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3D Concrete Printing for Facade Retrofitting: A Parametric Approach to Thermal and Indoor Acoustic Performance in a Residential Unit

Cagatay TAKVA[1,2,*], Sena Nur OZ[1], Huseyin ILCAN[3], Zeynep Yesim ILERISOY[2], Mustafa SAHMARAN[3]

[1]*Graduate School of Natural and Applied Sciences, Gazi University, Ankara, Türkiye*
[2]*Department of Architecture, Gazi University, Ankara, Türkiye*
[3]*Department of Civil Engineering, Hacettepe University, Beytepe, Ankara, Türkiye*

Highlights

- This study adopts an experimental and computational approach to facade retrofitting.
- Facade panels made from CDW-geopolymer material were produced through digital fabrication using 3DCP.
- Pre- and post-retrofit performance was analyzed using thermal and acoustic simulations.

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Abstract

A large share of the existing residential stock, particularly in countries that adopted mandatory thermal insulation codes relatively late, exhibits simultaneously poor thermal and acoustic performance. Although 3D Concrete Printing (3DCP) technology has been independently studied for thermal and acoustic applications, the potential to combine these two applications in a facade system constitutes a research gap. This study presents a case-study application of prefabricated 3DCP cladding panels, featuring a ribbed, geometrically complex surface texture, to the facade of a 50 m² precast Reinforced Concrete (RC) residential unit in Ankara, Türkiye, without major structural intervention. The facade panels are manufactured from geopolymer material based on Construction and Demolition Waste (CDW). A parametric workflow integrating Autodesk Revit with Dynamo-based Sabine acoustic analysis and an ISO 6946 DesignBuilder thermal simulation pipeline is employed to quantify pre- and post-retrofit performance. The 3DCP cladding reduces the composite wall U-value from 0.714 to 0.346 W/m²K (−51.5%) and lowers the mid-frequency reverberation time (RT60) from 1.54 s to 0.88 s (−42.9%), while the existing single-glazed windows are retained as a fixed boundary condition. A diagnostic sub-analysis isolates the acoustic contribution of the unchanged glazing, confirming that the 3DCP surface texture is the dominant driver of absorption improvement. The results demonstrate that 3DCP facade panels constitute a viable, multi-functional retrofit layer that simultaneously enhances thermal performance, interior acoustics, and architectural expression through a single intervention, offering a replicable methodology for performance-driven envelope renewal in the existing building stock.

1. INTRODUCTION

The built environment accounts for approximately 36% of global final energy consumption and 37% of energy-related CO_2 emissions [1]. Buildings constructed before the widespread adoption of mandatory thermal insulation codes, a substantial fraction of the existing residential stock in countries such as Türkiye, much of Southern Europe, and the broader Global South, present simultaneously energy-inefficient and acoustically deficient envelopes [2, 3]. Projections indicate that approximately 80% of buildings standing today will still be in use by 2050 [4], and operational carbon emissions account for around 75% of total building-sector emissions. Given these figures, retrofitting the existing stock rather than demolishing and rebuilding is widely recognized as the most carbon- and resource-efficient upgrade pathway: deep energy retrofits of existing structures can result in 50–75% less embodied carbon than equivalent new construction [5, 6]. Accordingly, both the European Union's revised Energy Performance of Buildings Directive (EPBD

*Corresponding author, e-mail: cagataytakva@gazi.edu.tr

2024/1275/EU) and national building codes in emerging economies are accelerating mandatory renovation rates, creating an urgent need for retrofit technologies that are technically effective, rapidly deployable, and architecturally responsive [7]. One of the areas that needs architectural retrofit and is effective in terms of thermal-acoustic performance is the facade [8].

Facade retrofitting occupies a distinctive position within this decarbonisation agenda because it addresses performance and architectural identity simultaneously [9]. A retrofit that over clads or reclads an existing skin therefore carries both an environmental mandate. Streicher et al. [10] identify deep facade retrofit as capable of reducing building energy use intensity by 80% or more when combined with systems upgrades. Procaccini and Monticelli [11] state that facades alone account for 20-30% of a building's total heat loss. From a typological standpoint, over cladding, adding a new facade layer without removing the existing skin, is gaining traction as a minimally disruptive retrofit strategy that simultaneously modernises architectural expression and improves envelope performance. Yang et al. [12] reveals that the dominant focus remains energy performance, with limited attention paid to acoustic improvement and even less to architectural expression as a co-equal design outcome. In this context, the integration of technological equipment for facade retrofitting is also important. 3DCP has potential in this regard [13].

The building facade performs multiple simultaneous roles: structural load transfer, weather resistance, thermal regulation, and acoustic attenuation. Jabłońska et al. [9] systematically categorised contemporary public building facades across European cities, demonstrating that facade character, expressed through scale, materiality, and surface articulation, is shaped by both climatic responsiveness. Similarly, Ezz et al. [14] argues that symmetry and surface organisation remain operative aesthetic principles in facade design, underscoring that formal decisions carry meaning beyond functional utility. The honest expression of structural logic, material properties, and assembly through visible form has been reinterpreted for the digital manufacturing age, integrating parametric modelling, robotic production, and environmental sensitivity as the foundation of architectural expression [15]. Within the discourse of sustainable architecture, retrofit strategies must negotiate between performance imperatives and the constraints of the existing structure, particularly with respect to added weight, fixing details, and thermal bridging at connections [16]. In addition, heating and cooling load requirements should be considered in retrofit applications on building facades. Sarihi et al. [17] highlighted that facade retrofitting can reduce energy consumption for heating and cooling by up to 50% through architectural interventions. Brito-Coimbra et al. [18] made inferences by examining studies using passive solar energy technologies in facade retrofitting applications in Portugal, a Mediterranean climate. Qi et al. [19] investigated the effect of green facade retrofitting applications on thermal performance and energy consumption in buildings under hot summer conditions in northern China, obtaining detailed data for building energy efficiency.

The architectural dimension of facade retrofitting has gained growing recognition in literature. In renovation projects, traditional exterior cladding systems homogenize the building's facade, limiting its material and formal originality. Therefore, a renovation technology capable of producing geometrically complex, textured surfaces at the panel level addresses both an architectural and environmental deficiency [20, 21]. External thermal insulation composite systems remain the dominant retrofit technology in Europe, capable of reducing wall U-values below 0.25 W/m^2K with mineral wool or EPS layers of 100-200 mm. However, these systems present a uniform, planar surface that contributes negligibly to sound diffusion or absorption at the facade surface, and they offer limited scope for geometric articulation or material honesty [22, 23]. Cladding materials such as fibre cement, terracotta, aluminium, and fibre-reinforced polymers are common options for facades, but they generally require larger air gaps, more complex substructures, and naturally do not adequately improve the acoustic performance of the interior [24, 25]. This convergence of limitations motivates the exploration of 3DCP as a material and formal system capable of simultaneously enhancing thermal performance, contributing measurably to interior acoustic absorption, and asserting a renewed architectural identity through surface geometry.

3DCP has emerged over the past decade as a transformative fabrication technology that enables the production of geometrically complex elements with high dimensional repeatability, reduced formwork requirements, and minimised material waste [26, 27]. Numerous studies have demonstrated 3DCP's potential for improving the thermal performance of building envelopes. Marais et al. [28] showed

computationally that cavity-based 3DCP wall topologies can meaningfully reduce U-values relative to solid concrete. Tamimi et al. [29] validated these improvements through in-situ U-value measurements on 3D-printed structures in the UAE. de Rubeis et al. [30] provided a comprehensive review of 3D printing strategies for thermal envelope enhancement. At the same time, a growing body of work has explored the acoustic potential of printed geometries. Setaki et al. [31] demonstrated that computationally designed, additively manufactured panels can achieve high broadband sound absorption through viscothermal wave propagation in prismatic channels. Li et al. [32] reviewed the sound absorption mechanisms of 3D-printed lattice structures, identifying surface morphology and pore interconnectivity as the dominant parameters.

Leschok et al. [33] assessed fabrication and performance methods for 3D-printed facades. Despite this parallel progress in thermal and acoustic research, the intersection of 3DCP with facade retrofitting, particularly as a dual-purpose cladding system targeting both domains simultaneously, has received limited attention, particularly as a strategy that unifies performance improvement with architectural renewal. 3DCP employs a computer-controlled extrusion head to deposit layers of printable concrete (typically with maximum aggregate size ≤ 2 mm) following a digital toolpath [34]. The process enables the fabrication of non-standard geometries without the cost premium associated with traditional formwork. Print parameters -layer height, nozzle speed, extrusion rate- directly influence the surface micro-texture, which in turn governs acoustic behaviour [32]. Shen et al. [35] fabricated 3DCP panel samples and determined the mid-frequency normal angle of incidence absorption coefficients using impedance tube tests performed in accordance with ISO 10534-2.

Literature contains limited research on the production of CDW-geopolymer facade panels via 3DCP and their application in facade retrofitting. Furthermore, there are few studies that analyse the thermal and acoustic performance of these panels together. In this context, this study aims to fill this research gap in the literature by presenting a case study of a 50 m² residential unit retrofitted with special 3DCP facade panels. The research questions of the study are as follows:
(1) Is it possible to produce facade panels that reduce carbon footprint and contribute to sustainability using CDW-geopolymer?
(2) Can the 3D-printed facade panels produced be used for facade retrofitting purposes?
(3) Are 3D-printed facade panels suitable for retrofit purposes in terms of thermal and acoustic performance?

This study sought solutions to these research questions. The study integrates architectural design, parametric BIM-based simulation, and environmental performance assessment within a unified Revit–Dynamo workflow to evaluate the multi-domain benefits of the intervention. The retrofit intervention is deliberately scoped to the facade cladding layer only: the existing single-glazed aluminium-framed windows are retained in their original condition, representing a deliberate boundary condition that reflects the most common real-world constraint in facade-only retrofit projects. The specific objectives are: (i) to design a 3DCP panel geometry optimised for over cladding retrofit application; (ii) to quantify thermal improvements via U-value calculation in accordance with ISO 6946; (iii) to quantify acoustic improvements via Sabine-based RT60 calculations implemented as custom Python nodes in Dynamo; and (iv) to characterise the contribution of the unchanged existing glazing to interior acoustic absorption, establishing a baseline for future fenestration retrofit studies.

2. MATERIALS AND METHODS

The aim of this study is to provide a facade retrofit for an existing building. In this context, a contribution to circularity in the built environment has been made by using sustainable and recyclable CDW. A geopolymer mix was obtained using CDW and combined with a 3D printer. A CDW-based geopolymer material was developed, ensuring the possibility of constructing a material suitable for 3DCP. After preparing the material for 3DCP, parametric facade panel trials were conducted. The produced panels were applied to the building's facade, completing a retrofit process. However, the developed system was supported by simulations. Building-specific evaluations were made by conducting thermal and acoustic validations and analyses. The degree of improvement achieved by integrating the facade panels into the existing building was observed. In this context, the flowchart of the study is given in Figure 1.

2.1. Case Study: the 50 m^2 Residential Unit

The study building is a single-storey residential unit of 50 m^2 gross floor area, located in Ankara, Türkiye. The existing structural shell consists of 250 mm precast RC panel walls, a 150 mm flat concrete roof slab, and a 150 mm ground-bearing concrete slab. The facade features six single-glazed aluminium-framed windows with a combined glazed area of approximately 8.4 m^2 (Figure 2). The precast RC panels are assumed to have a thermal transmittance of U = 0.714 W/m^{2}K, consistent with the TS 825:2024 reference value for uninsulated concrete precast panel walls. Prior to intervention, no supplementary insulation layer is present, and the interior finishes are unpainted concrete.

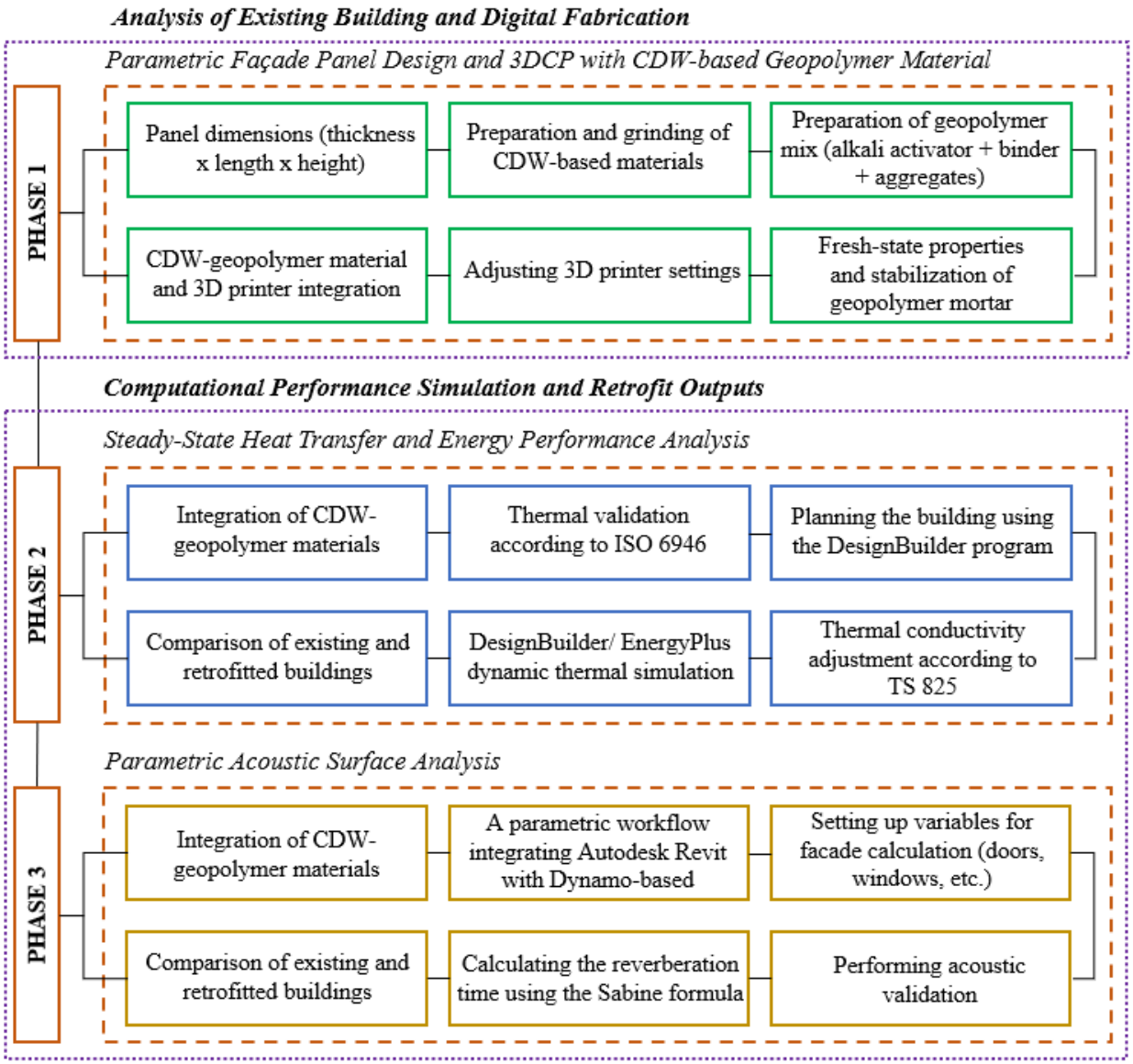


Figure 1. *Flowchart of the study addressing the retrofit process*

The building was modelled in Autodesk Revit 2025 with element-level material assignment, enabling Dynamo to access area, geometry, and parameter data through the Revit API. Two primary analysis scenarios were defined, both retaining the existing single-glazed windows as a fixed boundary condition: (A) pre-retrofit- existing precast RC panel walls, uninsulated, original windows in place; (B) post-retrofit- 3DCP facade panels applied over existing walls, original windows unchanged. A sensitivity sub-analysis was also conducted to isolate the acoustic contribution of the existing glazing, by comparing each scenario with and without the window absorption term active in the Sabine calculation. This sub-analysis is not a

design scenario but a diagnostic tool to understand how much improvement potential remains unlocked by the unchanged fenestration.

2.2. 3DCP Facade Panel Design

In this study, the 3DCP facade panels were produced using a sustainable, 3D-printable CDW-based geopolymer mixture. The detailed composition of the mixture is presented in Table 1. The binder phase consisted of CDW precursors, including powdered brick waste, concrete waste, and blast furnace slag (BFS) as an industrial by-product. The brick and concrete wastes were first crushed using a jaw crusher and subsequently ground in a horizontal mill to obtain a fine powder. These materials were activated through alkaline activation using a 5 M NaOH solution. Detailed information on these materials can be found in the authors' previously published studies [36]. Expanded perlite (particle size: 0–3 mm; bulk density: 50–60 kg/m^3) was used as aggregate to enhance the thermal insulation capacity of the mixture.



(a) (b)

Figure 2. *External views of the prototype building showing the applied facade panel system from different perspectives: (a) front facade, (b) side facade view*

Table 1. *Mixture details*

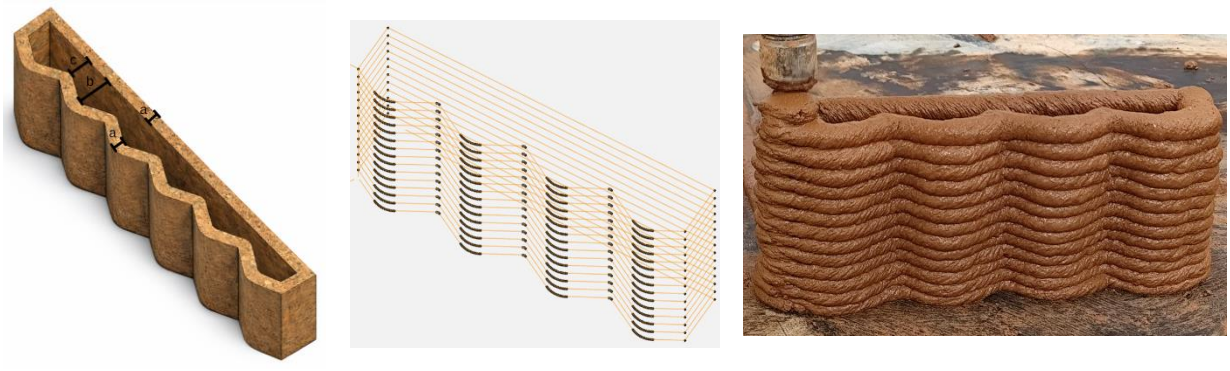
Brick Waste (g)	Concrete Waste (g)	BFS (g)	Expanded Perlite (g)	Alkaline Activator	Density (kg/m^3)	Thermal conductivity (W/mK)	
600	200	200	414.4	5 M NaOH	1549	~ 0.28	

The physical production of the 3DCP facade panels was carried out using a laboratory-scale gantry-type 3D printer with an effective printing area of 100 × 100 × 40 cm (x × y × z). The system consists of a pump, transmission pipe, CNC router, nozzle, printing platform, and control unit [37]. Detailed information regarding the printing system is presented in Figure 3. The printing process was performed at a constant speed of 50 mm/s using a circular nozzle with a diameter of 13.5 mm.



Figure 3. *Laboratory gantry-based 3D printing system*

The retrofit panels are designed as 300 × 300 mm prefabricated units, 75 mm thick at the base, with a ribbed external profile (rib height 15 mm, rib pitch 45 mm) (Figure 4). In Figure 4a, the value of 'a' is 15 mm depending on the nozzle diameter in 3DCP panels. Depending on the waveform of the parametric front surface according to the panel geometry, the value of 'b' is 45 mm and the value of 'c' is 25 mm. The rib geometry increases effective surface area by approximately 20% relative to the projected panel area, yielding the form factor of 1.2 applied in acoustic calculations. Panels are mechanically fixed to the existing wall through stainless steel brackets at 300 mm centres, providing a 25 mm air cavity that contributes to moisture management and reduces thermal bridging. In Figure 4b, the G-code data for the facade panel was obtained using ArtCAM and NC Viewer software. G-code refers to a programming language compatible with 3D printers. In Figure 4c, this coding system represents the nozzle's movement area according to the geometry of the parametric facade panel using a coordinate-based path.



(a) (b) (c)

Figure 4. *(a) Panel dimensions (a:15 mm, b:45 mm, c:25 mm), (b) G-code view of layers, (c) 3DCP result product*

2.3. Retrofitting Design

The retrofitting installation follows a coating methodology adapted for the 3DCP panel system, exhibiting a thermal and acoustic barrier effect. The procedure comprises three principal stages. In the first stage, the existing precast RC panel walls are surveyed for flatness and structural integrity, and anchor points are marked at 600 mm horizontal and vertical centres. Stainless-steel L-profile brackets (50×50×5 mm, grade 304) are then mechanically anchored to the existing wall using expansion bolts (M10×100 mm) torqued to the manufacturer's specified values. The brackets are shimmed where necessary to establish a uniform plane, providing a 25 mm stand-off that creates the air cavity between the existing wall surface and the back face of the 3DCP panels. In the second stage, the prefabricated 3DCP panels (300×300×75 mm). The feasibility of integrating 3DCP facade panels into one of the existing building's facades for retrofit purposes was also tested (Figure 5).



Figure 5. *Anchoring of 3DCP facade panels to the existing structure with L-profiles*

Each panel is secured to the L-profile brackets using stainless-steel self-drilling screws through pre-formed fixing slots cast into the panel edges during printing, allowing ±2 mm positional adjustment in the horizontal and vertical planes. In the third stage, panel-to-panel joints are sealed with a UV-resistant silicone sealant compatible with the cementitious substrate, and perimeter flashings are installed at window

reveals and parapet junctions to prevent moisture ingress into the cavity. The air gap creates a thermal barrier within the facade system, isolating the air from the external environment and creating stagnant space. The entire installation sequence for the 50 m^2 unit was completed within three working days by a two-person crew, demonstrating the rapid deployability of the system. Figure 6 illustrates the completed retrofitting assembly.



Figure 6. *Precast panel house retrofitting*

2.4. Thermal Validation

Thermal transmittance (U-value) was calculated in accordance with ISO 6946 using the series thermal resistance method. The formulas used in the analytical calculations are given in Equations (1) and (2).

$$R_{panel} = R_{si} + \frac{d}{\lambda} + R_{se} \ , \tag{1}$$

$$U_{panel} = \frac{1}{R_{panel}} \ . \tag{2}$$

The thermal conductivity of the 3DCP panel was determined experimentally: a 300 × 300 mm specimen was tested in a guarded hot-plate apparatus in accordance with EN 12664, yielding a measured thermal conductivity of λ = 0.15 W/mK. While the CDW-geopolymer material used in the facade panel has a λ value of 0.28, the λ value of the designed air-gap panel has reached 0.15. This value represents the effective conductivity of the ribbed panel cross-section, inclusive of its internal geometry. Treating the 75 mm panel as a single homogeneous layer with λ = 0.15 W/mK, the panel-level thermal resistance per ISO 6946 is:

R_panel = 0.13 + 0.5 + 0.04 = 0.67 m^2K/W,
U_panel = 1.49 W/m^2K.

The panel U-value, derived from the laboratory-measured thermal conductivity, is adopted for all subsequent simulations. The composite wall assembly (precast RC + air cavity + 3DCP panel) includes a 25 mm air gap between the existing precast RC panel wall and the 3DCP cladding (R = 0.15 m^2K/W, ISO 6946). This air gap is completely enclosed within the wall system and isolated from the external environment, in accordance with ISO 6946. In the DesignBuilder/EnergyPlus model, it is also configured in an isolated manner within the facade system. Annual space-heating and cooling energy demands were estimated using the simplified degree-day method, assuming an internal set-point of 20 °C (heating) and 26 °C (cooling), and a building envelope balance-point consistent with ASHRAE 90.1 simplified methodology. The composite wall assembly U-value was calculated analytically using the ISO 6946 series resistance method:

R_total = R_si (0.13) + R_precast (1/0.7 = 1.429) + R_cavity (0.15) + R_panel (1/1.49 = 0.671) + R_se (0.04) = 2.42 m^2K/W, yielding U_ISO_0 = 0.413 W/m^2K.

This analytical result was subsequently validated through DesignBuilder dynamic energy simulation (EnergyPlus v8.9) using Ankara IWEC weather data, which returned a simulated wall U-value of 0.346

W/m^{2}K. The 16% difference between the two methods is attributable to EnergyPlus's detailed multi-dimensional heat transfer modelling, which accounts for thermal bridging at convective effects within the air cavity that are not captured by the simplified ISO 6946 series assumption. In addition, while the formula neglects heat storage parameters such as the specific heat of materials, the thermal mass and heat storage capacity of materials are included in the DesignBuilder simulation [38].

2.5. Acoustic Validation

Reverberation time was calculated using Sabine's formula implemented as a custom Python node within a Dynamo graph linked to the Revit model. The workflow operates as follows Figure 7.

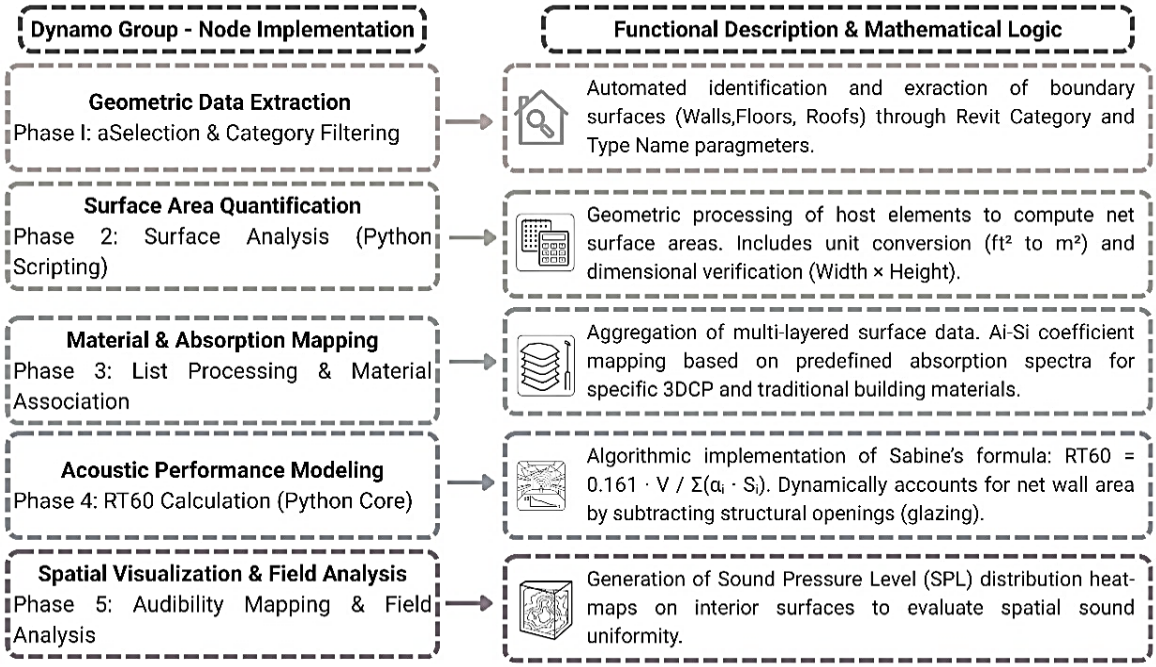


Figure 7. *Dynamo node architecture stages*

A critical implementation detail in the workflow is the treatment of the existing fixed glazing. Since the windows are retained unchanged across both retrofit scenarios, their area is consistently subtracted from the host wall area to avoid double-counting, and the glazing absorption ($\alpha = 0.03$, ISO 354) is added as a fixed surface contribution in all calculations. The window node can additionally be deactivated to isolate the wall-panel contribution alone, enabling a diagnostic comparison that reveals the acoustic headroom that would be unlocked by future fenestration replacement. Room volume is supplied as a user-adjustable number input node, set to 125 m^3 for a 50 m^2 plan and 2.5 m ceiling height (Table 2). The absorption coefficient of the Retrofitted Assembly is taken equal to that of the 3DCP panel outer face ($\alpha = 0.302$), as the panel constitutes the sole acoustically exposed surface in the post-retrofit configuration.

Table 2. *Material properties used in simulations and performance data*

Material/Assembly	Thickness (mm)	U-Value (W/m^{2}K)	α (500 Hz)
Existing Precast RC Panel	250	0.714	0.05
3DCP Facade Panel	75	1.49	0.302
Retrofitted Assembly (RC + 3DCP)	325	0.346 (simulation)/ 0.413 (ISO)	0.302

3. RESULTS AND DISCUSSION

This study investigated the feasibility of producing CDW and 3DCP facade panels on residential units, as well as their thermal and acoustic performance. The integration of facade panels in the residential unit has demonstrated that retrofit improvements to existing structures are possible in this way. In this context, prototype panels were obtained using 3DCP technology and applied to the facade of the existing building. However, thermal analytical calculations were performed based on the thermal conductivity and thickness data of the facade panels. DesignBuilder data was validated with these formulations. Additionally, acoustic data was obtained using the Revit-based Dynamo algorithm, and the contribution of these panels to improving indoor reverberation in existing structures was evaluated.

3.1. Thermal Performance

The ISO 6946 analytical calculation yields a composite wall U-value of 0.413 W/m^{2}K for the retrofitted assembly, representing a reduction of 41.1% relative to the pre-retrofit value of 0.7 W/m^{2}K. DesignBuilder/EnergyPlus dynamic simulation further validates this result, returning a film-inclusive U-value of 0.346 W/m^{2}K (−51.5% vs. pre-retrofit), with the 16% difference between methods attributable to multi-dimensional heat transfer effects modelled by EnergyPlus but not captured by the ISO 6946 series assumption. The U-value calculated through simulation meets the 0.35 W/m^{2}K limit of the TS 825:2024 standard for Ankara (4th climate zone). The U-value of prototype facade panels can initially be improved through geometric optimizations. In this regard, arranging the inner filling geometry in layers can act as additional insulation [39]. Besides geometric adjustments, improvements can also be made with additional material-specific insulation. Increasing the amount of perlite, which provides a thermal barrier, applying polyurethane foam, and using special insulating thermal paints can also reduce the U-value of the facade panel [40,41]. Reducing the U-value of the facade panel will also improve the thermal insulation of the wall structure element.

The degree-day energy estimates indicate that annual HVAC heating energy demand decreases by 47.3% following panel application, as reported by the EnergyPlus annual simulation output. Total site energy consumption falls by 15.5%, with the remaining demand attributable to internal equipment and lighting loads held constant across scenarios. Peak boiler capacity at design-day conditions (31 January) reduces by 47.3%, confirming a commensurate reduction in heating plant size requirements (Figure 8). The larger percentage reduction in heating versus cooling reflects the dominance of conductive envelope heat loss in the continental climate of Ankara.

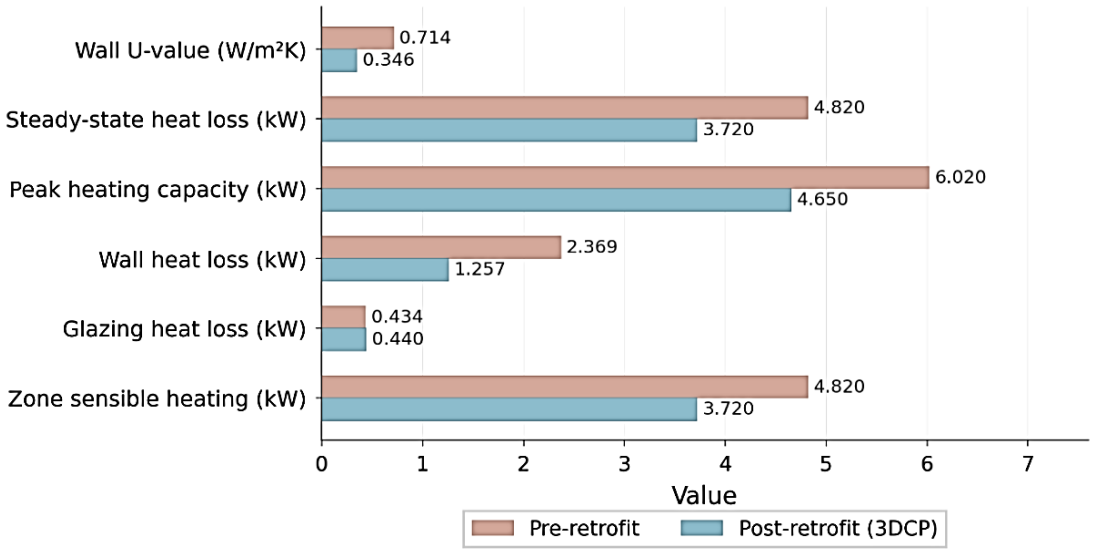


Figure 8. *Improving energy performance with 3DCP facade panels*

3.2. Acoustic Performance

Table 2 presents the RT60 results across all four scenarios. In the pre-retrofit baseline, the smooth concrete interior yields a total absorption area of 3.12 m^2 Sabine and RT60 = 1.54 s -more than twice the ISO 3382-2 upper limit of 0.6 s for speech intelligibility in a residential room of this volume.

Post-retrofit the 3DCP panels raise total absorption to 5.47 m^2 Sabine ($\alpha_eff = 0.302$ vs. 0.05 for smooth concrete), reducing RT60 to 0.88 s. While still above the ISO target, this represents a 42.9% improvement and places the room within a range that can be readily brought into compliance with the addition of soft furnishings, curtains, or a modest area of porous ceiling tiles - interventions that would be expected in any occupied residential unit (Figure 9).

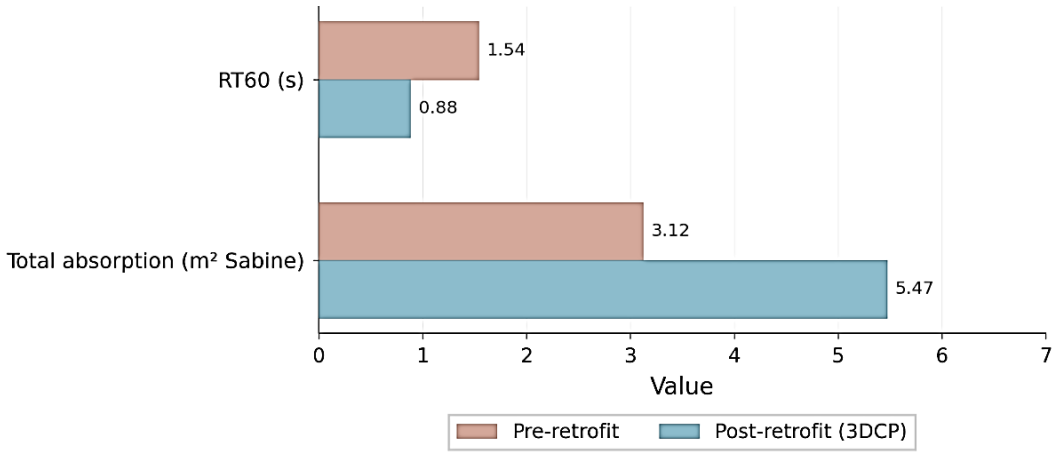


Figure 9. *Effect of 3DCP panels on acoustic performance (RT60 and total absorption)*

The existing single-glazed windows, retained unchanged in both scenarios, contribute a fixed acoustic absorption of approximately 0.25 m^2 Sabine ($\alpha = 0.03$, $S = 8.4\ m^2$). This contribution is modest but consistent: the diagnostic sub-analysis shows that deactivating the window node raises RT60 by only 0.03–0.05 s in either scenario, confirming that the dominant driver of acoustic improvement is the 3DCP surface texture rather than the glazing. The low absorption coefficient of single glazing (0.03 vs. 0.302 for 3DCP) means that even if windows were replaced with high-performance triple glazing ($\alpha \approx 0.02$), the acoustic benefit would be negligible. However, replacing single glazing with acoustic laminated glazing or secondary glazing systems could yield meaningful indoor reverberation improvements - a performance dimension orthogonal to the RT60 metric examined here, and one identified as a priority for future work.

Considering both thermal and acoustic outcomes together, the 3DCP retrofit demonstrates a genuinely multi-functional performance uplift from a single intervention layer. Conventional ETICS or mineral wool systems would achieve comparable or better thermal performance but would contribute $\alpha \approx 0.05$–0.1 to the interior - substantially less than the 3DCP panel's 0.302. Conversely, a porous acoustic absorber applied internally (e.g., mineral wool panels) would improve RT60 but provide no exterior thermal benefit. The 3DCP facade uniquely addresses both domains simultaneously, with additional value in architectural differentiation through the printed surface geometry.

The parametric Dynamo workflow enabled iterative scenario testing at negligible computational cost. Each RT60 recalculation executes in under 2 seconds within the Revit environment, allowing the designer to evaluate material substitutions, window area changes, or panel configurations without exporting data to a specialist acoustic simulation tool. This tight BIM–acoustic integration represents a methodological contribution applicable beyond the specific case study.

In addition to the thermal and acoustic properties of 3DCP facade panels, the differences between these panels and existing ones are also significant. The advantages of this innovative technology include its suitability for mass production and its ability to be manufactured in various geometric configurations, as

well as its use for facade retrofitting. These panels differ from existing facade panels due to their ability to be produced using CDW, geometric freedom, rapid buildability, and ease of installation and assembly. By reducing CDW levels, it lowers the carbon footprint, contributing to both sustainability and circularity.

4. CONCLUSION

This study investigated the application of 3DCP as a facade retrofitting strategy for a 50 m^2 residential unit in Ankara, Türkiye, evaluating both thermal and acoustic performance through an integrated Revit–Dynamo parametric workflow. The principal findings and implications are summarized below;

- The 3DCP cladding panel, with a laboratory-measured thermal conductivity of $\lambda = 0.15$ W/mK, reduces the composite wall U-value from 0.70 to 0.346 W/m^2K (DesignBuilder/EnergyPlus), corresponding to a 51.5% improvement and a 47.3% decrease in annual heating energy demand,
- The retrofitted assembly satisfies the TS 825:2024 limit of 0.35 W/m^2K for Ankara (climate zone 4), with the DesignBuilder/EnergyPlus simulation returning a composite wall U-value of 0.346 W/m^2K. Nevertheless, a modest margin of only 1.1% suggests that supplementary insulation - either within the air cavity or embedded between the panel face layers - would be advisable to ensure robust code compliance under construction tolerance and represents a priority direction for future system development,
- The ribbed surface texture of the 3DCP panels yields an effective mid-frequency absorption coefficient of $\alpha_eff = 0.302$, reducing the Sabine reverberation time from 1.54 s to 0.88 s (−42.9%). Although the post-retrofit RT60 remains above the ISO 3382-2 target of 0.6 s, the improvement places the room within a range readily achievable through the addition of soft furnishings and porous ceiling treatments typical of occupied residential interiors,
- The diagnostic sub-analysis confirms that the existing single-glazed windows contribute only 0.25 m^2 Sabine to total absorption; their replacement with higher-performance glazing would yield negligible RT60 benefit but could meaningfully improve indoor reverberation- a distinct performance dimension identified for future investigation,
- The parametric Revit–Dynamo workflow enables iterative, BIM-integrated acoustic and thermal evaluation at negligible computational cost, offering a methodological contribution applicable beyond this specific case study.

Taken together, the results demonstrate that 3DCP facade panels constitute a genuinely multi-functional retrofit layer, simultaneously addressing thermal performance, interior acoustics, and architectural expression through a single intervention. The software used for acoustic outputs has been used to observe mid-frequency reverberation behaviour. The validity of these outputs can be verified with real-time acoustic measurements of the facade system. Future work should explore hybrid panel configurations incorporating embedded insulation to achieve full regulatory compliance while preserving the acoustic and architectural advantages of the printed surface geometry.

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DECLARATION OF ARTIFICIAL INTELLIGENCE (AI) USE

When drafting the manuscript, neither generative AI agents nor large language models (LLMs) were used in any aspect of the study.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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