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A Review of Parametric Workflows for the Digital Fabrication of Nonstandard Facade Panels

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Abstract. In terms of creating geometric models, converting data formats, and digital construction, the use of nonstandard facade panels is becoming more common. This brings considerable difficulties. Parametric design and digital fabrication technologies have been seen as effective ways to support the custom generation and precise production of complex building parts. Accordingly, the 'design-to-fabrication' workflow has become an important research direction that links design and manufacturing. This paper makes a systematic summary of recent progress in parametric design and digital fabrication for this type of panel, first summarizing the development of this design thinking and digital fabrication technology in architectural practice, then carrying out a fairly comprehensive investigation of existing parametric approaches and 'design-to-fabrication' applications in complex curtain wall construction. From the review results, although existing studies have made some progress in generating geometric shapes, improving performance, and individual fabrication techniques, most of the work is still limited to isolated design stages. At present, there is still a lack of complete and adaptable workflow that can integrate parametric modeling, data conversion, fabrication preparation, and automated manufacturing. This study points out the main research gaps and highlights the future potential of developing integrated digital workflows to improve the efficiency and robustness of nonstandard facade construction.

Keywords: Parametric Design, Digital Fabrication, Nonstandard Facade Panels, Design to Fabrication, Computational Design

1. Introduction

In recent years, nonstandard building parts have been used more widely, especially in buildings with unusual shapes and complex outer wall systems [1, 2]. These components provide designers with more options to achieve their creative aims than standard elements. However, they also make factory production and on-site installation very difficult. Given that each component has its own form, modern digital building research has focused on converting early concept models into components that can be constructed and installed [3].

Nonstandard exterior wall panels are common examples of these components. Since they are part of the building exterior, they affect both the building's appearance and how it will be constructed and installed later. Even though modern parametric tools can quickly create complex shapes, there are

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still real-world problems when turning designs into production, particularly altering shapes, translating data formats, and processing parts for manufacturing [4-7].

Parametric design and digital fabrication offer practical ways to solve these challenges. With parametric software, complex shapes can be created and modified more efficiently [4, 8], while digital fabrication helps produce individual parts to meet specific requirements [9, 10]. As a result, integrated design-to-fabrication workflows have drawn growing attention [11]. These approaches connect information between different project phases, which helps reduce data gaps from design to production [12].

However, most existing studies focus primarily on parametric modeling methods, particular production techniques, or examples from individual projects. Few reviews provide a systematic summary of the whole process for nonstandard facade panels [13]. Current research remains, as a result, only loosely connected. To narrow this gap, this paper reviews recent research on parametric design, digital fabrication, and integrated workflows for nonstandard facade systems. Rather than just listing earlier studies, it focuses on how parametric tools are applied in facade design and which fabrication methods work better in actual projects. It also identifies where current workflows still have shortcomings. Through this analysis, the aim is to give researchers and practitioners a clear, practical reference for advancing the digital production of complex building components.

2. Parametric design in architecture

The way complex shapes are created in architecture has been greatly changed by parametric design. With traditional CAD software, geometry must be edited by hand. In parametric design, however, connected rules are used to control models. When the design needs change, the model is refreshed automatically after the parameters are updated, which saves time on repeated work. Woodbury [4] described parametric design as a method based on relation-based logic, not on simply editing geometry. This shows a clear difference from traditional CAD workflows. Following this idea, Burry [14] also pointed out that parametric design does not only change how architects work, but it also creates new possibilities for digital fabrication.

The growth of parametric design has been closely connected with progress in digital technology. Kolarevic [3] pointed out that digital tools help close the gap between design and construction, so complex geometry becomes buildable instead of staying only as an idea. Today, parametric design is widely used in buildings with unusual shapes, complex outer surfaces, and nonstandard parts, and it has become a basic method in digital architecture. The connections between parametric, generative, and algorithmic design show that parametric design does more than geometric modelling, as it also offers a way to arrange design information and support design exploration [8].

As research moves forward, the focus of parametric design keeps changing. In early studies, researchers mostly paid attention to shape generation based on algorithms to break away from traditional modelling limits, but today the focus has gone beyond just creating shapes, and more attention is given to improving the whole design process. Oxman [5] came up with the concept of parametric design thinking, and he treated it as a complete way of working rather than only a modelling tool. Parameter rules are not just used to generate forms, they can also organize design data, support performance analysis, and guide design revisions. This change indicates that parametric design has developed from a basic software skill into a complete workflow system.

When nonstandard components are being designed, these benefits become obvious. Since these parts are different in size and shape and changing them one by one in traditional CAD takes a lot of time and often causes mistakes. With parametric design, architects can set up one set of rules to produce different custom parts while keeping data consistent across the whole project. Beyond shape

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generation, parametric models also give unified data for refining shapes, labelling components, and preparing production outputs, which makes them a practical bridge to digital fabrication. Recent systematic reviews also show that visual programming tools like Grasshopper are increasingly being used together with BIM workflows to help manage geometry, support prefabrication, and plan fabrication for complex building parts [15].

Overall, this shift has changed the way architects' control and manage their design workflows. Although studies have shown that parametric design is valuable in complex projects, most research still pays attention to early-stage shape generation or design thinking, and as computational design projects become more complicated, managing parametric workflows and model changes has become increasingly critical [16]. However, the direct connection between parametric models and digital fabrication is still being studied. Because nonstandard parts are now used more often, modeling alone is not enough to cover the whole process, so connecting parametric design with digital fabrication through integrated workflows has become an important research focus.

3. Digital fabrication and design to fabrication for nonstandard facade panels

3.1. Digital fabrication for architectural components

The production of building elements has been reshaped substantially by digital fabrication. Conventional construction still leans on standardized mass production, an approach that becomes costly and labor-intensive once applied to complex freeform geometry, typically requiring custom molds and extensive manual finishing. Digital fabrication sidesteps much of this, components are generated directly from digital models, so intricate geometry can be translated into physical parts with a precision that narrows the traditional gap between design and manufacturing [3].

Three techniques dominate current architectural practice including CNC machining, additive manufacturing (3D printing), and robotic construction. Gramazio and Kohler [9] observed that digital fabrication reshapes not only how parts are produced but also the architect's role during construction, where design and manufacturing were once handled as sequential, separate phases. CAD/CAM systems now allow digital models to be converted directly into machine instructions for CNC equipment and robotic tools. Architects consequently take on responsibilities that extend well beyond geometry material selection, fabrication-method choices, and assembly planning all become part of the design task. This has drawn computational design and digital fabrication into closer alignment, to the point where designers can weigh design intent against fabrication constraints simultaneously rather than resolving them in a strict linear sequence [10].

Research priorities have shifted alongside this technical maturation. Where early work was largely concerned with demonstrating that CNC machines and robots could physically produce complex components [9], attention has since moved toward embedding fabrication within the broader design process itself. Sheil [17] claimed the value of digital fabrication lies less in new hardware than in the tighter coupling it enables between design, material, and construction, which means fabrication logic, material behavior, and assembly sequencing are treated as design decisions from the outset, not adjustments made after the fact.

Nonstandard components make this coupling especially consequential, since their variation in size, curvature, and connection detail means that a parametric model, however sophisticated, cannot on its own guaranteed buildability. Before fabrication can proceed, digital models typically require simplification, format conversion, and toolpath generation, while preparatory steps bear directly on both precision and production speed. Anticipating material behavior, machine performance, and toolpath planning early in the design process, rather than resolving these questions afterward, tends

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to improve production quality and reduce error [18]. This is part of a broader shift, noted by Sheil [17], away from treating production as the final stage of design and toward designing components that are inherently easier to manufacture.

Nevertheless, none of the three fabrication techniques are universally suitable, each carries its own strengths and constraints, so selecting an appropriate method still depends on material choice, part geometry, and site-specific conditions. What remains a persistent challenge across the field is converting early design models into models that are demonstrably buildable, a gap that continues to motivate research on nonstandard facade systems and on the workflows connecting design to fabrication.

3.2. Parametric design for nonstandard facade panels

Nonstandard building exterior systems are one of the most mature uses of parametric design in modern architecture. As designs with unusual shapes and complex outer surfaces become more popular, the shapes of building exteriors have turned much more intricate. Older methods that depend on standard parts and fixed molds can no longer meet these design needs. Kolarevic [3] pointed out that progress in digital tools makes it possible for complex geometry to move beyond being only an idea and enter actual construction, which pushes the growth of custom parts. In this situation, designing a facade is not just about shaping the outside of a building, because it also needs geometry control, making panel shapes more regular, and improving the ease of construction.

Pottmann *et al.* [1] used architectural geometry and discrete differential geometry to look at how complex shapes are linked with real construction, to deal with the construction problems of freeform designs. Their work shows that architectural form, structural systems, and paneling plans cannot be developed separately, and they need to be arranged together during the whole design process. Later studies made further improvements to facade paneling methods for freeform surfaces, showing that different paneling choices directly affect the number of parts, production costs, and the difficulty of installing them on site. This shows that parametric design for nonstandard facades is not just a simple modeling tool, but it is a practical way to make panel design better and organize production.

Recent studies have further helped to connect parametric design with industrial construction. Liu *et al.* [6] created a BIM-based generative design framework for Design for Manufacture and Assembly. This framework brings together BIM data processing, rule-based paneling methods, and event-based simulation. So several paneling options can be generated and compared automatically according to fabrication limits. Their results show that production efficiency can be improved and a more organized base for design decisions can be provided if manufacturing limits are considered during early design. Although their study mainly focused on lightweight building panels, not facade systems, but the workflow still combines parametric design with fabrication-oriented evaluation, which gives useful ideas for producing nonstandard facades.

Another key research focus has been on improving the way data flows between facade design and fabrication, not just on making panel layouts better. With older methods, making detailed production drawings for nonstandard panels takes a lot of time and needs a large amount of manual work. So to deal with this problem, Deng *et al.* [7] built a framework based on BIM that can produce these drawings directly from digital models. Tests in real projects showed that this approach reduces the need for manual data handling, and at the same time, it makes fabrication data more consistent and complete. This confirms that parametric models are not just useful for presenting designs, but can also be trusted as data sources for manufacturing.

At the same time, research on nonstandard facades is moving away from just creating shapes and toward making overall performance better. In a review about adaptive facades, Tabadkani *et al.* [2]

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noted that parametric tools are now widely used to check environmental performance, like daylighting and controlling sunlight. But they also pointed out that there are not many complete workflows that cover all design stages, especially when design outputs need to be turned into construction and fabrication data accurately.

Overall, parametric design can support shape generation, paneling optimization, and performance analysis for nonstandard exterior wall systems. It is being connected more with BIM and digital fabrication. However, most current studies still stay within separate stages, such as making panel shapes more regular, simulating performance, or producing shop drawings. Not many studies try to connect these separate steps into one continuous workflow from design to fabrication. The way data is passed between important phases like model conversion, preparation for fabrication, and on-site assembly is still broken into pieces. So creating a complete, practical, and well-connected system remains a main direction for future research in digital facade construction.

3.3. Design to fabrication workflow

As parametric design and digital fabrication technologies keep developing, closing the gap between design and manufacturing has become a major research focus. For nonstandard components, parametric modeling by itself cannot meet real production needs. A design model must go through several steps, such as improving the shape, making panel layouts more regular, converting data formats, and preparing for fabrication, before it can be produced. Therefore, building an efficient and integrated workflow from design to fabrication is a key topic in digital architecture. Kolarevic [3] pointed out that digital technologies change the link between design and construction, turning digital models into the main medium for passing information to manufacturing, rather than just static design files.

Raspall [11] proposed a system based on four core elements, which are goals, scope, tools, and workflows, to provide a clear framework for these integrated processes. The goals explain the purpose of integrated workflows, and they mainly focus on custom production and mass customization. The scope sets out what materials are included, what kinds of components are covered, and where the research limits are. Tools refer to software platforms that connect design and manufacturing, while workflows guide how data moves step by step from digital models to the factory floor. This framework gives different integrated projects a common starting point, and it also moves research attention away from separate fabrication tools and toward fully connected workflows. New digital manufacturing technologies are pushing Design to Fabrication workflows to develop toward more connected data structures. When data is organized in this unified way, different stages can work together more easily, people can cooperate more efficiently across the whole fabrication process [12].

Even after overall workflows have been set up, turning design models into buildable models is still a difficult technical problem. This step involves much more than simply changing file formats, because it must meet actual production needs like geometric accuracy, machining tolerance, and equipment limits. Design models usually require thorough geometric simplification, paneling, and the generation of machining code to match the needs of the shop floor and assembly.

In recent years, within research on connecting design to fabrication, managing data through the full life cycle has become a direction with a lot of potential. A study from 2024 brought in the digital thread concept, which was used to connect design plans, digital models, production machines, and actual building parts. With this shared data structure, different fields can work together more easily, and data errors during robotic fabrication become fewer. These improvements show that today's connected workflows are no longer limited to small changes in shapes, instead, they now pay more

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attention to managing data across the entire life cycle. The Digital Thread idea has also grown into a framework that focuses on the whole life cycle and brings together design, manufacturing, and operation data. Its main advantages are that different types of data can work together better and that the whole process can be traced from beginning to end [13].

4. Conclusion

The developments surveyed here indicate that parametric design and digital fabrication have moved nonstandard facade systems from the margins into mainstream practice, drawing design and construction into closer alignment than before. Parametric design has outgrown its original role as a shape-generation tool, now supporting multi-objective evaluation and environmental performance analysis as well, while digital fabrication techniques have matured to the point of producing custom components with markedly greater accuracy and speed. Together these developments have positioned integrated design-to-fabrication workflows as a central mechanism linking early-stage design directly to shop-floor production. The literature reviewed here nonetheless remains fragmented, most studies address isolated stages including modeling, fabrication, or performance evaluation. Without assembling them into a coherent, end-to-end method, and the diversity of software platforms, machinery, and techniques used across studies limits how transferable any single workflow is to a different project. Closing this gap will likely depend on three things, more seamless data sharing between design and production systems, more robust model-conversion methods, and workflow frameworks flexible enough to accommodate varied materials, fabrication processes, and project conditions. In synthesizing the current literature, mapping the trajectory of parametric digital construction, and identifying these gaps, this review aims to offer a practical reference point for both the design of individual nonstandard components and their integration into real construction projects.

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