Nexus Network Journal
https://doi.org/10.1007/s00004-025-00832-0

NEXUS NETWORK JOURNAL
Architecture and Mathematics

RESEARCH

User Perspectives on a Fabrication-Informed Design Workflow for Non-Standard Façade Elements with 3D-Printed Formwork

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Accepted: 11 July 2025

Abstract

This paper introduces a pedagogical and practical design-oriented fabrication-informed workflow that holistically investigates user experiences within parametric co-rationalisation, emphasising fabrication-informed exploration and early-stage integration of design and making constraints. The workflow targets non-standard façade elements using ultra-high-performance fibre-reinforced concrete (UHPFRC) and 3D-printed formwork (3DPF), integrating parametric modelling and fabrication constraints to facilitate informed design decisions. Experienced computational architectural designers then tested and validated the workflow's usability and effectiveness. The analysis of their design processes and the follow-up interviews reveal how users negotiated trade-offs between geometric complexity and fabrication feasibility, highlighting shifts in constraint prioritisation. The findings are consistent with prior work on co-rationalisation and early-stage fabrication-informed modelling, but extend them by capturing user-led constraint-driven decisions within parametric settings. This study incorporates user perspectives to enhance adaptability and constraint integration, resulting in a validated and accessible workflow that supports material-informed design education and early-stage fabrication-aware exploration.

Keywords Non-standard facade design · Fabrication-informed design · Design workflow · 3D printed formwork · Ultra-high performance fibre reinforced concrete

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Published online: 28 July 2025

Birkhäuser

Introduction

The advancement of digital tools has expanded architectural design possibilities, enabling integration between design and fabrication (Carpo 2017). However, despite these innovations, translating design intent into fabrication feasibility remains challenging. Current approaches often focus on isolated aspects such as material properties or fabrication technologies, rather than integrated workflows, which limits their applicability to non-standard and geometrically complex structures (Quan et al. 2023).

Fabrication-driven design has progressed, but early-stage integration of material and fabrication constraints remains underdeveloped. Existing methods often prioritise either geometric complexity or fabrication feasibility, resulting in a disconnect between designing and producing non-standard structures (Quan et al. 2022). A unified workflow is essential to address structural performance, material efficiency, and production precision, particularly in the prefabrication of architectural element. Yet, the absence of user-centred validation and experiential feedback further restricts real-world implementation, underscoring the need for integrated and practical workflows.

Concrete has long served as a key material in digital fabrication, offering high compressive strength and adaptability for forming complex geometries (Jipa and Dillenburger 2022). With the rise of 3D printing, new opportunities have emerged for geometrically intricate designs with enhanced material efficiency (Li et al. 2022). Among these, 3DPF has demonstrated substantial advantages over conventional methods, offering up to 14 times faster production than timber formwork and nine times faster than CNC milling options (Han et al. 2020). However, achieving high geometric complexity in practice remains challenging due to concrete's flow behaviour, the need for structural integrity and reinforcement constraints (Ko 2022).

To address these fabrication challenges, UHPFRC has been introduced for pairing with 3DPF. Its exceptional compressive and tensile strength supports the production of ultra-thin, lightweight, and geometrically intricate elements without traditional steel reinforcement (Tayeh et al. 2023). Its enhanced flowability and precision make it well-suited for integration with 3DPF, enabling the production of customised and structurally sound components. Compared to conventional concrete, UHPFRC offers improved material efficiency, surface quality, and reduced curing times (Gao et al. 2022), aligning well with the goals of fabrication-informed design for non-standard façade systems. However, despite its material advantages, the application of UHPFRC often remains constrained by the reuse of classic formwork, limiting geometric complexity and design flexibility (Gao et al. 2022).

In response to these challenges, this study proposes an integrated fabrication-informed design workflow that combines UHPFRC and 3DPF. The workflow enables architects with computational expertise to explore intricate geometries while addressing complex fabrication constraints. This paper presents the first phase of this study, focusing on users' perspectives in integrating fabrication constraints within parametric co-rationalisation methods. The aim is to investigate how user experience can serve as a critical parameter in fabrication-informed workflows, particularly in balancing design complexity and fabricability.

The novelty of the proposed workflow lies in two aspects: (1) the early-stage embedding of fabrication and material constraints directly into parametric modelling, and (2) the incorporation of user-participatory validation to capture real-time constraint negotiation and decision-making behaviours. While prior research has addressed co-rationalisation and fabrication-aware form-finding, few studies foreground the role of user adaptation and constraint management as observed through empirical testing. To this end, the study examines how users dynamically negotiate between geometric ambition and fabrication limitations within the proposed workflow. Specifically targeting non-standard façade elements, the workflow integrates form generation and constraint evaluation early in the design process to support more informed decisions.

The target users of this study include architectural designers and students with foundational knowledge in computational design. The study evaluates the workflow with five participants who have knowledge in digital design and fabrication, though not necessarily with prior experience in UHPFRC or 3DPF. A design task was conducted with participants of varying computational expertise levels, from medium to advanced. Their design processes were observed and analysed to understand how they navigated fabrication limitations and design trade-offs. This investigation assesses the usability and adaptability of the proposed workflow, particularly in how participants responded to material and fabrication constraints. The study contributes practical strategies for enhancing workflow adaptability, supporting parametric decision-making, and developing flexible digital design tools for non-standard architectural applications.

Research Context

To contextualise the proposed study, this section reviews three key areas of existing research: fabrication-informed design methods, design-to-fabrication workflows, and the integration of 3DPF with UHPFRC. These domains collectively inform the development of advanced architectural workflows, while also revealing existing limitations in how design complexity and fabrication constraints are negotiated—particularly from a user-centred perspective.

Fabrication-Informed Design and Rationalisation Techniques

Fabrication-informed design methods ensure constructability and geometric flexibility by integrating fabrication constraints into design processes. A key approach, rationalisation, enhances the feasibility of freeform geometries through systematic optimisation. Glymph and Whitehead introduced pre-rationalisation and post-rationalisation as two distinct strategies (Lindsey 2001; Whitehead 2003): pre-rationalisation incorporates fabrication constraints during initial design phases, while post-rationalisation adapts completed designs for constructability using computational tools (Attar et al. 2010; Dritsas 2012).

In pre-rationalisation, research has explored the integration of fabrication simulations into freeform geometry modelling, focusing on real-time geometry evaluation tools and ruled surface applications (Flöry et al. 2013; Pottmann et al. 2015; Deng et al. 2015). In post-rationalisation, studies have developed G-code for fabrication methods, such as milling, tailored to different geometries (Bermano et al. 2017; Louth et al. 2017; Tam et al. 2018; Koronaki et al. 2023; Baghi et al. 2022), demonstrating the potential of computational tools in optimising fabrication processes.

Beyond these, co-rationalisation extends rationalisation through continuous refinement using parametric modelling (Fischer 2007; Ceccato 2011). Pigram et al. (2016) emphasised the role of feedback loops in integrating design, fabrication and assembly dynamically. Austern et al. (2018a) introduced a taxonomy of parametric rationalisation techniques, later developing a Rhino/Grasshopper plugin to assess concrete mould fabrication feasibility (Austern et al. 2018b). Grobman (2018) and Stieler et al. (2022) proposed methodologies for early-stage evaluation of fabrication constraints in prefabrication, supporting mould-making techniques such as milling and hot wire cutting.

Co-rationalisation, as an iterative process, balances constraints with design evolution. Despite its theoretical significance, empirical research on how designers navigate parametric co-rationalisation in design-to-fabrication workflows remains limited. This underscores the need for workflows that bridge theoretical advancements with practical usability, addressing both design complexity and fabrication feasibility.

From Toolchains to Interactive Design-to-Fabrication Workflows

The digital workflow in architecture transforms how architects design, builders construct and the industry operates. Marble (2012) introduced "Designing Design," emphasising the shift from siloed processes to integrated systems that align design, construction, and production through digital tools. Research has developed practical design-to-fabrication workflows to address fabrication challenges. Bechthold et al. (2011) applied robotic fabrication to ceramic shading systems, while Costanzi et al. (2018) explored 3D concrete printing on flexible moulds for freeform structures. Larsen and Aagaard (2019) combined material scanning, CAD and robotic manufacturing for irregular sawlogs whereas Naboni et al. (2019) introduced a computational workflow integrating material testing and production management. Casucci et al. (2020) developed a funicular structure workflow using the Half-Edge mesh data structure for robotic fabrication. While these approaches connect digital design and fabrication, they often follow linear processes, lacking real-time interaction between fabrication constraints and design parameters.

Recent studies explore interactive workflows that integrate fabrication feedback into initial design. Gupta et al. (2020) developed an iterative workflow for knit membrane tensegrity shells, incorporating simulation-driven design, CNC knitting, and assembly rationalisation, validated through a 4 m-diameter pavilion prototype. Taher et al. (2023) introduced an additive manufacturing workflow for clay-based components, automating fabrication and testing through prototyping. Heywood and Nicholas (2024) proposed a 3D concrete printing workflow, integrating optimisation, analysis, and fabrication tools. Applied to the Hybrid Slab case study, it explored material, geometric, and assembly strategies for hybrid construction. While these workflows enhance efficiency and design flexibility, challenges persist in validating their practical applicability in architectural projects.

Raspall (2015) emphasised the need to align research around common methodologies, positioning design-to-fabrication workflows as a distinct academic discipline, particularly in education. He highlighted their pedagogical value in bridging digital design and physical production. However, despite advancements, research on multi-case and user-centred workflow remains limited, underscoring the need for further practical implementation studies.

Beyond technical integration, the accessibility of design-to-fabrication workflows across varying levels of expertise has emerged as a critical dimension in contemporary architectural discourse. Kolarevic and Duarte (2018) argue that mass customisation, enabled by digital technologies, offers not only geometric and formal variability but also the potential to democratise design. This requires workflows that can serve both expert users and those with limited computational experience. Accordingly, user-friendly systems that translate fabrication constraints into intuitive design parameters are essential for supporting wider adoption.

Material-System Integration: 3DPF and UHPFRC for Non-Standard Concrete Elements

The application of 3DPF for concrete has significantly expanded design possibilities, enabling precise and large-scale formwork production and reducing fabrication time (Jipa and Dillenburger 2022; Li et al. 2022). Polymer-based 3DPF achieves a speed up to 14 times faster than timber and 9 times faster than CNC-milled formwork, making it adaptable to various applications, from desktop prototypes to robotic gantry systems (Han et al. 2020).

Early projects, such as Cellular Fabrication (Boyd IV and Disanto 2017), integrated polymer extrusion for formwork and reinforcement, while advancements in precision formwork—exemplified by the Concrete Canoe (Burger et al. 2020) and Funicular Slab (Jipa et al. 2019)—demonstrate 3DPF's role in reducing material waste and optimising concrete use. However, reinforcement integration and geometric constraints remain key challenges. The layer-by-layer printing process limits cantilever angles, while hydrostatic pressure from wet concrete necessitates staged casting, complicating reinforcement placement. Addressing these issues is essential for scaling 3DPF in architectural applications.

UHPFRC offers solutions to reinforcement challenges in 3DPF-based workflows (Gao et al. 2022). Its high strength and durability enable thinner, more efficient structures (Tayeh et al. 2023), while rapid curing supports faster prefabrication cycles (Fan et al. 2024). Notable applications include prefabricated UHPFRC façades, such as the Musée des Civilisations de l'Europe et de la Méditerranée and Stade Jean Bouin, where lightweight and complex panels enhance structural and aesthetic performance (Azmee and Shafiq 2018; Yoo and Yoon 2016). Digital fabrication advancements have further expanded UHPFRC's applications, as demonstrated in 3D-printed UHPFRC walls at the Ou-River Crystal Boxes Restaurant (Antistatics 2019). Despite its advantages, traditional formwork restricts UHPFRC's geometric complexity, resulting in repetitive and 2.5D-curved designs. Integrating 3DPF with

UHPFRC enables the fabrication of highly customised ultra-thin freeform elements, eliminating formwork constraints and enhancing efficiency. By bridging material and fabrication considerations, this integration fosters a more flexible and sustainable approach to concrete component production.

While significant advances have been made in fabrication-informed and material-based workflows, existing studies rarely address how designers interact with these systems in practice. The reviewed studies highlight a lack of empirical investigation into user-centred validation in relation to adaptation, constraint negotiation and workflow usability. These limitations form the basis for the present study, which foregrounds user experience within a fabrication-informed design workflow.

Methodology

In response to the identified gaps, this section introduces the proposed workflow and outlines the methodological framework developed to evaluate it.

Proposed Fabrication and Material-Informed Design Workflow

The proposed workflow integrates parametric co-rationalisation, empirical validation, and design exploration to address fabrication and material constraints systematically. By incorporating predefined fabrication parameters, the workflow ensures modular façade feasibility. As shown in Fig. 1, the process unfolds in three stages: Conceptual Design, Fabrication-Informed Design, and Application Assessment.

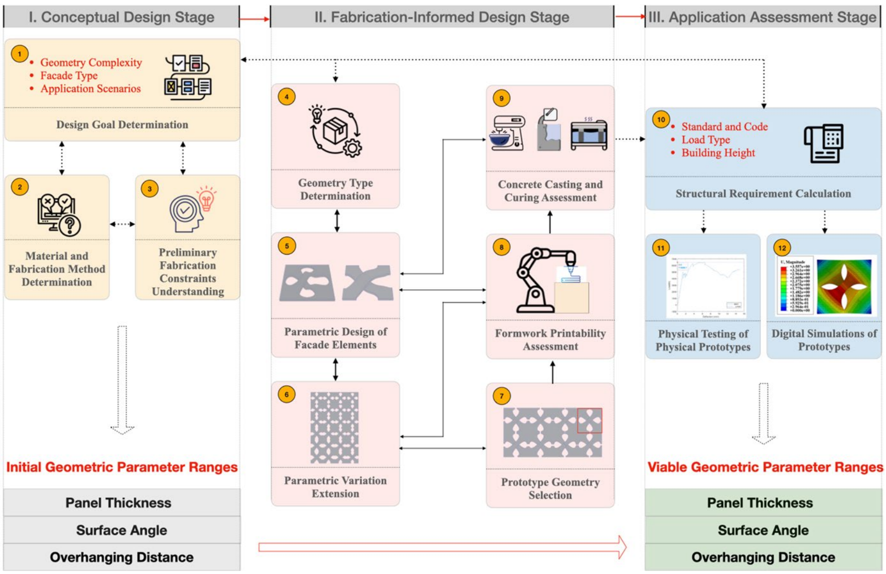

Fig. 1 Proposed fabrication and material-informed design workflow

The Conceptual Design Stage establishes the design framework, beginning with design goal determination, defining geometric complexity, façade typology, and application scenarios. Material and fabrication method selection introduces preliminary fabrication constraints, providing a foundation for material performance and manufacturing limitations. Initial geometric parameters—such as panel thickness (25–60 mm), surface angles (45°–135°), and overhanging distances (up to 5 mm)—were defined based on theoretical fabrication constraints informed by material properties and robotic printing capabilities. These values were subsequently refined through iterative prototyping and physical validation.

The Fabrication-Informed Design Stage represents the core of the proposed methodology, where iterative parametric modelling integrates fabrication considerations. Geometric variations are explored by systematically adjusting initial parameters, allowing for an adaptive refinement process that ensures fabrication feasibility. Following the parametric design phase, fabrication feasibility is assessed through an iterative prototyping process, involving two key steps. First, 3D printing of formwork evaluates geometric parameters such as angles and overhangs, with surface angles ranging between 30°–150°, assessing their compatibility with predefined fabrication constraints. Second, the selected material for casting the façade modules was UHPFRC, chosen for its high strength, thin-section casting capability (down to 25 mm), and compatibility with 3DPF. UHPFRC casting and curing within the printed formwork further validate the feasibility of the proposed geometries.

The Application Assessment Stage ensures structural viability through digital simulations and physical testing. Load-bearing capacity and material efficiency are evaluated under real-world conditions, with panel thicknesses validated in the range of 20 to 25 mm. By integrating material constraints, parametric flexibility and iterative validation, the workflow generates final viable geometric parameter ranges for angles, thickness and overhang distances.

Participant Description

Participants were selected with expertise in parametric design and digital fabrication to ensure alignment with the objectives of the fabrication-informed workflow. Eligible participants were required to demonstrate practical experience in computational design and robotic 3D printing. Five participants, representing the intended user group of architectural students and professionals, possessed both academic knowledge and practical experience, enabling critical evaluation of the workflow's adaptability to real-world scenarios. The number of participants aligns with established practices in exploratory design research, where small and targeted samples enable in-depth qualitative analysis. This size allowed for detailed observation while ensuring diversity in design approaches and skill levels. Data saturation was observed through recurring behavioural patterns and feedback themes.

The classification into "intermediate" and "advanced" expertise groups was based on a their self-assessment. Intermediate users indicated foundational understanding but limited direct exposure to the specific tools and workflows applied in this study. Advanced users reported extensive experience with computational design tools and fabrication methods, demonstrating proficiency in applying these techniques to practical design and fabrication scenarios.

Experiment Procedures

This study employs design experiments and observational analysis to examine how architectural designers interact with the proposed workflow. The experiments focus on design intent, constraint-handling strategies, and usability challenges.The procedure comprises four main steps.

First, ethics approval was obtained from the university's research ethics committee prior to participant recruitment. Second, five participants were provided with a design brief and had the option to use a pre-structured Grasshopper script or develop independent parametric solutions. Each participant then completed a one-hour design experiment during which their design processes were observed and recorded. The one-hour timeframe was informed by pilot trials, which demonstrated that participants could complete full design iterations and meaningfully reflect on constraint negotiation within this period. Although not aimed at exhaustive optimisation, the duration was sufficient to capture authentic decision-making under defined fabrication constraints. Additional time was permitted where necessary to accommodate different working styles. Third, semi-structured interviews were conducted to elaborate on design decisions and constraint integration. Finally, the collected data were analysed to evaluate the workflow's strengths, limitations and user experience.

Data Collection

The data collection process involved direct observation of participants' interactions with the workflow during the design tasks. All design steps in Rhinoceros and Grasshopper were screen-recorded, and participants' hand drawings and sketches were scanned and collected. Observations were documented in written field notes, focusing on participants' design strategies, constraint negotiation behaviours and adaptation processes. Following task completion, semi-structured interviews were conducted to capture participants' reflections on workflow usability, perceived constraints and design decision-making. Interview transcripts were analysed using thematic coding to identify recurring patterns and critical insights related to fabrication-oriented reasoning and constraint management.

Computational Setup

Participants used Grasshopper integrated with Rhinoceros 3D to construct parametric models, with control over geometric variables such as panel dimensions, curvature, surface thickness and overhang angles. Participants were permitted to use any Grasshopper plug-ins they were familiar with.

Design Brief for Participants

The design task builds upon the authors' previous empirical design explorations, applying the workflow to modular freeform UHPFRC façade elements fabricated using 3DPF. Fabrication constraints were summarised into key design guidelines, ensuring alignment with material and production considerations.

Façade and Geometry Types in Design Tasks

The modular façade system is designed as a secondary façade integrated into a glazed curtain wall. Each 1 × 1 meter module forms a repeating unit that complements the primary structure. As illustrated in Fig. 2, three variations of modular façade elements were presented, demonstrating geometric diversity in elevation, perspective, and sectional views.

This design draws inspiration from Erwin Hauer's modular structures of the 1950s, which pioneered double-curved geometries characterised by interconnected voids and seamless surfaces. Hauer's designs, originally applied to interior screens, have since been adapted for façades due to their dynamic light-filtering effects and structural integrity. However, despite advances in digital fabrication, reproducing such geometries remains challenging due to complex curvature and fabrication constraints. Building upon these principles, the design task employs a geometric typol-

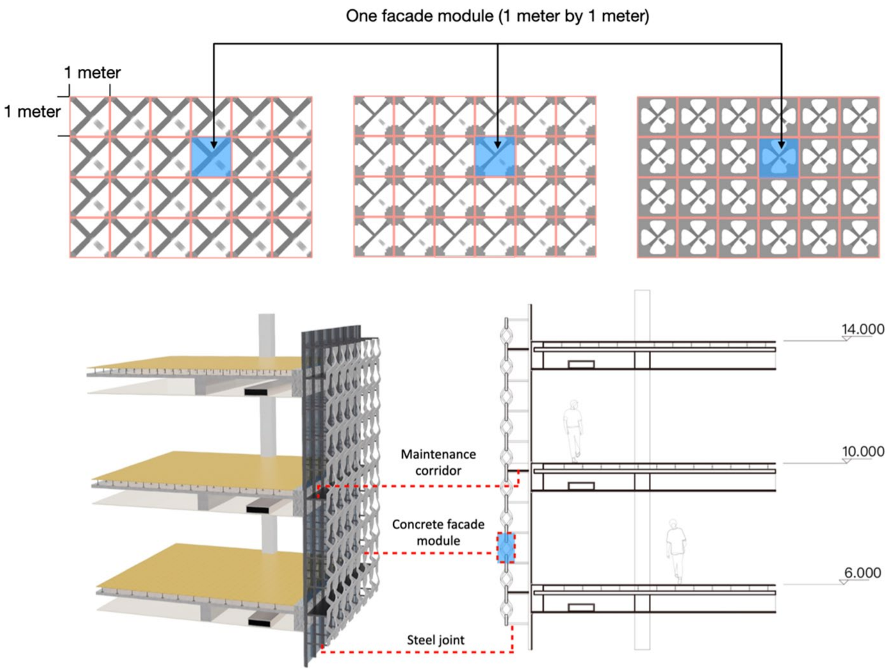

Fig. 2 Façade type and design case applications

ogy suited to modern façade systems and advanced fabrication methods. The selected geometries incorporate:

- Double-curved surfaces, which enhance aesthetic fluidity and structural performance.
- Planar Boundaries and Arched Elements, which facilitate modular integration while adding depth and architectural interest.

Dimensional Limitations Informed by Materials

The modular façade elements adhere to a 1-meter standard size with a minimum accepted thickness of 25 mm, a constraint derived from UHPFRC properties. The use of ultra-short and thin fibres in UHPFRC eliminates the need for traditional reinforcement, enabling ultra-thin yet structurally robust components. However, elements below 25 mm thickness may result in uneven fibre distribution, compromising mechanical performance. Thus, this minimum threshold ensures both structural integrity and geometric flexibility.

Angular Limitations Informed by Fabrication

Geometric limitations related to angle printability are critical to the feasibility of robotic 3D printing. Standard layer-by-layer 3D printing systems typically operate within a 45°–135° range (Hanon et al. 2021), as illustrated in Fig. 3 with reference to Angle A and Angle B. However, in this study, through adjustments to layer thickness and printing speed, the feasible range was extended to 30°–150°, as shown in Fig. 4. Experimental trials demonstrated that printing at angles even below 30° is possible, but the resulting surface quality significantly deteriorates when angles fall below this threshold.

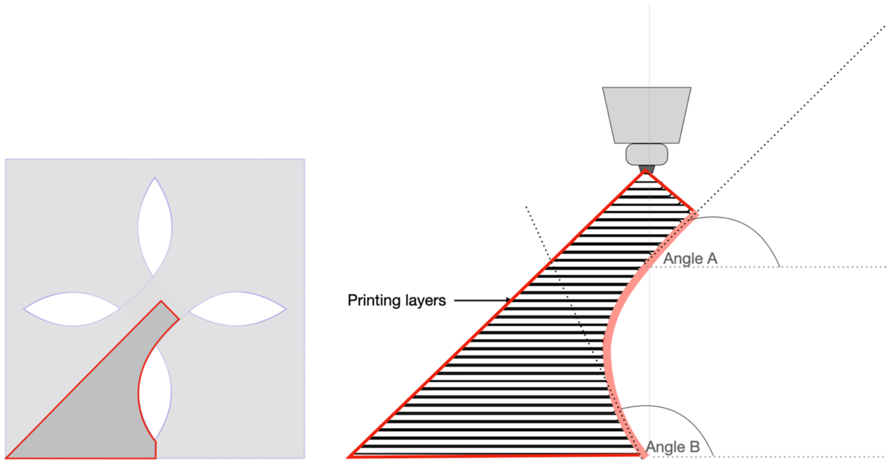

Fig. 3 Printability of the geometric angle

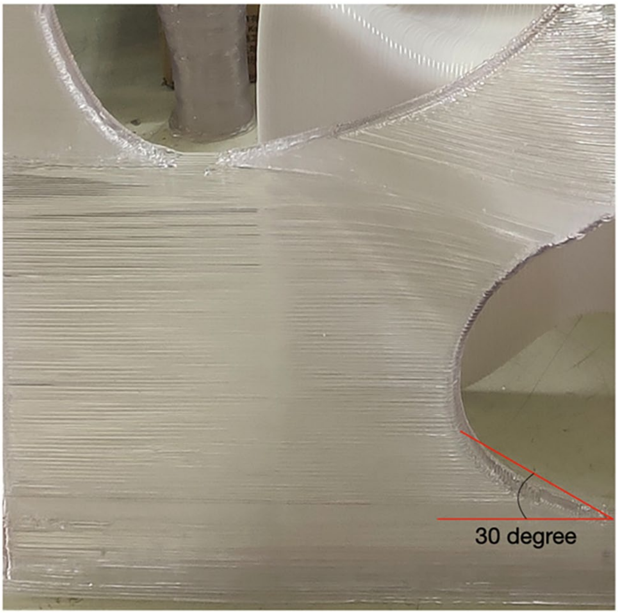

Fig. 4 Printability of the geometric angle

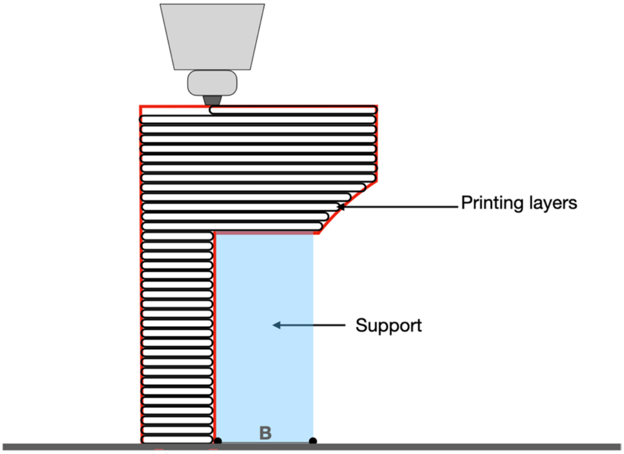

Fig. 5 Printing supports

Therefore, the following constraints were established to ensure print quality and structural reliability:

- Angle A ≥ 30° prevents sagging during printing.
- Angle B ≤ 150° maintains structural stability and avoids excessive overextension.

These constraints ensure geometric variability while maintaining printability.

Overhanging Geometric Limitations Informed by Fabrication

Overhanging geometries in 3DPF require support structures to maintain stability during printing. Supports are necessary under conditions illustrated in Fig. 5, demonstrating how supports interact with various overhanging geometries.

- Overhangs (Distance B) < 5 mm ensures structural integrity by preventing collapse or distortion.

Applied User-Centric Validation of the Fabrication-Informed Workflow

With the workflow structure and experimental setup established, the following section presents how users engaged with the design tasks and navigated fabrication constraints in practice.

Design Task

The experiment began with a 10-minute orientation session, during which participants reviewed and signed an information sheet outlining the task details and ethical considerations. This was followed by a 20-minute familiarisation phase, providing participants with an opportunity to review the task, understand the design scripts, and select appropriate tools. Before beginning the main design tasks, participants were provided with a detailed design brief as well as design cases developed by the authors.

The recommended design procedure outlined four steps: Step 1—Review the fabrication and material constraints presented in the design brief; Step 2—Develop a modular façade geometry that incorporates shading functionality; Step 3—Create variations of the proposed module geometry; and Step 4—Identify viable parameter ranges that align with the design objectives and fabrication constraints described in the design brief. Participants were given 1 h to complete the task, focusing on integrating fabrication constraints and addressing both technical and conceptual challenges. The provided Grasshopper script served as a starting point, offering participants the opportunity to refine the design or create custom scripts tailored to their ideas.

Provided Design Cases

Participants were provided with six modular design cases and their corresponding Grasshopper scripts, developed using the proposed design workflow. As illustrated in Fig. 6, these cases highlight three key aspects: the modelling sequence of modular units, geometric variations within a single module, and modular tessellation feasibility for façade applications. The cases were designed based on four primary criteria: Parametric Controllability, Geometric Complexity, Printability, and Modular Connection, ensuring alignment with both fabrication and application requirements.

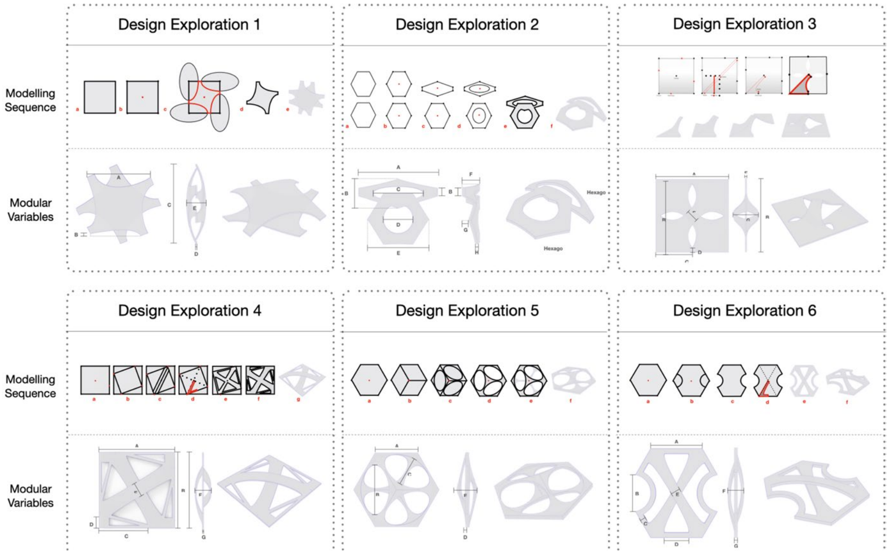

Fig. 6 Modular geometric design cases

- *Parametric Controllability* measures the variability in geometric parameters, reflecting the module's flexibility and adaptability.
- *Geometric Complexity* evaluates adherence to design criteria, such as double-curved surfaces and arched elements.
- *Printability* examines the type and quantity of supports needed for fabrication, distinguishing between customised and regular temporary supports.
- *Modular Connection* assesses the feasibility of connections, considering self-supporting and the practicality of assembling modules into larger façade systems.

To illustrate the assessment criteria, Design 3 is examined in detail. As shown in Fig. 6, it features seven controllable geometric parameters, indicating high parametric controllability. The combination of planar and 3D arched geometries categorises it as medium complexity. In terms of printability, six removable temporary supports are required, with no customised supports needed due to their controlled curvature. Lastly, for modular connection, Design 3 employs a planar flat connection, enhancing efficiency in installation within a primary façade system.

Participants' Design Result Analysis

Table 1 presents an overview of the design decisions made by each participant, focusing on how they addressed key fabrication constraints. It also records whether the final geometry complied with the design brief and how each participant approached modularity and assembly patterns.

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Table 1 Summary of participants' design decisions, constraint-handling strategies, and alignment with the design brief

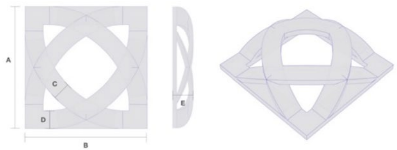
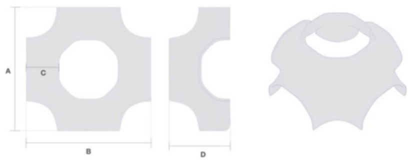
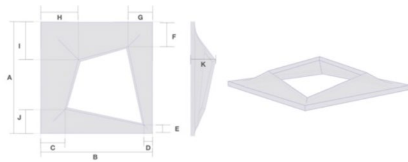
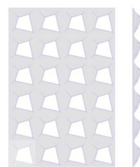
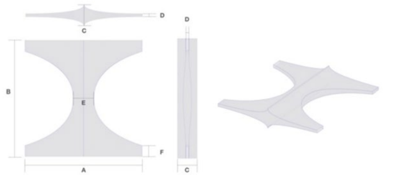
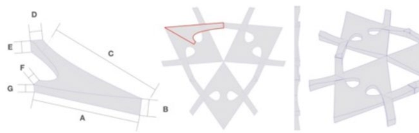
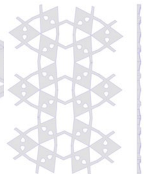
	Geometry complying with design brief	Thickness control strategy	Surface angle control strategy	Strategies to minimise the number of supports	Modular geometry and variables	Modular connection method
1	Yes	Extrude planar boundary and arches evenly, with two adjustable thicknesses	Modify curvature of four double-curved arches to suit printability	Implement custom supports for the bottom part of two arches		
2	No	Extrude the integral surface evenly, with one adjustable thickness	Modified threshold in Kangaroo solver for printability	Mainly control the angle around 45 degrees		
3	Yes	Extrude the integral surface evenly, with one adjustable thickness	Define four corners' angles separately	Selected viable angles for lower geometry only		

Table 1 (continued)

	Geometry complying with design brief	Thickness control strategy	Surface angle control strategy	Strategies to minimise the number of supports	Modular geometry and variables	Modular connection method
4	No	Applied gradient thickness between maximum and minimum limits	Modelling logic aligned with 45-degree printability limitations	Controlled angles around 45 degrees for support minimisation		
5	No	Applied gradient thickness between maximum and minimum limits	Modelling logic aligned with 45-degree printability limitations	N/A		

larity and assembly patterns. The design files were uploaded to GitHub, which can be accessed through the link provided in "Appendix 2".

Participant 1 fulfilled the design brief requirements by using a consistent thickness for extruded boundaries and arches, adjusting surface curvature to improve printability. However, the design still required custom supports for parts of the geometry. Participant 2 explored a non-compliant geometry, prioritising simplified extrusion with consistent thickness and angle control around 45°, using solver-based optimisation to enhance printability. Participant 2 reflected, 'My priority was getting a form that would print reliably without too many supports.'

Participant 3 followed the required geometry type and adapted each corner angle individually to stay within printable ranges, applying selective optimisation for lower regions to avoid excessive supports As Participant 3 noted, 'It was important to adjust each corner independently—even small angle differences affected whether supports were needed or not.' Participants 4 and 5 employed gradient thickness strategies, varying the thickness across surfaces to improve structural efficiency. While their geometry diverged from the original brief, their printability-focused modelling logic and angle constraints (around 45°) aimed to reduce the need for additional support structures. Participant 5 noted, 'It was hard to get the geometry to behave—I spent a lot of time trying to make the surfaces connect cleanly without warping.'

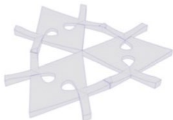
Overall, the table demonstrates how participants employed fabrication-informed strategies to negotiate between design intent and fabrication constraints, revealing both the versatility and current limitations of the proposed workflow in addressing printability and geometric complexity. The diversity of design approaches across participants underscores the workflow's adaptive potential, while also exposing specific challenges—particularly in support reduction techniques and the precision of parametric control.

Participants' Design Procedure Analysis

Participants' design procedures were analysed through observations and semi-structured interviews to assess their strategies for addressing material and fabrication constraints. Observations focused on design decision-making, while interviews explored constraint integration, challenges, and the impact on flexibility (see "Appendix 1" for interview questions).

As summarised in Table 2, participants with advanced expertise (1, 3) adopted structured parametric workflows, incorporating constraints early. Table 2 includes distinctions of which design steps explicitly addressed fabrication or material constraints. Participant 1 focused on curve generation, surface extrusion, and parametric refinement, while Participant 3 emphasised boundary definition and material distribution to balance geometric complexity and feasibility. Intermediate participants (2, 4, 5) employed alternative approaches. Participant 2 optimised curvature and angles using the Kangaroo solver, ensuring printability. Participant 4 successfully integrated curvy surfaces with fabrication constraints, whereas Participant 5 struggled with non-coplanar surface formation. This structure clarifies the role of constraint-responsive strategies in the design sequence, supporting a transparent evaluation of procedural effectiveness. While the workflow provided structured guidance, challenges in geo-

Table 2 Analysis of design procedure

	Designed geometry	Self-assessed expertise	Main design steps (with constraint-related actions annotated)	Design flexibility influenced	Challenges	Workflow impact and flexibility
1		Advanced	1. Establish the foundation and diagonal division (to align module layout with formwork constraints); 2. Curve generation (ensures double-curvature within printable surface angles); 3. Surface extrusion; 4. Mirroring and integration; 5. Refinement of arches (adjusted curvature for support minimisation); 6. Parametric adjustments	No	Modelling surfaces extrusion from complex curves and Boolean calculations	Integrated constraints at early design stage Adjusted curvature and thickness parameter Tested with supports
2		Intermediate	1. Define the bounding box; 2. Explode and offset (calculated printable angles for surface boundaries); 3. Surfaces join; 4. Set the Kangaroo solver (evaluated sagging using form-finding); 5. Array, extrude and define thickness	No	Precisely adjusting curvature and angles in Kangaroo solver algorithms	Curvature refinement via form-finding Defined angle and minimum thickness thresholds
3		Advanced	1. Establish the foundation; 2. Define outer and inner boundaries (aligned with printability constraints); 3. Establish module depth and thickness; 4. Adjust curvature and angles (targeted 30°–150° for printing feasibility)	No	Completing the façade geometry design within the 1.5-hour timeframe	Full design parameter mapping Refined angles and curvature for support reduction
4		Intermediate	1. Define a square and offset its boundary; 2. Generate curves from polylines; 3. Generate flat surface; 4. Define curvy surfaces (adjusted curvature within printable limits); 5. Surfaces join	Yes	Generating the anticipated curves and curvy surfaces	Achieved flexibility in surface shaping Early constraint alignment in design process
5		Intermediate	1. Analyse provided script examples; 2. Establish module boundary; 3. Join side surfaces and determine corner heights (adjusted to minimise height offset); 4. Establish the solid 3D geometry	No	Generating surface formation problem of non-coplanar points	Set parameter ranges manually Faced challenge with geometry alignment

metric complexity and fabrication feasibility remained. Participants emphasised the need for real-time feedback tools to enhance constraint evaluation and design adaptability within fabrication-informed workflows.

Discussion

The variations in participants' approaches highlight opportunities and challenges in fabrication-informed design, particularly in balancing geometric flexibility with fabrication constraints such as printability and support reduction. Participants who prioritised geometry type (e.g., Participants 1 and 3) encountered difficulties in minimising support structures due to their complex designs. Conversely, those who focused on gradient thicknesses (e.g., Participants 4 and 5) deviated from strict geometric parameters to optimise material properties and ease of printing. These findings underscore the challenges of managing conflicting parameters in parametric workflows, emphasising the need for clearer strategies to integrate multiple constraints. This highlights the need for adaptable toolsets that can assist architects in real-time decision-making, particularly when balancing design ambition with printability. The insights are directly applicable to early-stage façade design, where understanding trade-offs between surface articulation and manufacturability can prevent costly rework and material waste.

Participants addressed fabrication and material constraints at different stages of the design process. Advanced users tended to incorporate constraints early, enabling better parametric control over curvature, thickness, and other geometric parameters. In contrast, intermediate users often introduced constraints during or after form generation, leading to challenges in managing double-curved surfaces and ensuring precision in curvature and angle modifications. Late-stage constraint integration also resulted in issues such as non-coplanar surface formation, reinforcing the importance of early constraint consideration to streamline workflows. These findings are consistent with prior work on co-rationalisation (e.g. Pigram et al. 2016) and early-stage fabrication informed modelling (Austern et al. 2018b), but extend them by capturing user-led constraint negotiation in parametric settings. The results reinforce the study's objective of evaluating user strategies and highlight the workflow's practical relevance across different levels of computational proficiency.

The proposed workflow effectively guided constraint integration, supporting curvature and thickness definition while facilitating the strategic use of computational tools. However, findings indicate a need for automated tools and user-centric features to reduce computational effort and improve accessibility, particularly for less experienced users. Compared to existing fabrication-informed workflows that prioritise geometric feasibility or scripting complexity (Austern et al. 2018a; b; Grobman 2018; Stieler et al. 2022), the proposed workflow integrates empirical feedback and participatory input to support the analysis of user experience. By capturing how users iteratively align geometry with fabrication logic, this approach facilitates more intuitive trade-off resolution than fixed parametric scripts or purely simulation-based tools. This directly supports the objective of evaluating fabrication feasibility handling in early-stage design, and expands upon co-rationalisation framework by integrating empirical design feedback.

Overall, while advanced users benefited from structured methods aligned with their expertise, intermediate users required additional support to navigate geometric complexity and precise adjustments. These insights underscore the potential of the proposed workflow to enhance design flexibility and efficiency, particularly when integrated with adaptive tools that better address user needs. For example, an architect designing a modular UHPFRC facade could use this workflow to pre-validate panel curvature and thickness in Grasshopper before engaging manufacturers, reducing rework cycles. Similarly, engineers can assess printability thresholds early to optimise robotic tool paths and reduce material waste.

Conclusion

This study introduced a fabrication-informed design workflow that is novel in its dual emphasis on early-stage constraint embedding and user-participatory validation. Aimed at enhancing constraint integration within parametric design processes for non-standard façade elements, the workflow foregrounds how designers negotiate geometric and fabrication trade-offs during early form exploration. While this study focuses on UHPFRC and 3DPF, the proposed workflow is not strictly material-specific. Its core logic—early integration of fabrication constraints and parametric adaptability—can be extended to other materials including printable composites. The framework can also be applied to different façade typologies where form complexity should be balanced with fabrication feasibility.

Through participatory experimentation and qualitative analysis, the study investigated how architectural designers with different levels of computational expertise address fabrication and material constraints, such as printability, thickness of façade elements and the minimisation of the number of supports. The results demonstrate that while advanced users integrated constraints early and benefited from structured workflows, intermediate users encountered challenges in managing geometric complexity and required real-time guidance.

The workflow facilitated strategic decision-making related to UHPFRC casting and 3DPF, supporting geometric adaptability while aligning with fabrication feasibility. Compared to previous studies that focused on either geometric rationalisation or tool-specific implementation, this study foregrounds the user experience and offers an adaptable design framework that can be applied by practitioners across varying levels of expertise. This aligns with the broader objective of design democratisation, where design-to-fabrication workflows must accommodate diverse user groups with varying levels of technical knowledge. As noted by Kolarevic and Duarte (2018), enabling mass customisation and expanding access to computational design require not only formal flexibility but also workflows that are legible and operable. In this context, improving the accessibility and adaptability of fabrication-informed workflows is essential for bridging the gap between digital tools and real-world applications.

Rather than proposing a novel algorithm or fabrication method, this study contributes a practical and pedagogically valuable design framework that integrates material awareness and user feedback into parametric workflows, supporting both applied design practice and education. While the study offers practical value, its small sample size and controlled experimental setting may limit the generalisability of the findings to professional practice. The deliberate focus on a limited number of skilled participants allowed for in-depth qualitative insights into workflow interactions; however, broader validation is required. Future research should expand the participant pool, simulate collaborative and multi-stakeholder scenarios to better reflect real-world conditions. Assessing the workflow's scalability across various façade typologies—while integrating live feedback on printability and structural performance—would enhance its relevance and applicability to full-scale implementation.

Appendix 1: Interview Questions

1. Have you applied parametric design techniques in your previous design projects? How would you describe your level of expertise: basic, intermediate, or advanced?
2. Have you utilised digital fabrication techniques (e.g., laser cutting, 3D printing, or CNC milling) in your previous projects? How would you describe your level of expertise: basic, intermediate, or advanced?
3. At what stage of the design process do you typically determine the physical material and fabrication method for your design projects?
4. In your opinion, how significant is the integration of parametric design and digital fabrication in achieving design objectives? Please provide examples or insights to support your viewpoint.
5. In this design task, did you design the geometry based on the notified fabrication constraints, or did you adjust your design parameters after creating the geometry?
6. Did you encounter challenges when coordinating fabrication constraints and aligning them with your design intentions? If so, please specify the challenges you faced.
7. Did you feel comfortable when accommodating your designs based on material and fabrication constraints? If not, please explain how your design experience was influenced.
8. In your opinion, will the fabrication-informed design process influence the design flexibility of parametric design and the creativity of the designer?
9. When architects apply the fabrication-informed design process, which aspects could present challenges (e.g., parametric design techniques, fabrication technology, or material knowledge)? Please feel free to mention any other potential challenges.
10. Do you have any final comments or suggestions regarding this guided design experience?

Appendix 2: Participant Design Files

https://github.com/coliandro/UHPFRC

Acknowledgments Many thanks to all the participants who contributed to the design experiments. This study was supported by Xi'an Jiaotong-Liverpool University (RDF17-01-26).

Funding The funding was provided by Xi'an Jiaotong-Liverpool University, Grant No. RDF-17-01-26.

Data availability The data that support the findings of this study are openly available in GitHub at https://github.com/coliandro/UHPFRC.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approvals The authors declare that their Institutional Ethics Committee confirmed that no ethical review was required for this study.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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