were calculated as per the depth of air-pockets trapped in them and the thickness of PLA in the walls of the module.

A 1:1 proof of concept prototype was displayed in the Bartlett School of Architecture's Autumn show 2024. The prototype experimented with custom printing profiles for large format printing and optimising print speeds and time for manufacturing this system.

Figure 8:
Testing out ReFront Algorithm on Digital twins of actual buildings in London with Variations.

Building Type	Standard Georgian Wall	Standard Insulated Wall	ReFront Hemp Wall	ReFront Air Wall
Cooling Load (kW)	1.2012	1.2975	1.26845	1.392
Heating Load (kW)	111.1488	68.8922	76.3241	65.4014
Lighting Load (kW)	11.131	11.131	11.131	11.131
Equipment Load (kW)	32.118	32.118	32.118	32.118
Hot Water Load (kW)	31.5071	31.5071	31.5071	31.5071
Operational Load (kW)	112.35	70.1897	77.59255	66.7934
Other Loads (kW)	74.7561	74.7561	74.7561	74.7561
Operational Carbon (Kg annually per sqm)	23.2643145	14.53418118	16.06708933	13.83090934
Floor area	161.2	161.2	161.2	161.2
Total Annual Operational Carbon	3750.207497	2342.910006	2590.0148	2229.542585
Total Annual Operational Carbon Saved (KG)		1407.297491	1160.192698	1520.664912
Embodied Carbon (KG)	1361	14658	-300	600
Embodied Carbon Saved (KG)		-13297	1661	761

Table 3:
Comparative adaptiveness of the ReFront algorithms and its response to different building type inputs.

Figure 9:
Comparative Energy Plus Analysis of buildings without insulation, with conventional insulation and with ReFront (left to right)

Figure 10:
Images of the ReFront proof of concept displayed at the Autumn Show 2024, Bartlett School of Architecture, UCL

5. FINDINGS, LIMITATIONS, AND FUTURE WORK

ReFront can be described as a fresh attempt to streamline the process of façade retrofitting through a user driven application. The conceptual testing of the process is promising. The impact of the solution was assessed for ReFront and summarised in a table. Compared to traditional aluminium cladding systems in the London Market, ReFront saves 89% embodied carbon and creates an impact equivalent to planting 626 trees. Other comparisons are as follows:

Category	Typical Retrofit Façade	Composite Insulated Façade	ReFront Façade Solution
Embodied Carbon	1361 kg	14658 kg	600 kg
Operational Carbon Saving	None	1400 kg/year	1500 kg/year
Circularity	No	No	Yes
Installation Time	3-4 months	2 months	12 days
Material Cost	£20/sq.m	£30/sq.m	£80/sq.m

Table 5:
Comparative analysis of performance Matrix of Facade solutions.

6. CONCLUSION

The research efforts of this paper introduce an innovative approach to building retrofitting, integrating environmental analysis, digital design, and 3D printing to create tailored façade solutions. By leveraging machine learning and parametric design, ReFront ensures that retrofitting is not only efficient but also sustainable. The success of the project in various case studies suggests that this method can be scaled across different architectural styles and regions, allowing for broad applicability in urban environments. However, challenges remain in terms of refining the CGAN's predictive accuracy and expanding the system's database to cover a more diverse range of buildings. ReFront aims to provide a forward-thinking solution to the growing demand for sustainable building retrofitting. Its innovative use of machine learning, 3D printing, and computational algorithms positions it as a key player in the global effort to reduce carbon emissions and enhance building performance. Through successful case studies and a commitment to improving the system's scalability, ReFront sets a new standard for sustainable architectural practices, making retrofitting more accessible, efficient, and eco-friendly.

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