Converting Algorithms into Tangible Solutions

A workflow for materializing algorithmic facade designs

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Abstract. Two main concerns drive the architectural practice: the design and the construction of buildings. This makes the creative practice highly dependent on construction viability, most design decisions having to consider, among others, the available materials and construction techniques and the associated manufacturing costs. Nevertheless, the desire to conceive complex geometries has always been present in architecture, often leading to innovative solutions and structures that go beyond what had been done to date. The emergence of computational design in the last decades has further accentuated this ambition by providing architects with unprecedented design freedom. The realization of such shapes, however, is not as easy as its 3D modeling due to limitations in the available manufacturing strategies. In this paper, we address this problem with Algorithm Design (AD), a design approach based on algorithms, presenting a design workflow that benefits from its (1) geometric freedom in developing facade design solutions and (2) expressiveness in converting and detailing the obtained solutions for manufacturing. We evaluate our proposal with an algorithmically developed prototype of a geometrically complex facade. The aim is to illustrate its potential in exploring design alternatives that consider multiple design criteria, while automatically detailing them for construction and producing the corresponding technical documentation. We also intend to demonstrate the importance of the proposal's flexibility in considering different construction schemes that, in turn, result in different aesthetic outcomes and manufacturing needs.

Keywords: Algorithmic Design, Facade Design, Design-to-Fabrication, Design Workflow.

1 Introduction

The emergence of new digital means in the last decades had several positive effects in architecture. The first one was providing architects with unprecedented design freedom

[1], which facilitated the development of unconventional shapes, as well as the integration of different performance criteria in the design process. The emergence of Computational Design (CD) tools, such as Computer-Aided Design (CAD) and Building Information Modeling (BIM), not only increased the architects' design efficiency and precision, but also improved design visualization and collaboration among different practitioners. Another critical change was enabling the automation of manufacturing processes, making it possible to materialize the design freedom allowed by CD tools accurately and with acceptable time and effort. The emergence of Digital Fabrication (DF) tools made the production of unique building elements more accessible, partially solving the lack of flexibility of traditional construction methods [2]. As a result, the architectural production also changed, especially regarding the design of building facades, motivating the development of unique building shapes and geometric patterns that simultaneously respond to multiple requirements.

Nevertheless, there are still limitations in the realization of less conventional shapes, such as the associated manufacturing costs, which are often expensive, and the complexity and context-specificity of the resulting technical documentation, which must ensure accurate manufacturing and assembly on site. In this paper, we address some of these limitations with Algorithm Design (AD), a design approach based on algorithms [3], proposing a design workflow that facilitates the algorithmic development and manufacturing of facade design solutions. The focus on building facades is due to the importance of this architectural element in the aesthetics [4–7], performance [4,6,8], and urban communication [5,7,9] of buildings, as well as the design complexity and multiplicity of criteria of its design [1,8,10].

2 Methodology

This investigation aims to solve part of the existing gaps in the design and manufacturing of building facades. It adopts an AD approach due to its advantages in terms of design efficiency, flexibility, and accuracy, and is based on a mathematical theory for the design, analysis, and realization of facade design solutions [11]. In this paper, the implementation of the theory as a library of predefined algorithms [12] is evaluated in terms of creative support. The library aims at facilitating the testing of different design solutions and manufacturing strategies, while assessing their mutual impact in the solutions' aesthetic quality and feasibility. The result is a three-stage methodology encompassing:

- the analysis of the currently predominant DF techniques to identify their requirements in terms of technical documentation and modeling representation.
- the identification of the most relevant manufacturing-related functionalities, while structuring them in a mathematical perspective.
- the extension of the library with functionalities to automate construction detailing and the production of technical drawings for different manufacturing strategies.

The results of these tasks are summarized in sections 3 and 4. To evaluate our proposal, we apply it in the algorithmic development of a geometrically complex facade design responding to different aesthetic, performance, and construction requirements. The aim is to illustrate the framework greater design freedom in exploring wider design spaces and balancing multiple criteria, while automatically detailing the solutions and producing technical documentation according to the selected manufacturing strategy. We also aim to demonstrate how its flexibility increases the range of construction schemes considered, as well as the perception of their impact on the solutions' aesthetics and feasibility. The results are presented in section 5. Finally, in sections 6 and 7, we analyze the previous findings, making some final considerations on the proposal's (1) flexibility in terms of design exploration, (2) ability to automatically produce construction details and documentation, and (3) potential to extend creative processes with manufacturing-related principles.

3 Making the Digital Real

There are two main concerns that drive the architectural practice: the design and the construction of buildings [13]. Originally, the profession of architecture involved both tasks, the creative practice being highly dependent on the solutions' construction viability [14]. The architect had a central role in the entire process, not only establishing the relationship between design, structure, and materiality, but also managing the available materials and construction techniques and their associated costs. This is visible in ancient iconic buildings such as Egyptian pyramids, Greek temples, and Gothic cathedrals [2]. The separation of architecture and construction occurred during the Renaissance period, where architects started to differentiate themselves from master builders and craftsmen [14,15]. Nevertheless, the construction viability of the solutions conceived remained a constant concern of architects and engineers, as is visible in the works of Pier Luigi Nervi, Eladio Dieste, and Antoni Gaudí, among others, who applied simple construction techniques to build unconventional shapes [16].

The desire for complex geometries that defied the laws of nature has always been present in architecture. Architects have always ambitioned to design and construct innovative shapes and structures that went beyond what had been done to date. The reinforced concrete freeform shapes of Buckminster Fuller, Frei Otto, and Heinz Isler are some examples prior to the rise of digital tools that reflect such desire. At the time, they used physical models to explore unprecedented shapes and study their corresponding structural behavior [17]. With the emergence of digital tools and CD approaches, such as AD, architects and engineers were provided with unprecedented design freedom, facilitating not only the study of shape and structure, but also the manufacturing of unconventional shapes. The works of recently established design studios such as Zaha Hadid Architects, Foster+Partners, Frank Gehry, and UNStudio constitute some well-known examples of this.

Unfortunately, the design freedom allowed by CD tools is often constrained by the lack of flexibility of most construction methods [2]. Although the available DF strategies are gradually changing this reality, they still present limitations that hinder their widespread use [16]. Moreover, converting abstract geometric models into structurally sound physical ones remains a laborious and time-consuming task that requires the development of construction details and assembly strategies that are, in most cases, context specific. Another challenge is the complexity of the resulting construction information, which often requires the elaboration of specific technical documentation and labelling strategies ensuring an accurate manufacturing and assembly on site. A last, and often critical barrier is the resulting manufacturing costs, which are often too high.

3.1 New Manufacturing Strategies

Nowadays, there is a wide variety of DF techniques available, which vary in terms of shaping process, materials supported, size and shape constraints, and surface finishing, among others. These technologies are based on the use of Computer Numerical Control (CNC) machines to control the manufacturing of differently shaped elements, increasing the design flexibility and the fluidity between design and fabrication processes and thus reducing the distance between design thinking and making [13,18]. By allowing the design data to directly flow between design and manufacturing stages [13], architects can control the entirety of both processes in a fully digital manner, producing unique building elements with high levels of precision in a viable way [19]. This would ideally enable the conversion of traditional manufacturing processes, where only the mass production and assembly of standard elements is economically viable [13], into new ones benefiting from mass-customization strategies to produce multiple non-standard elements at low costs [20]. Unfortunately, this scenario remains a challenge due to high costs, machining time, scale and material limitations, material waste, and required spatial conditions (e.g., air extraction and workspace area).

DF strategies can be *additive*, when the adopted technique is based on the addition of material layers to produce the desired shape [19]; *subtractive*, when it uses different strategies to remove or separate particles of raw material form an existing shape [21]; *formative*, when it applies mechanical forces to reshape or deform materials into the intended shape [21]; *robotic*, when it uses robotic arms or drones to accurately place elements in layers [22]; or *cutting*, when it is based on the extraction of two-dimensional planar elements from sheet materials by using strategies like contouring, triangulation, and unfolding, among others [19]. In this paper, we focus on the latter strategy due to its high popularity in the field [13,23], especially to manufacture building facade elements with nonstandard shapes and geometric patterns. Among the advantages of *cutting* is the ability to produce elements on a wide range of scales and with high geometric precision within acceptable machining time and cost [13]. Regarding its limitations, *cutting* tends to produce considerable material waste [19], can only handle a limited range of material types and thicknesses, and requires different technologies according to the material being used [13,23].

3.2 Fabricating through Algorithms

Nowadays, CD approaches play a critical role in architecture, not only extending the architects' creative freedom, but also improving the efficiency and accuracy of their design processes. Nevertheless, architects still face several limitations when converting their conceptual designs into physical ones, especially because most manufacturing technologies do not yet support the increased design complexity allowed by CD strategies. As a result, architects are often forced to simplify their designs to make them feasible. Manufacturing thus becomes a critical barrier to their creative design thinking.

DF is gradually changing this scenario, but there are still some limitations hindering its widespread use. The complexity of the construction information needed to accurately produce nonstandard designs is one such example, often involving the production of context-specific technical documentation guiding both their manufacture and assembly on site. Traditionally, this process was entirely manual, being not only laborious and highly time-consuming but also highly prone to information loss and the accumulation of errors. Fortunately, part of these barriers can be alleviated with AD, a design approach where the designer creates an algorithm that, when executed, generates the intended design [3]. AD facilitates design changes and the automation of repetitive design tasks, thus having the potential to automate the production of technical details and documentation, not only reducing the time and effort spent in these tasks, but also increasing their precision and accuracy. Nevertheless, AD is an abstract approach that deviates from the visual mindset of architecture, requiring programming experience, which most architects do not have.

To address the previous limitations in the context of facade design, some authors studied the potential of different DF strategies to develop facade elements [10,19,24], whereas others proposed frameworks for either developing knowledge-based digital tools informing about the manufacturing viability of facade design solutions [25] or creating large-scale facade frame systems [26]. The literature also includes some research projects and methodologies combining AD and DF strategies to produce, for instance, functionally graded facade elements [27], ceramic self-supporting facades components [28], or casted concrete facade elements [29]. However, most proposals focus on a specific manufacturing strategy or material [10,24,27–29] and are based on visual programming languages [25,26,28,29], often requiring the development of custom scripts to overcome the latter’s limitations. Some also have limited modeling flexibility [25,27,29] or do not entirely automate the design-to-manufacture process, often resorting to import/export operations between tools [26], which potentially lead to information loss and accumulation of errors.

Along the same lines, several AD tools for manufacturing have also been released, which include (1) the Grasshopper’s plug-ins FabTools (2013), to accelerate the scripting task and improve the fabrication workflow; Bowerbird (2015) to create waffle structures, layer models, section models, and text for both fabrication and engraving purposes; Xylinus (2016), to generate G code directly from Rhino and Grasshopper for 3D printing; Droid (2019) to control model slicing, custom paths, and G code generation for 3D printing; Kuka Prc (2019) to directly program industrial robots; RoboDK (2019) to combine Rhino's CAD modeling software with RoboDK (a software for programming industrial robots); OpenNest (2021) to pack 2D closed polygons for CNC cutting; and Ivy (2021), to perform mesh segmentation and flat fabrication inside Grasshopper; (2) Dynamo’s addons DynaFabrication, Fabrication API, 3BMLabs.DigiFab, and ParametricMonkey; and (3) the Laser Slicer addon (2019) for Blender.

However, these tools are based on visual programming languages, often lacking the scalability and expressive power [30] needed to support the development of complex solutions [31–33]. They also usually present an accentuated decrease in performance [34–36] when executing larger AD programs, or are restricted to specific modeling tools and fabrication strategies, forcing architects to use multiple tools to assess different construction schemes. Finally, most tools hardly automate the entire process, often requiring manual- or script-based interventions to extend the solutions for fabrication and extract the corresponding technical documentation. Besides being time-consuming and challenging to produce, these interventions are context-specific, varying with the design's geometric and material characteristics and manufacturing strategy and, thus, can hardly be reused in different projects without major modifications.

Considering the current state-of-the-art, it is therefore important to close the gap between AD and DF and provide architects with a methodology that facilitates the design and manufacture of architectural solutions of varying complexities, encompassing not only different manufacturing strategies and construction schemes but also the automation of most of its related tasks.

4 Algorithmic Framework

Our proposal adopts a text-based AD approach due to its flexibility, expressiveness, and scalability [37]. The proposal is based on a mathematical theory for facade design, providing a set of strategies to guide the algorithmic development, evaluation, and concretization of facade design solutions [11]. To facilitate their selection and combination, the available strategies are classified according to their type and role in facade design processes, resulting in a multi-dimensional space addressing the shaping, patterning, analysis, optimization, and fabrication of building facades. To make them useful for architectural practice, these were implemented in Khepri [38], an AD tool portable between different design tools and optimization libraries [39,40] that facilitates the alternation between them according to the task at hand. The result is a library of predefined algorithms that can be easily combined in the development of new facade design solutions responding to different aesthetic, performance, and construction requirements [12].

In the current investigation, we expand the previous library with manufacturing-related algorithms, whose selection and combination follows the same principles of previous research [11,12]. Besides extending the solutions with construction details fitting their geometric characteristics, the selected fabrication strategy, and the existing assembly/fixation requirements [41,42], which may require, for instance, the creation of holes to place screws or profiles, metal profiles to increase the design's stability and connect different elements, or panel interlocking legs to create connections between panels and other structural elements; these algorithms also automate the production of technical documentation, creating, for example, two-dimensional paths or slices in the case of 3D printing, three-dimensional custom mold models when using casting strategies, and element contour plots in the case of CNC cutting. They also support engraving text or textures on each manufactured element for labeling or aesthetic purposes, using different line colors, thicknesses, and types.

Fig. 1 illustrates the AD workflow supported by the extended algorithmic library. The aim is to facilitate the integration of manufacturing constraints in design exploration processes, while smoothing the transition between both stages.

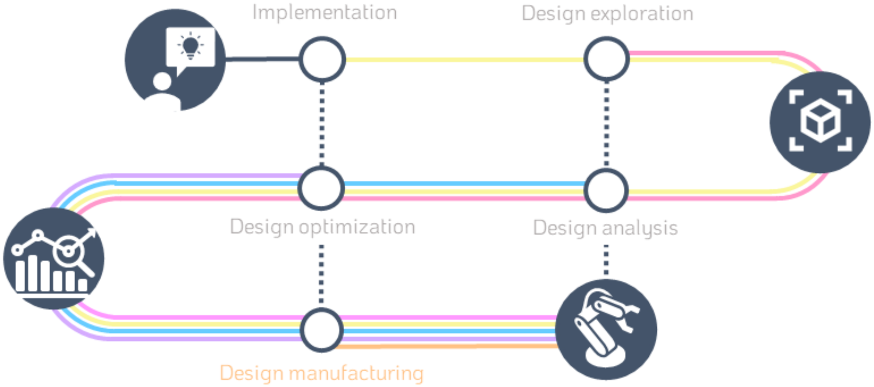

Fig. 1. AD workflow: the colored lines represent the different algorithmic categories used and the dashed lines the supported shortcuts between design stages.

5 Evaluation

We evaluate our proposal by applying it in the algorithmic development of a parametric facade design solution and in its detailing according to different fabrication schemes. To that end, we select the most relevant algorithms, combining them in a step-by-step process based on iterative visualizations of the solution and its incremental refinement in terms of design intent, performance goals, and construction requirements. As a result, we obtain a set of facade design solutions with different geometric configurations, construction schemes, and surface finishings that, in turn, originate different visual outcomes and demand different technical documentation. In the next sections we elaborate on each step of the design process.

5.1 Design Intent

The first stage entails the algorithmic implementation of the design intent, which considers different conceptual and performance requirements, such as creating a nonstandard facade design that (1) has a triangular configuration, (2) produces a dynamic three-dimensional visual effect, (3) conveys a sense of randomness between its parts, (4) adapts its permeability level according to both functional and privacy requirements, and (5) prevents direct sunlight penetration from above.

We address the first two requirements by developing a solution based on square-based pyramidal elements (Fig. 2A): on the one hand, their lateral faces create the desired triangular configuration, and, on the other hand, their volumetry produces the intended three-dimensional effect. To increase the design's irregularity, while giving it a random nature, we make the pyramids' height vary randomly (Fig. 2B) and we apply a randomly controlled deformation factor to their bases (Fig. 2C). Finally, to further accentuate the intended three-dimensional effect, we also increase the surface's convexity, while making the pyramids' height vary in both ways, i.e., towards the inside and the outside (Fig. 2D).

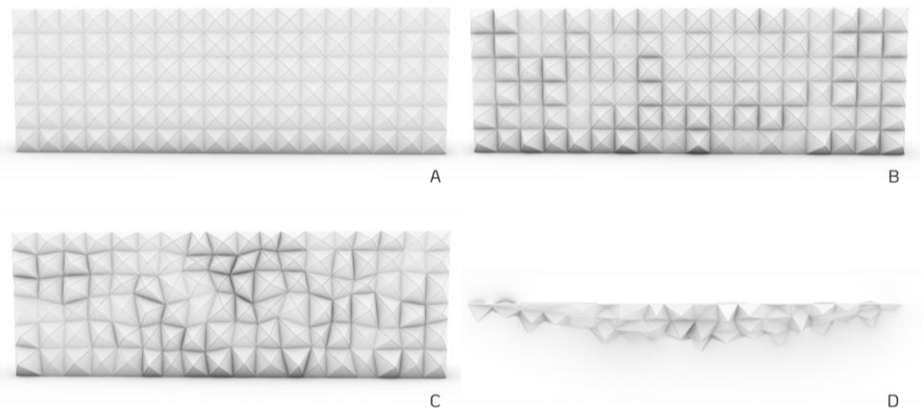

Fig. 2. Design geometric evolution: creation of squared-based pyramidal elements with (A) equal and (B) random heights, followed by the (C) random deformation of their bases and (D) their distribution on a convex surface together with their heights varying in both directions.

Regarding the remaining requirements, we then create holes on the pyramids' triangular faces to obtain the desired permeability (Fig. 3A), controlling their size in a random way to emphasize the requirement for irregularity (Fig. 3B). Nevertheless, since each facade area must meet specific functional, privacy, and shading requirements, which translate into different levels of surface permeability, using a randomly controlled factor makes this difficult. To ensure each facade area reaches the desired permeability levels, we replace the random factor with one entirely controlled by us that allows manipulating the holes' size according to the existing requirements (Fig. 3C).

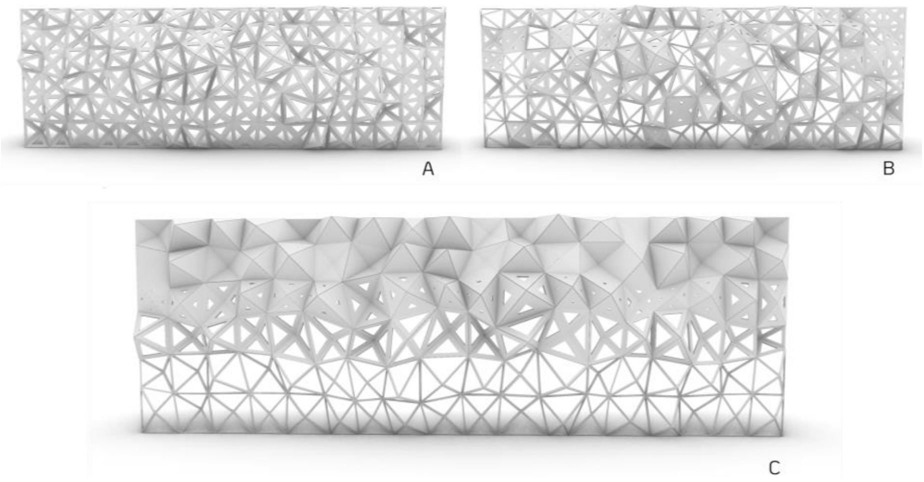

Fig. 3. Performance-related design variables: obtaining different permeability levels through the creation of panel holes with fixed (A), random (B), and gradually changing (C) sizes.

5.2 Geometric Exploration

The next stage encompasses the geometric exploration of the facade design solution. To that end, we iteratively assign different values to its parameters, while visualizing the results in the modeling tool. This allows us to incrementally refine the solution easily and quickly until it successfully balances the design intent and the existing functional and performance requirements.

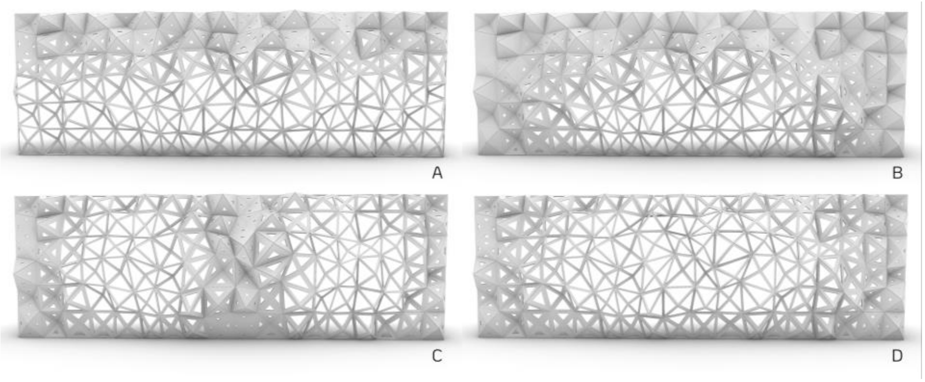

Fig. 4. Design iterations resulting from different aperture factors.

Fig. 4 illustrates part of this process with four design variations resulting from the same algorithmic description: Example A, for instance, is an attempt to smooth the visual effect of Fig. 3C; Example B further accentuates the previous effect by making the holes' size gradually decrease in the horizontal direction as well; Example C explores the creation of radial permeable areas; and Example D creates a central permeable area. The different iterations respond to the needs of each functional area, which require specific privacy and shading levels.

5.3 Manufacturing-related Information

This stage addresses feasibility and preparation for fabrication. To that end, we select one of the previous solutions (Fig. 4A) and the material to use (metal).

Considering both the geometric and structural simplicity of the previous solution, it is important we detail it for fabrication. To that end, we first focus on investigating the best way to discretize the resulting facade tiling so that it can be easily manufactured and assembled on site, while ensuring its structural stability. Given the geometric irregularity of the pyramidal elements, we decide to fabricate the triangular panels individually. To ensure their subsequent connection and fixation into a larger sound structure, we use the framework to create panels with folded ends to link them to the neighboring panels. Given its algorithmic nature, the produced construction extensions not only automatically adapt to the panels' ever-changing geometry, but can also be adjusted in terms of size, shape, and thickness, among others, easily and almost instantaneously (Fig. 5).

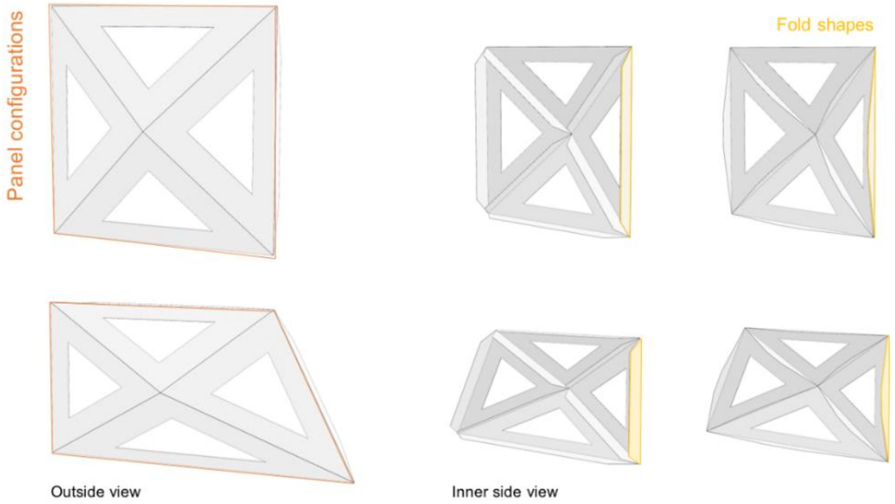

Fig. 5. Algorithmically generated construction details: on the left, two panel configurations and, on the right, their extension with folded ends of varying sizes and shapes.

The next task encompasses the discretization of the solution into smaller parts that are not only self-supporting but also easily transported and assembled on site. We use the available algorithms to divide the solution into three modules, each with the size of 3x3 meters and composed of 36 quad-based pyramids (or 144 triangular panels) of different sizes and shapes (Fig. 6A). Given the number and geometric irregularity of the panels, we use the framework to create an outer metal frame grouping them (Fig. 6B). This solution not only enhances the structural stability of each module, but also enables the assembly of each of its 144 panels at the factory, which is critical for achieving higher levels of production quality and accuracy, and their later transportation and installation on site. Moreover, having a regular supporting grid will allow not only the use of identical linear elements joining the modules, but also the creation of punctual fixing points attaching their vertices to the building structure. This, however, slightly reduces the geometric irregularity of the original solution since it forces straight alignments to exist at every 3 meters. Nevertheless, considering the resulting manufacturing and construction gains, we considered this reduction to be acceptable.

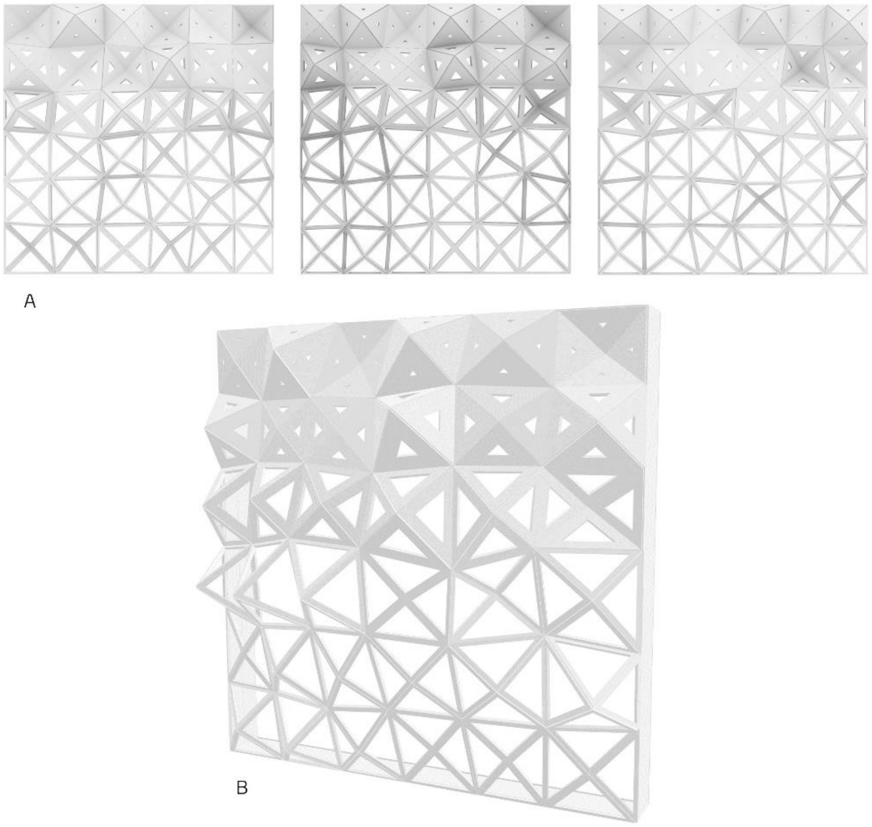

Fig. 6. (A) The division of the solution into equally sized parts (i.e., modules); (B) The creation of an outer frame increasing the modules' structural stability and facilitating their fixation to the building structure.

5.4 Design Prototyping

This stage encompasses the production of a scaled prototype. For summarization purposes, we will focus on the technical documentation, manufacturing, and prototyping of a single module.

Considering the triangular panels' geometric characteristics and material, laser-cutting seems to be an adequate method for their fabrication. To produce the two-dimensional unfolded technical drawings required by this strategy, we select the algorithms tailored for that purpose, automatically obtaining each triangular panel manufacturing documentation indicating the cutting and folding edges with different line types (Fig. 7).

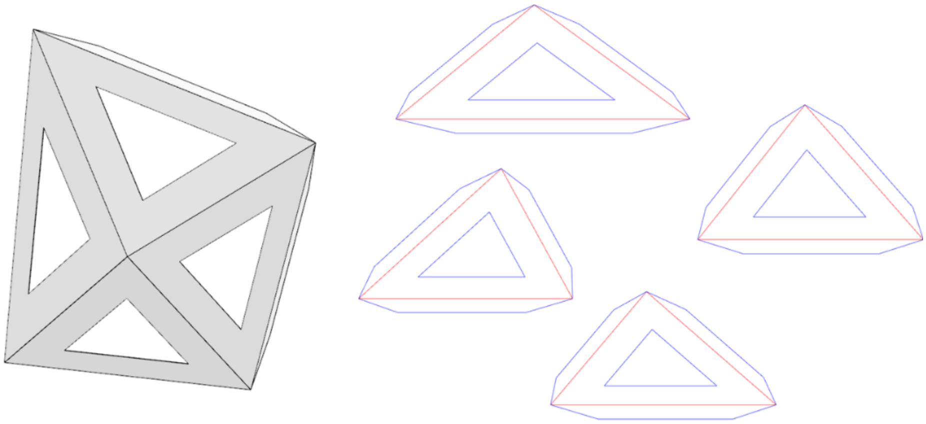

Fig. 7. Pyramidal element 3D model (left) and corresponding unfolded drawings (right).

In a first phase, we use the framework's algorithms to automatically produce two-dimensional scaled drawings of the selected module, obtaining a set of 144 unfolded triangular panel drawings of different sizes and shapes. Given the geometric complexity of the triangular tiling, as well as the number of different panels composing it, we anticipate a challenging and time-consuming assembly process. To simplify this task and minimize the accumulation of errors, we identify the different triangular panels with installation guiding labels that indicate their sequence and matching panel folded end. We also reduce material waste in the manufacture of the 144 panels through nesting strategies.

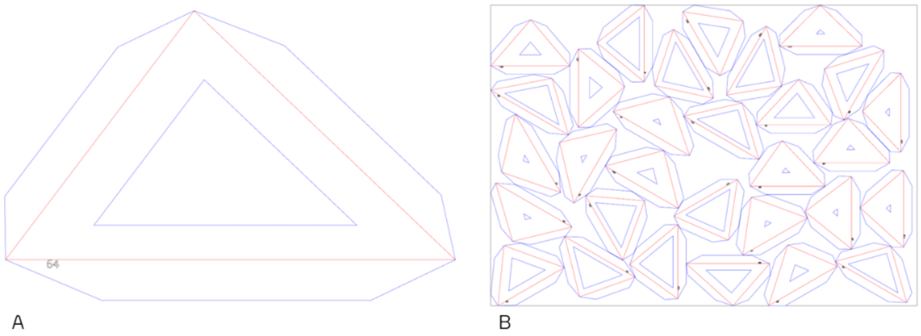

Fig. 8. (A) Triangular panel labeling; (B) Nesting of the triangular panels' unfolded drawings.

Given the AD extensions available containing ready-to-use functionalities to solve similar manufacturing-related issues, at this stage, we benefit from some of the latter to (1) label the triangular panels and (2) organize their unfolded representations in the best way. In this workflow, we combine our framework with the Grasshopper plug-in OpenNest to create numbers on each triangular panel folded end identifying their order of installation (Fig. 8A) and then, to benefit from its nesting algorithm to distribute the panels' unfolded representations, while minimizing the gaps between them (Fig. 8B). Finally, we send the resulting drawings to the laser cutter to produce the 144 scaled triangular panels, which we then fold and assemble according to the labeling instructions (Fig. 9).

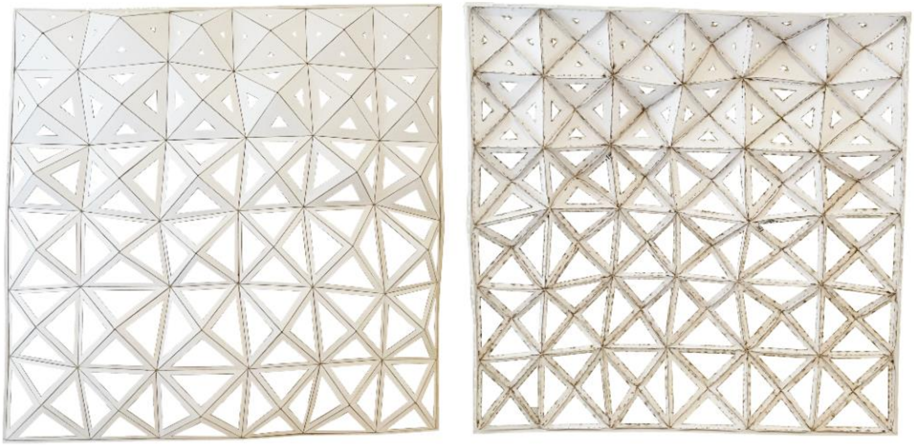

Fig. 9. Facade module prototype: outside (left) and inside (right) views.

5.5 Aesthetical Consideration

The construction of the prototype allowed us to have a better perception of the solution's physical outcome. Regarding its aesthetics, we realized that, although it satisfies the design intent from an outside perspective, originating the desired three-dimensional random-based and irregular triangular tiling, the same does not happen from an inside perspective. First, because the fluidity of its triangular tiling is broken by the panels' folds. Second, because, while all the other facade elements have either random or irregular geometric characteristics, these elements do not, thus deviating from the design intent (Fig. 10A). Given the flexibility of our proposal, we can quickly and easily test other construction schemes for our solution, while assessing their aesthetic impact. During this process, we can also effortlessly produce the technical documentation needed in case we want to prototype any of the alternatives.

Assuming that construction elements like these ones have to exist to connect the triangular panels, we now try to break their geometric constancy by varying their widths in a dynamic way, making them either directly or inversely proportional to the panels' opening size (Fig. 10B-C). Again, during this process, the solutions' three-dimensional model and technical documentation are automatically produced, allowing us to effortlessly test design alternatives until reaching a solution that we are most satisfied with. For instance, we can opt to simply change the shape of the triangular panels' folds, obtaining either rectangular (Fig. 11A) or trapezoidal connecting elements (Fig. 11B), or apply more drastic changes and either produce each pyramidal element as a single foldable panel, whose inner connections are hidden by U-profiles (Fig. 11C), or convert the originally two-dimensional triangular panels into three-dimensional elements, whose inner volume adapts to both their thicknesses and opening sizes (Fig. 11D).

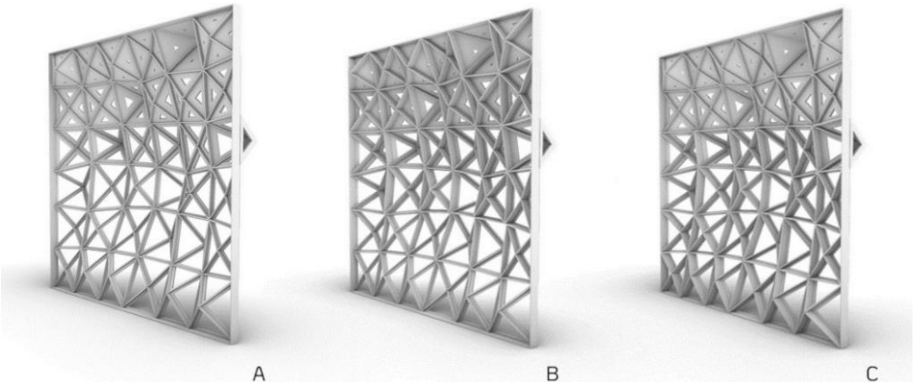

Fig. 10. Prototype interior view: panels with folded ends with (A) fixed sizes or with their size (B) inversely proportional or (C) directly proportional to the panels' hole.

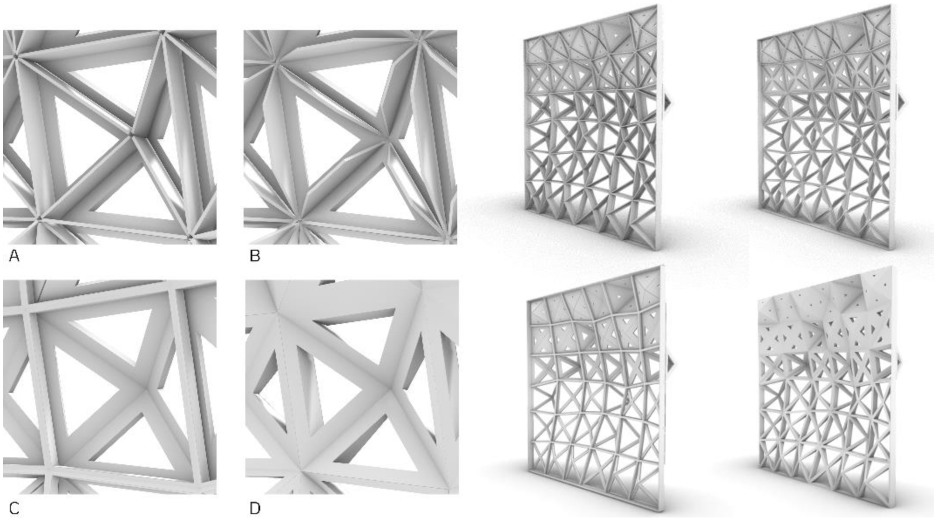

Fig. 11. Algorithmic exploration of different construction schemes: (A) triangular panels with rectangular folds; (B) triangular panels with trapezoidal folds; (C) pyramidal folded panels with U-profiles hiding connecting folds; (D) three-dimensional triangular panels. On the left, their close-up view and, on the right, the resulting prototype interior view.

After deciding for the best solution in terms of design intent, functional requirements, and feasibility, we can proceed to the next stage and, first, produce another prototype to confirm the result viability and then, manufacture the final solution. As, in this process, the solutions' technical documentation is constantly updated to accommodate the design changes made and the specificities of the selected manufacturing strategy, not only is it always up to date and accurate, but also the time and effort spent on its production is largely reduced. In case we need to complement the resulting drawings with additional context-specific information and details, such as screw holes, we can extend our AD solution with further manufacturing-related functionalities available in the framework or even combine it with external AD libraries when necessary.

We are currently considering manufacturing the triangular panels and their supporting frames in aluminum. To that end, we can use laser cutting or water jet techniques to cut the aluminum sheets in the desired shapes, and CNC bending technologies, e.g., die bending or swing-folding machines, to bend the triangular panels' ends according to their respective angles. For their assembly, we can simply use structural adhesive to bond the triangular panels' folded ends or, in case this does not provide enough stability, we can either use welding strategies, melting, fusing, and solidifying adjacent panel ends, or applying rivets to hold them in pairs. To help choose the best assembly option, we can perform wind flow analyses, assessing the effect of both wind pressure and speed on the irregular triangular panels. In a first stage, we can use a simple model with uniformly distributed loads and, based on the results, we can decide if using structural adhesive is a viable option or if we must consider one of the other options, performing further analyses to refine them.

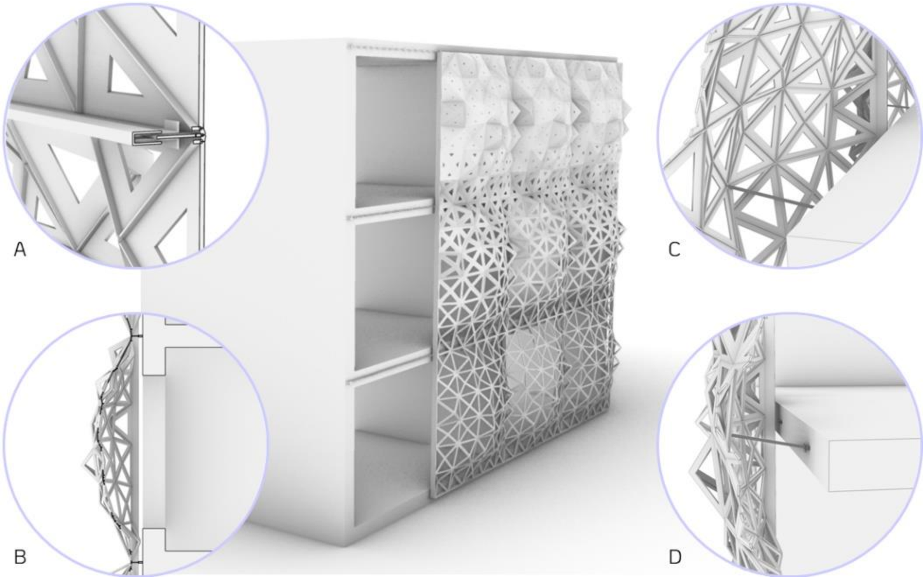

Fig. 12. Prototype fixation strategies: (A) continuous horizontal supporting rails; (B) airspace layer; (C) punctual supports; (D) punctual supports with articulated joints.

Regarding the modules' fixation to the building's load-bearing facade, there are two possible strategies: (1) explore the geometric regularity and planarity of their outer frame (in this case, a 3x3 meter planar squared shape) by using continuous horizontal and/or vertical supporting rails matching the existence of slabs or walls, respectively, with supporting brackets fixing them (Fig. 12A); or, (2) using punctual supports with or without articulated joints that either fix specific connecting points between triangular panels (Fig. 12C) or adapt their inclination to neutralize the existing *module-structure* misalignments (Fig. 12D). In either case, the resulting facade design presents an air space layer between its loadbearing and cladding structures (Fig. 12B), which is advantageous in terms of not only thermal insulation, substantially improving the building thermal efficiency, but also structural behavior, increasing air circulation and thus reducing the air pressure difference between inside and outside spaces [43].

6 Discussion

In this section we discuss the previous results and make some final considerations on the proposal's flexibility in terms of design exploration, ability to automate the production of construction details and technical documentation, and potential to extend creative processes.

Regarding the first stage, the framework facilitated the implementation of the design intent due to reducing the time and effort spent with the programming task. It also facilitated iterative design changes and the integration of different design constraints and requirements, such as obtaining a certain geometric irregularity and responding to different shading and privacy needs. As, during this process, immediate feedback was provided, the process evolved in a more conscious and informed way, increasing our perception of the solutions and the impact of our changes and, therefore, allowing satisfactory results to be achieved more quickly. This, in turn, enabled us to spend more time and effort on creative tasks, exploring a wider design space and considering design solutions and strategies beyond those initially imagined.

In the second stage, the framework made it easier to apply iterative design changes and quickly produce design variations, increasing the perception of the impact of design changes and, thus, guiding the design's incremental refinement. Having an informed decision-making process allowed us to more easily balance the design intent with not only the privacy and shading requirements but also its feasibility. Moreover, the framework also reduced the time and effort needed to detail the solution, automatically generating panels with folded ends fitting the design's geometry and selected fabrication scheme. Given its algorithmic nature, we could also easily manipulate the size of the produced details according to context-specific structural and aesthetic requirements.

Regarding the third stage, the available manufacturing algorithms made it easier to materialize the solution into a small-scale prototype, which was critical to increase our perception of the design's physical outcome and, therefore, guide future design changes. As the framework automates the production of construction documentation, it also ensures its accuracy and adaptation to the selected manufacturing strategy. In this case, it generated unfolded drawings of the panels using the respective line types for cutting, folding, and engraving purposes. Furthermore, its algorithmic nature allowed us to easily combine the framework with an external AD library and benefit from a wider range of manufacturing-related functionalities. In this case, this flexibility allowed us to, in a first stage, create custom labels on the panels to guide their assembly process and, in a second one, arrange the manufacturing documentation in a way that minimized material waste.

Finally, in the last stage, the framework allowed us to test different construction schemes, while assessing their impact on the solution's aesthetic quality. As, during this process, the construction details were automatically updated to accommodate the design changes and the experimentation of different construction schemes, the resulting digital model and corresponding technical documentation were always up to date. This not only spared us from this hardworking and time-consuming task, but also decreased the chances of accumulating design errors, smoothing the transition between creative exploration and realization.

Based on the previous results, we conclude that the proposed framework and workflow were successful in:

- supporting the ever-changing nature of architectural design problems,
- increasing the time available for creative tasks,
- integrating different requirements in the design exploration process,
- smoothing the transition between design exploration and fabrication stages,
- balancing construction and aesthetic preferences.

Despite being still under development, the proposed framework extension proved to enhance AD processes, especially those addressing the design of building facades. It not only reduced the programming effort, but also increased design flexibility and the workflow fluidity, lowering the barriers between design stages and their specific design tasks and information, while allowing critical creative rethinking from design conception to fabrication.

7 Conclusion

Architecture is guided by both design and construction principles [13], which means that creative processes have to consider the construction viability of the solutions [14]. With the emergence of computational design approaches, architects gained unprecedented design freedom [1], facilitating the development of unconventional design solutions. However, their realization is often constrained by the limitations of the available manufacturing technologies. We addressed this problem by using Algorithm Design (AD), a design approach based on algorithms that has several advantages for the design and construction of architectural solutions. In this paper, an AD workflow was extended to support, not just the architect's design exploration process, but also the subsequent detailing of the solutions for manufacturing purposes.

To evaluate the proposal, we used it in the development of a facade design prototype whose geometric characteristics varied according to different requirements. The results demonstrated its potential to quickly explore multiple facade design alternatives, and effortlessly and conscientiously balance different types of criteria, in this case, aesthetic, privacy, and shading ones. The results also proved its ability to automatically detail the solutions according to different construction schemes, while accurately producing the corresponding technical documentation. Finally, the results also illustrated how the time and effort saved in different manufacturing-related tasks allowed the exploration of a wider range of construction schemes, not only assessing their impact on the solutions' visual expression, but also contemplating other design possibilities beyond those initially considered.

Based on the previous findings, we conclude that our proposal smooths the transition between design exploration and manufacturing stages, especially in what regards the production of construction details and technical documentation. The proposal implementation encompasses multiple design workflows, interoperating with a wide range of digital tools and AD programming environments, including visual-based ones.

For a more complete evaluation of the proposal, we plan to build a full-scale prototype, which was not yet possible to do due to time and, above all, budget constraints. Therefore, as future work, we plan to develop the solution by first simulating its structural behavior in a virtual environment, adjusting both its construction and assembly details accordingly, and then producing a small-scale prototype to assess its structural integrity. After the successful completion of these steps, we will proceed to the construction and evaluation of a full-scale prototype. We also plan to extend the framework with further manufacturing-related algorithms, covering more specific construction requirements and a wider range of fabrication strategies. Lastly, we also intend to apply it in the production of other facade design prototypes with different geometric characteristics and fabrication strategies (e.g., 3D printing or casting).

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