The Right Algorithm for the Right Shape

An algorithmic framework for efficient design and conception of building facades

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List of Abbreviations

AD – Algorithmic Design
ADO – Architectural Design Optimization
AEC – Architecture, Engineering, and Construction
CNC - Computer Numerical Control
DF – Digital Fabrication
GUI – Graphical User Interface
IEQ – Indoor Environmental Quality
SDGs – Sustainable Development Goals

Architecture and design for Industry 4.0: theory and practice
Edited by: Maurizio Barberio, Micaela Colella, Angelo Figliola, Alessandra Battisti
To be published by Springer

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Abstract. Buildings are a critical element of civilization, within which we spend over around 70% of our lifetime, but also one of the main contributors to the greenhouse effect. It is therefore important to ensure their design guarantees good indoor conditions, while minimizing the environmental footprint. Among the different building elements, the facade is one that most influences these two requisites and thus its design requires, in addition to the traditional aesthetic and functional requirements, the integration of performance criteria from early design stages. However, there are still some barriers to this integration, such as the limited flexibility of design tools, the need for multiple analysis and optimization tools, and their high computational cost. Recent computational design approaches, such as Algorithmic Design (AD), have been facilitating the combination of creative processes with the search for better performing and more sustainable design solutions. However, these approaches require programming skills, which most architects do not have. To maximize its potential for architectural design, efforts should be made to reduce the complexity of AD and approximate it to the architects' design practice. We address this by proposing an AD methodology and algorithmic framework for facade design that encompasses its different stages, from conceptual to manufacturing, and requirements, such as aesthetics, environmental performance, comfort, and costs, among others, while supporting the variability and diversity that is typical of architectural design problems. By combining the framework's ready-to-use algorithms, multiple design scenarios can be considered, and various design requirements addressed, helping to achieve the goals established by both the 2030 Agenda and Industry 4.0.

Keywords: Computational and Parametric Design, Performance-based Architecture, Algorithmic Workflow, Computational Design Analysis, Digital Fabrication.

United Nations' Sustainable Development Goals: Goal 9 – industry, innovation, and infrastructure; Goal 11 – sustainable cities and communities; Goal 12 – responsible consumption and production.

1 Introduction

Buildings are one of the main CO_2 emitters and spenders of energy resources [1–3] but also a critical element of civilization, within which we spend over around 70% of our lifetime [4]. Half of these emissions results from the operational costs of buildings, such as heating, cooling, lighting, and ventilation; and the other half from the construction processes, namely the production, transport, and manufacture of building elements, and material disposal [2]. To meet the United Nation's Sustainable Development Goals (SDGs) [5] building design must provide good indoor conditions while minimizing the environmental footprint.

Among the different building elements, the facade is one that most influences the buildings' Indoor Environmental Quality (IEQ) and environmental performance [4, 6–10]. Therefore, in addition to aesthetic and functional requirements, facade design requires the integration of performance criteria from early design stages, as well as manufacturing-related strategies assessing the construction viability of the developed solutions.

Unfortunately, there are still barriers to such integration. One is the limited flexibility of design tools, hampering the application of iterative design changes in the search for improved solutions. Another is the large computational resources and specialized knowledge needed by analysis and optimization tools [11, 12], resulting in time-consuming and computationally-expensive processes whose results are difficult to interpret. A third barrier emerges when it becomes necessary to use multiple tools that hardly interoperate with each other, increasing the propensity for information loss and error accumulation [12]. A last critical barrier is the time and effort needed to address manufacturing and cost-related constraints [13], especially when dealing with unconventional design solutions. All these obstacles make the integration of performance and manufacturing-related design variables incompatible with project deadlines and resources, hindering the development of more ambitious facade designs whose performance goes beyond minimum regulatory requirements.

Advancements in computational design approaches have improved the integration of performance criteria within the design practice, making it easier for architects to combine creative processes with the search for better solutions in terms of environmental performance, IEQ, production costs, among others [14–16]. Algorithmic Design (AD), a design process based on algorithms [17], is one such approach that allows for (1) greater design flexibility, (2) the automation of repetitive and error-prone tasks, (3) the integration of different types of data in a single model, (4) the coordination of different design tools, such as modelling, analysis, and fabrication tools, and (5) the automatic extraction of technical information. AD has large potential for reducing the environmental footprint and meeting the 2030 SDGs Agenda for a more sustainable built environment [5].

Nevertheless, AD is an abstract approach that requires programming experience, which most architects do not have. To maximize AD's potential for architectural design and motivate the search for more sustainable design solutions, efforts should be made to reduce the technical complexity of AD strategies and make them more accessible to a wider audience. Considering the current state of the art, it is therefore important to systematize and structure the algorithmic generation of design solutions in an architectural-oriented methodology that considers the diversity of architectural design problems and their different aesthetic, performance, and construction requirements. To successfully deal with the variability and context-specificity typical of architectural practice, the proposed methodology must have enough flexibility to adapt to multiple design briefs and workflows, while providing control over the coordination of different types of information and over the translation of digital designs into actual constructions [18–20].

This chapter addresses this goal by placing particular emphasis on the field of facade design due to the aesthetic and performance relevance of this building element, as well as due to its design complexity and impact on the projects' feasibility. Given the universality and problem-solving capabilities of mathematics, this research uses its language to address the above-mentioned goal, adopting a strategy that encompasses:

- The architects' creative process, by systematizing the design complexity of current facade design strategies, while helping with the algorithmic development of new facade design solutions.
- The coordination of different conceptual and performance requirements, by automating analysis and optimization processes from early design stages, providing reliable feedback on the solutions' performance and aesthetical quality.
- The context specificity of architectural design problems, by guiding the selection of geometry- and performance-related algorithms based on the type, scale, and complexity of the problem addressed.
- The materialization of the resulting solutions, informing about their viability in terms of cost, waste, and resources, while automating the production of technical documentation for the selected fabrication strategy.

To that end, an extensive investigation on contemporary architectural processes is first presented, which discusses the impact of the growing environmental awareness and new computational design means on both facade design strategies and the increased complexity of construction processes. A mathematics-based methodology is then proposed, together with its implementation in an AD framework containing different algorithms embracing the complexity of procedural modelling, performance simulation, design optimization strategies, and fabrication techniques. To evaluate the potential of the proposal to support design workflows encompassing creative intents, performance requirements, and fabrication constraints, from conceptual design to manufacturing stages, a set of case studies is then presented and discussed. Finally, the chapter concludes with considerations on the case studies' results, elaborating on the proposal's suitability to meet the 2030 SDGs Agenda and approximate the Architecture, Engineering, and Construction (AEC) field to the Industry 4.0 paradigm.

2 Facing New Challenges

The need to successfully respond to the growing concern with the buildings' ecological footprint motivated the increasing integration of design performance in architecture, triggering new design approaches that go beyond aesthetic and functional levels [21, 22]. As a result, design practices that are more environmentally-aware emerged [23]. Under the names of performance-based, performance-driven, performance-oriented, or even performative design, this design paradigm has been gaining ground in the literature [24–27] as well as in architectural practice, particularly in the design of facades due to the aesthetic and environmental relevance of this building element [7].

2.1 Environmental Concerns

We are currently facing an environmental problem and the AEC sector is one of the main contributors. According to the literature, buildings are responsible for 50% of natural resources consumption, 42% of the total energy consumption, and 35% of greenhouse gas emissions [2], which are among the main contributors for climate change and global warming [28]. Half of these emissions result from the operational costs of buildings, such as heating, cooling, lighting, and ventilation, and the other half from construction processes, namely the production, transport, and manufacture of building elements and the disposal of building materials [2]. In 2012, for instance, buildings were responsible for around 75% of Europe's energy consumption, and almost 70% of it was for space heating [3].

Given the urgent need to minimize the buildings' ecological footprint [3, 4] and stop the growing trend of CO_2 emissions [3], several regulations and incentives were established worldwide [29]. The Building Research Establishment Environmental Assessment Method (BREEAM), first published in 1990, is the oldest method for assessing, rating, and certifying the buildings' sustainability regarding a wide range of environmental issues. This method was followed by several other regulations, including the Kyoto protocol signed in 1997, one of the first initiatives to limit CO_2 emissions; the European Union's Energy Performance of Buildings Directive (2002/91/EC, 2010/31/EU, and COM/2016/0765) targeting the improvement of buildings' energy performance; the U.S. Green Building Council's certification Leadership in Energy and Environmental Design (LEED); and the Japanese Comprehensive Assessment System for Built Environment Efficiency (CASBEE).

The existing legislation, however, requires architects to evaluate the performance of their designs regarding different criteria [11] to ensure the proposed metrics are met [12]. As a result, building design has become an even more demanding task, since it must simultaneously respond to the already existing aesthetic, structural, and IEQ requirements, plus the increasing number of performance metrics established worldwide.

2.2 The Role of Performance Analysis

In the last decades, several analysis tools were released to help architects evaluate the performance of their designs regarding different criteria. Examples of analysis tools include EnergyPlus and TRNSYS for whole-building energy simulations, Radiance for (day)lighting analysis, and DAYSIM for climate-based daylight simulations. Using these tools, architects become more aware of their designs' ecological footprint, as well as the impact of design changes on the solutions' environmental performance [4].

Unfortunately, many practitioners still do not use any kind of digital analysis tool in their design processes and those who do rarely benefit from these tools to support their creative process, using them instead to validate the performance of already well-defined solutions [12, 28, 30]. Moreover, obtaining accurate analysis results remains a challenging task due to the wide variety of factors that affect building performance [4], including external ones (e.g., climate, geographic location, site conditions, etc.) and internal ones (e.g., occupants' behavior [31], spatial orientation [32], envelope transmittance [33], etc.).

The need for specialized knowledge, the lack of intuitive Graphical User Interfaces (GUI), the long computation times, the poor interoperability with the architects' preferred tools, and the idea that analysis tools restrict creative processes are some of the barriers to their widespread adoption [4, 11, 12]. Furthermore, the performance evaluation of a building requires the laborious and time-consuming production of an analytical model containing only the data needed for the intended analysis. Additionally, most analysis tools are single domain, forcing the use of multiple tools to evaluate different criteria, each one requiring a specific analytical model [30], resulting in a process that is prone to information loss and error accumulation [12]. Since a performance-based design process needs to analyze multiple design instances, the number of analytical models required grows considerably. Given the constant pressure for short deadlines in the AEC industry, evaluating an acceptable sample of possible solutions is, usually, an impracticable scenario [11].

To address the need for a faster and more reliable data-flow process suiting the iterative nature of architectural practice and minimize the alternation between different analysis tools, some modelling tools started to integrate their own analysis strategies [34]. However, the proposed solutions present some limitations in terms of (1) modelling flexibility and accuracy, particularly in representing and analyzing less conventional solutions and construction schemes, and (2) information support, often making no suggestions about which design direction to follow and how to translate analysis results into design changes.

2.3 Searching for the Best Performance

Architectural Design Optimization (ADO) was motivated by the need to more effectively explore the design space in the search for better-performing design solutions [11]. By minimizing the buildings' ecological footprint, ADO can contribute to reduce the negative impact of the AEC sector [5].

In addition to simplifying real-world complex problems, often dealing with multiple conflicting requirements [15], into mathematical ones, ADO requires the iterative remodeling of designs and their subsequent performance evaluation to check if the fitness goals are met [28]. As multiple conflicting goals often result in a set of possible solutions that are not optimal for all requirements [15], ADO does not ensure the global optimum is reached [11]. Nevertheless, it increases the chances of finding it or, at least, of getting close to it [29]. In any case, the probability of obtaining more sustainable solutions is still much higher than that of traditional practices where no optimization is applied [11, 35]. Moreover, these processes are important to remind architects of possible design solutions that might otherwise not occur to them [36].

To successfully reduce the environmental impact of buildings, architects need to adopt either passive or active design strategies that consider both the existing performance requirements and the design variables affecting these [28] from early design stages, where major performance improvements can be achieved [37]. Nevertheless, the strategies employed often do not affect the buildings' shape, let alone guide the exploration process in an environmentally driven way. Moreover, only a few requirements are usually considered at initial design stages, e.g., aesthetic and functional ones, the others being typically postponed to later stages, where the design idea is already well-established [28, 38]. However, at these stages, most design changes are quite complicated, or even impossible, due to the lack of flexibility of most design models [38]. As in most cases architects explore the design space by manually adapting the solutions according to a few analysis results [23], only a few and small design changes are often evaluated due to time and effort constraints [12, 14]. As a result, the efficacy of the ADO process often becomes compromised [38], potentially leading to unrealistic or low performance results [28].

3 Sketching Through Algorithms

The technological evolution of the last decades has provided architects with the means to explore unprecedented design solutions, facilitating the production of unconventional facade elements of different shapes, patterns, and materials [39]. In addition to enhancing the architects' creative process, emerging design technologies have been allowing the integration of building performance requirements in an environmentally aware perspective. Combined with the architects' innate desire to go beyond conventional geometries and the usually tight time and economic constraints of architectural projects [12], the process of designing building facades grew in complexity [40]. Fortunately, part of this complexity can be reduced through AD, which provides the flexibility needed to coordinate multiple design requirements and data in the search for more sustainable facade design solutions [3, 4, 6].

3.1 Extending Design Creativity

AD is a design approach based on algorithms that has been gaining prominence in architecture [41–46] and that greatly contributes to the movement of the AEC sector towards both the Industry 4.0 and the United Nations' 2030 Agenda goals. The increased design efficiency, flexibility, accuracy, and automation of this design approach have been motivating a new generation of architects to increasingly adopt AD strategies in their design practice [43]. To do so, however, architects have to acquire new skills, such as learning programming techniques, which often ends up being a barrier to AD's widespread adoption [47].

Two main AD paradigms currently stand out, the main difference between them being the type of algorithmic representation used, which can be textual or visual. Among the two, the visual paradigm is more popular within the architectural community but current practices have evidenced several shortcomings that hinder the development of large AD programs [45, 48, 49], making the long-term use of visual-based AD strategies difficult [50]. The absence of abstraction mechanisms addressing scalability issues [49, 51], the poor intelligibility and difficult manipulation of the resulting AD programs [48, 52–54], the accentuated drop in performance when executing large AD programs [55–57], and the lack of version control mechanisms supporting collaborative design practices [52, 58] are among the limitations of visual AD. All these shortcomings have motivated the transition from this paradigm to the textual paradigm to benefit from the expressiveness and scalability of textual programming strategies [49]. Accordingly, some of the existing visual-based AD tools were extended with textual programming mechanisms [49, 51], such as loop iterations, recursive functions, and higher-order functions. Nevertheless, in most cases, it remains difficult to develop large-scale AD programs in these extended tools due to their inability to support the division of an AD file into multiple files.

Although learning textual programming has become an evident need, the transition from the visual to the textual paradigm is not trivial, often lacking the consolidation of important theoretical bases of textual programming strategies; a drawback that gets even worse when addressing more complex design problems. Moreover, as it still takes time to achieve the level of programming proficiency needed to deal with large-scale design problems, which typically involve multiple context-specific design requirements, architects usually spend more time solving programming problems than in creative and design exploration processes. Also, given the uniqueness and variability of architectural design problems, architects often face unanticipated changes that are not contemplated in the structure of their AD program, lacking the parameters needed to modify the model in the desired way and thus forcing its redesign and delaying the design process [59].

3.2 Algorithmic Analysis and Optimization

The growing awareness on climate change and the need to reduce the AEC sector's ecological footprint has motivated the implementation of several building regulations aiming at meeting the United Nations' SDGs [5]. This has forced architects to increasingly resort to analysis tools to check if their designs meet the established criteria and, when they don't, to rethink their designs and repeat the process, considerably increasing the complexity of their design processes.

With the advent of new computational design approaches, such as AD, these processes can be improved. Besides facilitating design changes and supporting higher levels of design complexity, AD allows automating labor-intensive and error prone tasks such as those of analysis processes, particularly, the generation of analytical models [60] and the setup of analyses whenever the design changes. Therefore, by using AD, it becomes possible to not only perform several iterative design analyses with less time and effort [15], but also automate them in optimization routines and evaluate larger design spaces in the search for better-performing solutions [61].

To address the need to use multiple design tools and evaluate the solutions regarding different metrics, several AD tools started to integrate functionalities that embraced different analysis and optimization strategies. One example is Grasshopper's plugins for (1) structural analysis and form-finding, e.g., Kangaroo, Karamba3D, Millipede, and Peregrine; (2) lighting and thermal analysis, e.g., Ladybug, Honeybee, DIVA, and ClimateStudio; and (3) design optimization, e.g., Galapagos, Goat, Octopus, Wallacei, and Opossum. Other examples include Dynamo's addons for structural, energy, daylighting, and thermodynamic analysis, and optimization.

Nevertheless, despite AD facilitating the application of design analysis and optimization routines since early design stages, their use remains difficult due to (1) the uniqueness and conflicting nature of most design requirements [29]; (2) the need to explore wide design spaces in order to achieve acceptable results [29]; (3) the technical complexity and poor intuitiveness of most analysis/optimization tools; and (4) the need to convert ADO problems into abstract, mathematical formulations [30, 62]. Despite the existing AD tools to solve some of these barriers, they are mostly based on the visual programming paradigm and thus quickly become unable to cope with the complexity typical of large-scale architectural design problems.

The need to make design analysis and optimization strategies more accessible to architects from early design stages has been increasingly addressed in the literature [4, 29, 35, 63, 64]: Schlueter & Thesseling [65], for instance, assessed the integration of a prototype tool to assist energy/exergy calculations from early stages; Petersen & Svendsen [66] presented a proposal to help designers make informed design decisions at early stages regarding energy and inside spaces' environmental performance [66]; Madrazo et al. [67] proposed a method to recover information from repositories, hold calculation results, and support early-stage design decisions; Attia et al. [68] developed an energy-oriented software tool to support the design of zero energy buildings in an Egyptian context; Lin & Gerber [69] presented a framework to guide early-stage design exploration and decision-making processes based on energy performance; Negendahl [70] proposed an alternative method to the current IFC implementation to support early stages design processes combining different design, AD, and analysis tools; Finally, Konis et al. [71] presented a framework to improve daylighting and natural ventilation performances at early design stages.

The proposed solutions, however, do not entirely solve the challenges of early-stage ADO problems due to still presenting (1) limited modelling flexibility; (2) reduced interoperability; (3) few performance criteria; and (4) a narrow scope of application.

4 The Case of Building Facades

Architectural design problems are unique because, besides involving several design requirements that can be global or context-specific, straightforward or abstract, and fixed or evolving, they must respond to unpredictable creative intents and design briefs [3, 4, 40]. The design of building facades is a particularly relevant case because of the environmental impact of this architectural element [7, 8], as well as its design complexity [6, 40] and critical role in improving the IEQ of buildings. Nevertheless, it is often the case that the design means used do not provide the flexibility needed to quickly explore and evaluate a wide range of design solutions, hindering not only the architects' creative process but also the search for more sustainable solutions.

Among its different applications, AD has proved to be particularly advantageous for facade design processes, providing the flexibility needed to coordinate multiple design requirements [21, 72] and thus achieve design solutions with reduced environmental impact and minimum energy demands. Moreover, AD motivated the gradual shift towards Industry 4.0, allowing not only the automation of manufacturing and construction processes, reducing their production times, energy consumption, and resource waste, but also the production of unconventional facade elements whose manufacture was previously not viable [73–75].

4.1 Geometric Exploration

To reduce the complexity of AD and facilitate the algorithmic development of facade design solutions, several AD tools were released. One example is ParaCloud Gem, a generative 3D design tool that provides features to (1) map 3D elements on a mesh, (2) subdivide and edit surfaces, (3) integrate fitness requirements, and (4) 3D print the resulting solutions. Another example is Dynamo's packages Quads from Rectangular Grid, Ampersand, Clockwork, LunchBox, MapToSurface, Pattern Toolkit, and LynnPkg, which include features for surface paneling, mapping elements on a surface, and pattern creation. A last example is Grashopper's multiple plugins, such as: (1) PanelingTools, which provides surface paneling functionalities and rationalization techniques for analysis and fabrication; (2) LunchBox, which integrates functionalities to explore mathematical shapes, surface paneling, and wire structures; (3) Weaverbird, which contains mesh subdivision procedures and mechanisms to help prepare meshes for fabrication; (4) Parakeet, which provides functionalities to develop algorithmic patterns resulting from tiling, geometric shapes and grid subdivisions, edge deformation, etc.; and (5) SkinDesigner, which includes mechanisms to produce facade designs made of repeating elements.

Despite facilitating algorithmic activities typical of facade design processes, such as creating point-grids on a surface, mapping elements in different ways, manipulating the elements' size, shape, rotation, etc., by applying rules or attractors, these tools still present some limitations. The first shortcoming is the fact that most of these tools are based on visual programming and thus suffer from the limitations of this AD paradigm [48, 49], particularly, scalability. Another limitation is the tools' limited ability to directly address relevant facade design concepts such as materiality and tectonic relation between elements, often only addressing generic panelization, subdivision, and population of surfaces. Finally, most of these tools are limited by the available predefined operators, which can hardly be configured by the user to respond to more specific problems [45].

4.2 Analysis and Optimization

Building facades are one of the most optimized elements in architecture because of their important role in the buildings' environmental performance [4, 11, 12, 29, 63, 76–79], their design greatly contributing to meet the United Nations' goal of making the production and consumption of cities sustainable. Fig. 1 presents a set of architectural examples whose building envelope design was guided by performance.

Fig. 1. Institut du Monde Arabe (©authors); Campus Kolding of the University of Southern Denmark (©Henning Larsen); Al Bahr Towers (©Andrew Shenouda); Louvre Abu Dhabi (©authors); City Hall (©authors).

To deal with the design complexity of this building element and its multiple and context-specific design requirements, several facade-oriented optimization methodologies have been proposed in the literature. These include Bouchlaghem's [80] computer-based model to design building facades based on their thermal performance; Wang et al. [81] multi-objective optimization model to design green buildings; Ochoa and Capeluto's [79] model to materialize design ideas based on climate and visual comfort strategies; Gagne and Andersen's [82, 83] tool to guide facade design exploration based on illuminance and glare levels; Jin and Overend's [84] optimization prototype to identify optimal facade designs regarding functional, financial, and environmental requirements; Gamas et al. [85] study on the use of evolutionary multi-objective algorithms to optimize building envelopes in terms of thermal and daylight performance; Elghandour et al. [86] method to improve facade design daylight performance; and finally, Pantazis and Gerber's [87] agent-based framework for generating, evaluating, and optimizing facade designs from early design stages.

Despite the extensive literature, most proposals are (1) context-specific [79, 81, 83], (2) have limited modelling flexibility [80, 81, 83, 84], (3) address a single requirement (mostly energy consumption) [80, 83], and (4) require knowing in advance which optimization technique best suits a specific problem (a task that needs experience and specialized knowledge) [81, 84]. These limitations therefore make the proposals' widespread application often difficult, forcing architects to master and use an extensive range of tools/strategies to address the multiplicity of requirements guiding facade design problems. Moreover, some proposals do not present a GUI displaying the resulting solutions [80, 81, 84], making their use little intuitive and insufficiently user-friendly, or do not directly communicate with the design tools architects use [79–81, 84], often leading to interoperability issues and increasing the efforts associated with the transition between tools. The existing exceptions [82, 86, 87], however, are based on visual programming, thus sharing its limitations [49].

5 Making Digital Real

The desire for unprecedented shapes and structures has always been present in architecture, becoming further accentuated with the emergence of digital design tools, which provided architects with the freedom to design any shape they wanted. However, given the limitations of traditional construction methods, the realization of such shapes is often compromised. Digital Fabrication (DF) strategies are gradually changing this reality, albeit still with some limitations [88]. By combining DF with AD strategies, architects can control the entire design-to-manufacturing process in an informed way, reducing the distance between design thinking and making [89, 90], which is critical to bring the AEC sector closer to the Industry 4.0 and ensure sustainable industrialization and production.

5.1 Digital Fabrication Strategies

DF encompasses fabrication strategies based on Computerized Numerical Control (CNC) machines that automate manufacturing processes and the production of building elements of varying geometries and materials. These methods allow architects to control the entire design-to-fabrication process in an entirely digital manner [89] and not only achieve higher levels of design complexity and accuracy, but also produce nonstandard building elements that would otherwise be unviable to produce [91].

Ideally, DF strategies would enable the conversion of traditional manufacturing processes, where only the mass production and assembly of standard elements is economically viable [89], into new ones benefiting from mass-customization strategies to produce multiple unique elements at low costs [92]. This scenario, however, remains a challenge in the AEC industry because of the uniqueness of architectural projects, which require the production of multiple context-specific elements [92], and the limitations of the available manufacturing technologies in terms of cost, machining time, scale limitations, material waste, and special spatial conditions. Nevertheless, their gradual cost decrease is motivating their increasing use in architecture [93].

DF encompasses a wide variety of manufacturing strategies that vary in terms of (1) the process used to shape the elements, e.g., by adding, removing, cutting, or deforming materials; (2) materials supported, (3) element shapes and scales allowed; and (4) type of surface finishes created, e.g., smooth, textured, printed, perforated, bumped, etc. DF strategies are generally categorized into five groups of manufacturing processes, namely *additive*, *subtractive*, *formative* [91, 93–96], *cutting* [89, 97, 98], and *robotic* [99].

The first one, *additive*, is based on the addition of material layers to produce the desired shape [91], requiring the translation of the digital model into a sequence of two-dimensional paths [89]. 3D printing is the most popular *additive* process in architecture but there are other techniques available, such as stereolithography, fused deposition modelling, laser sintering, and digital light processing [91, 96]. These methods have the advantage of directly converting digital models into physical elements without requiring additional devices and allowing the production of a wide range of shapes in a viable way [96]. Moreover, the available machines are often silent, produce reduced material waste, and do not require programming expertise [89]. Among their limitations are the difficulty to produce large-scale building elements [93], the poor surface finishing quality achieved, and the large production times [96]. Examples of 3D printed facade elements include those of the *Arachne project* in China (Fig. 2 left), the *Cabin of 3D printed Curiosities* in California (Fig. 2 middle); and the *Europe Building* in Amsterdam (Fig. 2 right).

Fig. 2. Additive manufacturing: Arachne 3D printed facade (©Archi-Solution Workshop); House of 3D Printed Curiosities (©Matthew Millman Photography / Emerging Objects); EU Building 3D printed facade (©Ossip van Duivenbode).

The second group, s*ubtractive*, uses electro-, chemically, or mechanically reduced techniques to remove or separate particles of raw material from an existing solid [91, 98] to achieve the desired shape [93]. In architecture, CNC milling and routing processes are the most applied techniques [93]. Compared to *additive* processes, these technologies support a wider range of element scales and materials, have a higher geometric precision and production efficiency [89], but also produce a lot more material waste [91]. These methods have been applied in architecture, for instance, to (1) carve facade elements, e.g., the cork panels of a house in Aroeira, Portugal (Fig. 3 left); (2) perforate and bump sheet facade panels, e.g., the metal panels of *de Young Museum* in San Francisco (Fig. 3 middle); and (3) produce customized molds to cast facade elements, e.g., the concrete facade of *MaoHaus* in Beijing (Fig. 3 right).

Fig. 3. Subtractive manufacturing: cork facade (©GenCork and Sofalca); De Young Museum (©David Basulto via flickr); MaoHaus facade (©XiaZhi ou ©Antistatics).

The third group, *formative*, uses mechanical forces to reshape or deform materials into the intended shape [93], often resorting to heating to make the material adapt to the new geometry and then to cooling to keep the new geometry stable [89]. CNC folding, CNC bending, CNC punching, hydro morphing, and welding are some examples [91]. In architecture, these techniques have been mostly applied in the manufacturing of (1) unconventional metal panels [92], such as those of the *Experience Music Project* in Seattle (Fig. 4 left), and (2) heat-slumped or heat-bended glass facade elements [100], such as those of the *Holt Renfrew flagship store* in Vancouver (Fig. 4 middle) and the *Elbphilharmonie* in Hamburg (Fig. 4 right), respectively. Nevertheless, given the still expensive price of both the machines and material used by these methods [91], their use remains limited in the field.

Fig. 4. Formative manufacturing: Experience Music Project (©Jon Stockton / CC BY-SA 3.0); Holt Renfrew flagship store in Vancouver (©Marc Simmons / FrontInc); Elbphilharmonie Hamburg (©Bahman Engheta / CC BY-SA 4.0).

The next group, *cutting*, involves the extraction of two-dimensional planar elements from surfaces or solids by using strategies like contouring, triangulation, and unfolding, among others [91]. These processes follow a set of instructions provided by the digital model to produce flat components with the desired shape [93], often resorting to laser-beam, plasma-arc, and waterjet technologies. *Cutting* is a very popular strategy in the field, probably the most used one [89, 98], especially to produce complex facade panel patterns. Among its advantages are its geometric precision and both its reduced cost and production times. Among its limitations are the limited range of materials and thicknesses supported and the need to adapt the technology used accordingly [89, 98]. Examples of its application include the ceiling of the *Trumpf Campus Gatehouse* in Stuttgart [101] and the facade panels of the *Megalithic Museum* in Mora, Portugal (Fig. 5 left examples).

The last group involves the use of *robotic* arms or drones to accurately place elements in layers by controlling their location and position. These methods make it possible to reduce or even remove the lack of accuracy typical of manual assembly processes, allowing a rigorous correspondence between the intended design and its final product [95]. Examples of robotic strategies include the brick facades of the *Chi She Gallery* and the *Winery Gantenbein* in Switzerland (Fig. 5 right examples).

Fig. 5. Cutting and robotic manufacturing: House 77 by dIONISO LAB (©FG|SG Fotografia de Arquitetura); Megalithic Museum by CVDB Arquitetos (©Fernando Guerra | FG+SG); Chi She Gallery (©Su Shengliang ou ©Trevor Patt); Winery Gantenbein (©Christoph Kadel via flickr).

5.2 Balancing Creativity and Feasibility

Despite the currently available mass-production techniques to manufacture non-conventional elements at low cost, none of them is entirely suitable to deal with the geometric diversity of architectural design, which usually requires the manufacturing of hundreds or thousands of non-standard elements [92] that are often project-specific. To make the construction of free-form shapes and complex facade patterns possible, architects have been increasingly adopting *geometric optimization* techniques [102] in their design practice. These strategies allow architects to gain more insight and control over their designs [40], facilitating the latter's gradual adaptation until reaching the desired feasibility [13]. Popular examples of geometric optimization strategies for architectural design include *design rationalization* and *surface paneling*.

Design rationalization is an example of a *geometric optimization* strategy that focuses on subtly adjusting the building elements that are expensive to produce until meeting the established economic and construction requirements and without compromising the design's aesthetics [92, 103]. Based on the literature [13, 40, 104–106], design rationalization can vary in terms of temporal application in the design process, i.e., before, during, or after the design development process, and target of the rationalization process, i.e., the building elements to which it is applied, e.g., frames, facade panels, wall tiles, and shading devices. Fig. 6 presents some architectural examples resulting from the application of rationalization strategies at different design stages.

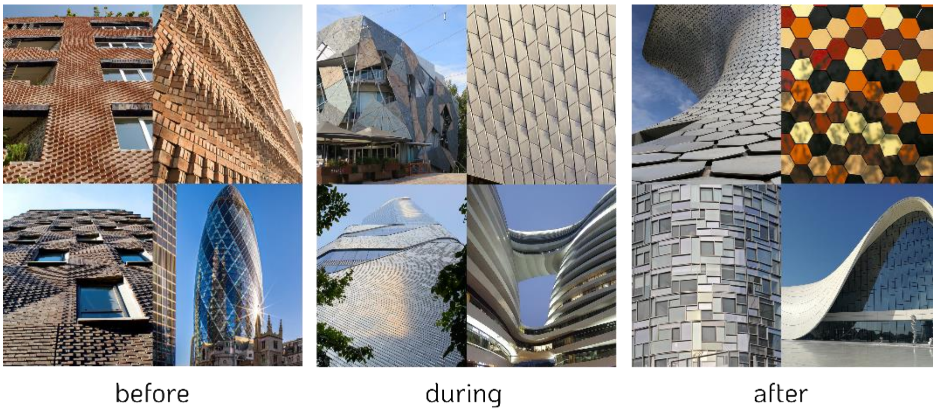

Fig. 6. Architectural rationalization (from top-left to bottom-right): DIY For Architects (©Sstudiomm); South Asian Human Rights Documentation Centre (©AnagramArchitects); Federation Square by LAB architecture studio (©authors); MAAT (©Hufton+Crow/AL_A); Museo Soumaya by FR-EE / Fernando Romero Enterprise (©naturemyhome via Needpix); Spanish Pavilion 2005 (©Edmund Sumner); 290 Mulberry Street by SHoP Architects (©Amy Barkow); 30 St Mary Axe by Foster + Partners (©Suhail Akhtar via flickr[1]); Bangkok Central Embassy (©Hufton+Crow/AL_A); Galaxy SOHO by Zaha Hadid Architects (©authors); 100 11th Avenue by Ateliers Jean Nouvel - delivery architect: Beyer Blinder Belle Architects (©Philippe Ruault); Heydar Aliyev Center by Zaha Hadid Architects (©Aleksandr Zykov via flickr).

Panelization, or *paneling*, is a geometric optimization strategy that focuses on dividing a large surface into smaller panels of constructable size and acceptable cost, while preserving the design intent [92, 106, 107]. This strategy involves two dependent tasks: the segmentation of the original shape into smaller pieces and the approximation of each smaller piece to a shape that can be manufactured at a reasonable cost.

Dividing a surface into smaller planar surfaces of different polygonal shapes, like triangular, quadrilateral, and polygonal, is the cheapest paneling strategy. Another strategy involves the division of the original surface into smoothly bent stripes, also known as single-curved panels or developable surfaces, that can be produced by simply bending a flat piece of metal sheet; a

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[1] https://www.flickr.com/photos/192540662@N04/

technique that has been showing gradual improvements over time [106]. Another paneling strategy focuses on dividing the surface into double-curved perfectly fitting panels, resulting in smooth curved surfaces with a high finishing quality. Among the three, the last strategy is the most precise but also the most expensive as it often requires the production of several customized molds [107]. Fig. 7 presents some examples of paneling strategies organized by type.

Despite the variety of existing technologies and architectural examples, the production of large-scale free-form facades with either unconventional or intricate geometric patterns remains a challenging, and often expensive, task [107–110]. Moreover, the existing literature and practical examples mostly focus on simple patterning techniques, i.e., triangular, quadrangular, and hexagonal panels, rarely considering other shapes or geometric patterns.

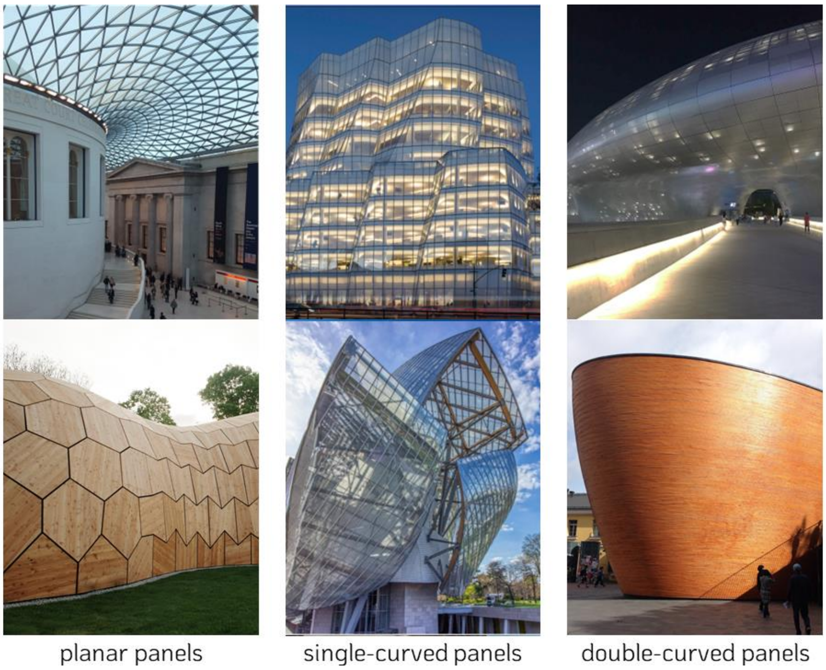

Fig. 7. Paneling strategies (from top-left to bottom right): British Museum Great Court (©authors); IAC building (©Peter Miller via flickr); Dongdaemun Design Plaza (©authors); Landesgartenschau Exhibition Hall (©ICD/ITKE/IIGS University Stuttgart); Foundation Louis Vuitton (©BarrieT via flickr); Kamppi Chapel (©authors).

To make the digitally produced design solutions feasible, several tools were released to facilitate the manufacturing and assembly of shapes with higher levels of design complexity. These include, among others, the Grasshopper's plugins HAL, FabTools, BowerBird, OpenNest and Kuka|PRC, Xylinus, Droid, RoboDK, Robot Components, Robots, Bark beetle, and Ivy; Dynamo's addons DynaFabrication, Fabrication API, 3BMLabs.DigiFab, and ParametricMonkey; and Blender's addon Laser Slicer. However, as these plugins only target the visual programming paradigm, the manufacturing of more complex solutions is often difficult [45, 48, 49, 51, 55–57]. Moreover, these plugins are mostly tool-specific, requiring the use of tools to assess different construction schemes. Additionally, they do not entirely automate the design-to-fabrication conversion nor the extraction of technical documentation, since they often depend on manual- or script-based interventions that are laborious, time-consuming, and error prone. Given the uniqueness of architectural design problems, these interventions can hardly be reused in different projects without major modifications, thus hindering the testing of different manufacturing possibilities to assess their aesthetic and environmental impact.

6 The Mathematics of Facades

AD has the potential to improve AEC's ecological footprint. However, it has also a higher level of complexity and abstraction that hampers its widespread use. To motivate the adoption of AD, it is critical to provide strategies systematizing and structuring the algorithmic generation of design solutions in an architectural-oriented way. We address this by proposing a mathematics-based methodology and framework to support the algorithmic development of building facades from conceptual to later design stages. The proposed solution considers the wide variety of design briefs as well as different aesthetic intents, performance requirements, and fabrication strategies. Its use promises to decrease the time and effort spent with the algorithmic implementation of new facade designs, while providing the flexibility needed to handle the design complexity and variability of facade design processes.

With this proposal we aim to promote informed design practices aligned with the need to reduce the environmental footprint of the AEC sector. By facilitating design experimentation and the coordination of different types of data and requirements, we expect architects to evaluate wider design spaces within an acceptable time and effort, increasing the chances of achieving more sustainable solutions in terms of energy consumption, environmental impact, waste production, etc. We also aim to increase the control over design-to-manufacturing processes, reducing the gap between what can be digitally explored through AD and its subsequent manufacturing. Lastly, by democratizing design exploration and manufacturing in an AD workflow entirely driven by architects, we also expect to increase the accuracy and quality of the produced solutions, as well as the perception of how different design strategies and DF technologies can lead to more sustainable design outcomes.

6.1 Structuring a Design Theory

To successfully handle the variability and context-specificity of architectural design through AD, we must address the practice's challenges through a computational perspective. Considering that computational tools operate by following a set of instructions, described through programming languages that are increasingly imitating the universally understood language of mathematics, we propose using the latter formalism to (1) structure the AD methodology, (2) define the different AD strategies, and (3) implement both (1) and (2) in an AD framework targeting facade design processes.

During this process, it is important to ensure the resulting methodology supports the *variability* of architectural practice, the *uniqueness* of design briefs, and the *diversity* of existing design requirements in a coherent and flexible way. Clearly, covering all possible design scenarios would be an impossible task. Nevertheless, we believe that by providing the solutions that more frequently occur, or whose application is more generic, we can not only reduce the initial investment required by AD, but also embrace a large range of design scenarios and problems. Moreover, by benefiting from these strategies since early design stages, we expect architects to spend much less time and effort with programming and debugging tasks, sparing them from having to write all the algorithms from scratch each time they start a new project.

Based on a previous analysis of a wide range of contemporary building facades and different facade-oriented classifications [111–115], the proposed methodology and framework is organized in a six-fold structure containing different types of facade design strategies, whose categorization follows an algorithmic perspective (Fig. 8):

1. Geometry: to shape the building facade.
2. Distribution: to differently distribute the facade elements.
3. Pattern: to geometrically manipulate the facade elements.
4. Optimization: to adapt the facade design according to one or more fitness criteria.
5. Rationalization: to control the facade design’s feasibility.
6. Fabrication: to prepare the facade design for manufacturing.

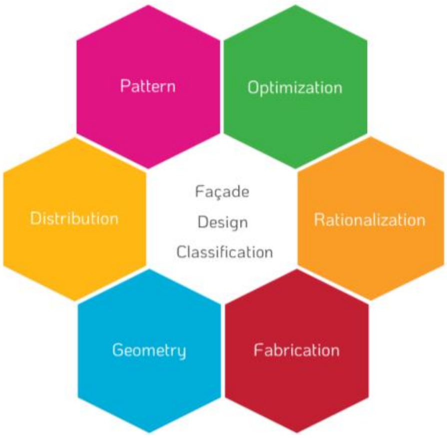

Fig. 8. Algorithmic-based classification of facade design strategies according to their role in the design process.

By using this categorization, the architect is guided towards the most suitable algorithms in terms of design intent, performance requirements, available resources, and construction means. Not only does this resolve many of the limitations found when using AD, particularly those related with the programming task, but it also facilitates the architects’ response to the context-specificity and variability of design processes. The idea to use generic solutions to recurrent design problems draws inspiration from previous works [47, 116–121], which focused on providing sets of predefined reusable algorithms to reduce AD’s initial investment. Nevertheless, our solution has the novelty of (1) focusing on the textual programming paradigm, benefiting from its scalability and expressiveness; and (2) going beyond initial design stages, integrating relevant design strategies and specialized tools beyond those of geometric exploration processes, such as analysis, optimization, and fabrication. Some of the predefined AD strategies are illustrated in Fig. 9, their mathematical structure and implementation being further elaborated in [122].

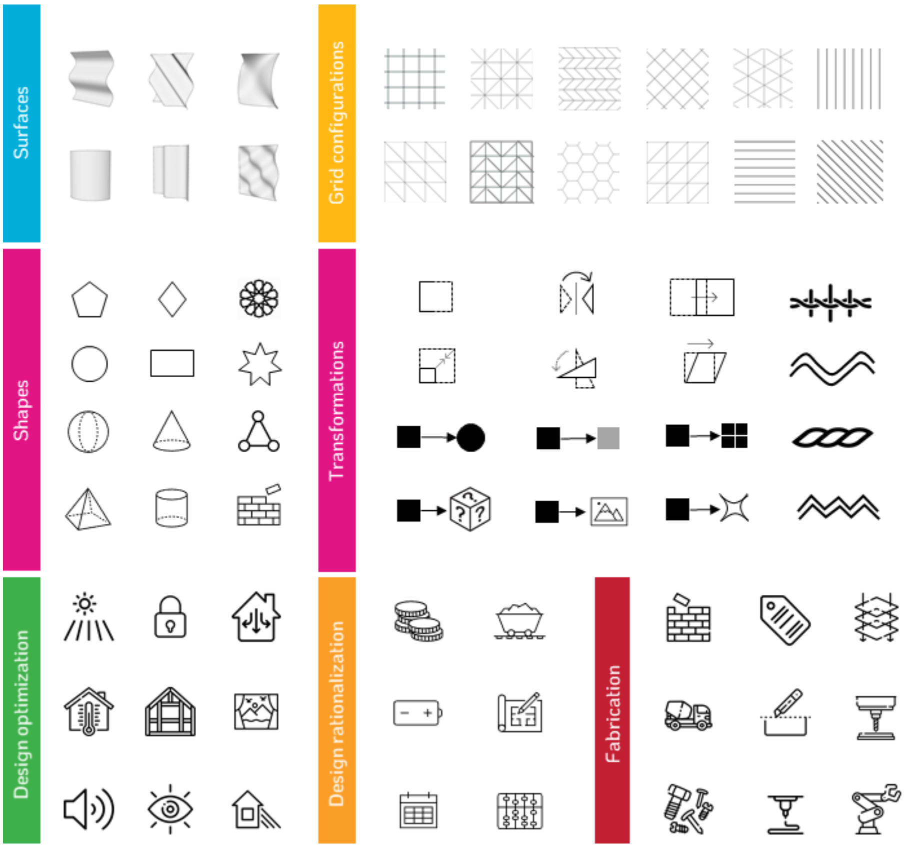

Fig. 9. AD framework conceptual representation: some of the implemented facade design strategies organized by category.

Given the diversity and uniqueness of most facade design requirements, it is not reasonable to expect that this matching process yields a complete algorithmic solution. Our proposal therefore assumes the architect as the one responsible for (1) dividing the whole design into parts, (2) establishing the dependencies between them, (3) instantiating and combining the different strategies dealing with each part, (4) implementing additional algorithms when needed, and (5) evaluating the results. Even so, we believe our proposal will increase the architects' design freedom, while improving the design process precision and ability to adapt to different design briefs. Additionally, by smoothing the design-to-fabrication transition, we expect our solution to improve the coordination between the geometry-, performance-, and fabrication-related information, and thus support more informed design processes towards environmentally aware solutions.

6.2 Conscientiously driven Design Workflows

As mentioned in the beginning of this section, the goal of this research is to simplify the use of AD. To that end, a methodology and framework are proposed, focusing on the field of facade design. To evaluate the proposal's suitability for architectural practice and its ability to support more conscientious design processes, we applied the framework in the development of a set of case studies in collaboration with practice-based architectural design studios without AD skills. Fig. 10 presents an overview of the resulting AD workflows by establishing a correlation between the different design stages and the algorithmic strategies used in each one. Further details of the selected case studies and their results can be found in [123–126].

Fig. 10. Case studies' AD workflow: the design stages encompassed (top) and the algorithmic categories used in each one identified with different colors (below).

The analysis of the previous results shows the ubiquity of the different algorithmic categories in the studios' design process, continuously supporting the architects' different design tasks, while actively coordinating the multiple types of data and tools involved.

Regarding the first example, the aim was to develop a set of facade shading panels made of horizontal wood elements whose size and position addressed different daylight/shading requirements and privacy levels. In the first stage (geometric exploration), the design studio implemented the design intent and explored different variations of it by benefiting from different geometry-related algorithms (Fig. 11, blue, yellow, and pink lines), as well as performance and rationalization ones (Fig. 11, green and orange lines, respectively). While the first algorithms allowed the architects to set geometric constraints and dependencies between them according to their design intent, i.e., creating wood bars of alternating sizes, with the smaller bars randomly varying their length and position; the second algorithms allowed them to iteratively adjust the parameters and dependencies of the geometry-related algorithms, either increasing or decreasing the smaller bars' length and in-between distances, according to the existing shading and privacy requirements. Finally, the rationalization algorithms enabled the architects to gradually decrease the design's geometric freedom to ensure the solution fit the budget, restricting the range of possible sizes for the small bars.

As it is visible in Fig.11, a similar scenario occurred in the following design stages (Design analysis and optimization), since both processes were guided by performance requirements and analysis results (green line) as well as aesthetic and cost considerations (pink and orange lines). The result was a set of design solutions that comply with the architects' creative intent and the existing cost, shading, and privacy requirements, from which the architects could then select the one that most pleased them.

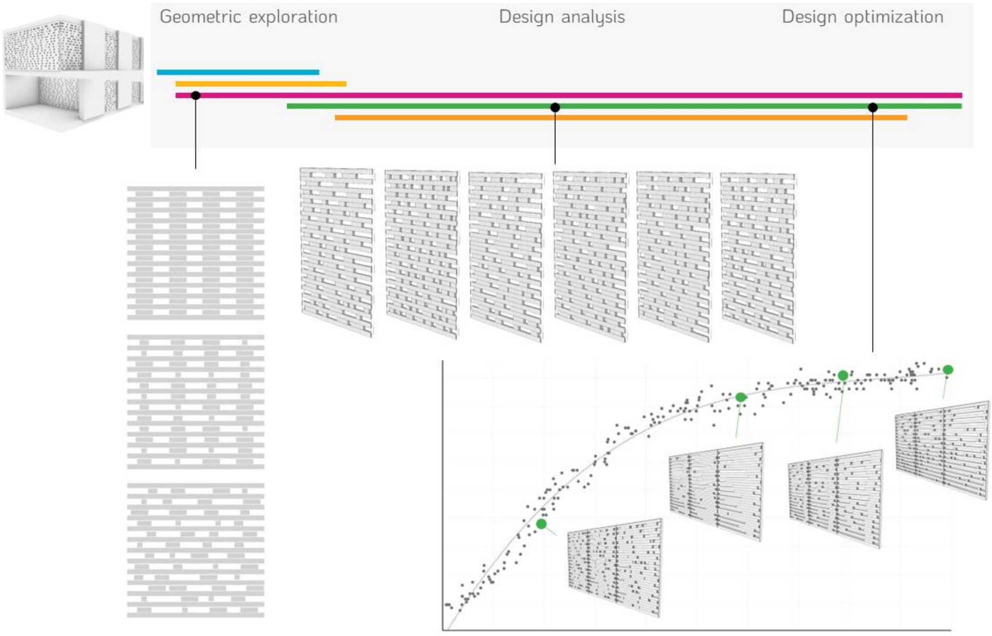

Fig. 11. Design workflow of a set of facade shading panels with some key moments of its AD process (from left to right): design intent implementation, environmentally driven geometric variation, and design optimization.

In the second example the aim was to develop a set of building facades entirely made of *cobogó*-inspired elements of unique sizes and shapes, whose geometric characteristics created a complex, apparently random, visual effect and simultaneously adapted to the building inside functions. Like the previous case study, the first stage (Geometric exploration) benefited from geometry-related algorithms (the blue, yellow, and pink lines in Fig. 12) as well as performance and rationalization ones (the green and orange lines in the same figure).

The same can be said about the second stage (Design analysis), which benefited from the same categories of algorithms to iteratively adjust the design's geometric characteristics according to the existing daylight, privacy, and natural ventilation needs. The result was a set of *cobogó*-inspired elements of different opacity, whose random spatial distribution met the performance needs of each adjacent area (Fig. 12, Design analysis).

Regarding the design optimization stage, it focused on minimizing the solution's fabrication costs (Fig. 12, orange line), by reducing the variety of facade elements, without compromising the design intent and the existing performance requirements (Fig. 12, pink and green lines). This concern was carried over to the ensuing design stage (Fabrication) and coordinated with the available resources and manufacturing means (Fig. 12, red line).

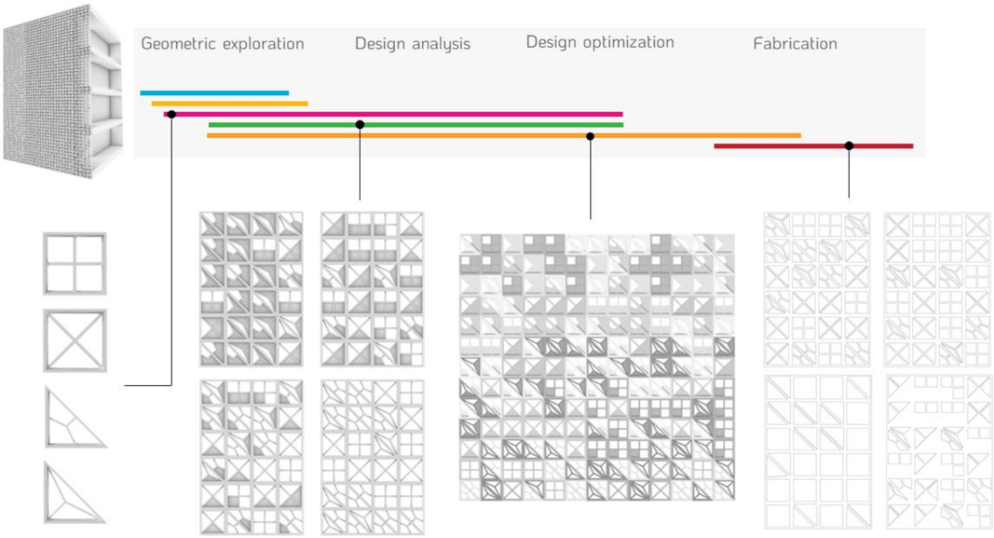

Fig. 12. Design workflow of a set of *cobogó*-inspired facade panels with some key moments of its AD process (from left to right): *cobogó* elements geometric exploration, aesthetic- and performance-based design variations of the facade panels, control of manufacturing costs, and automatic extraction of technical drawings for fabrication.

Regarding the third case study, the aim was to create a visually dynamic brick facade responding to different privacy and daylight requirements. As in the previous examples, all design stages (exploration, analysis, and optimization) resulted from a coordination between aesthetic intents, performance requirements, and economic constraints. As illustrated in Fig. 13, in the first stage (geometric exploration), the architects used different categories of algorithms to implement their design intent, namely (1) geometry-related algorithms (blue, yellow, and pink lines) to generate a facade pattern made of differently sized and randomly distributed and protruded bricks creating punctual voids, and (2) cost-related algorithms to reduce the design geometric freedom, restricting the range of possible brick sizes and protrusion positions. In the second stage (Design analysis), the architects added some performance algorithms to the previous combination to test different design variations with varying levels of permeability and ratios between brick sizes and protrusion positions. In the third stage (Design optimization), the architects used the available rationalization algorithms to control the range of configurations allowed, reducing the solution's manufacturing costs and waste. In the last stage (Fabrication), the architects took advantage of the existing manufacturing-related algorithms (Fig. 13, red line) to detail the solution as well as to extract information about the quantities and position of the existing brick typologies.

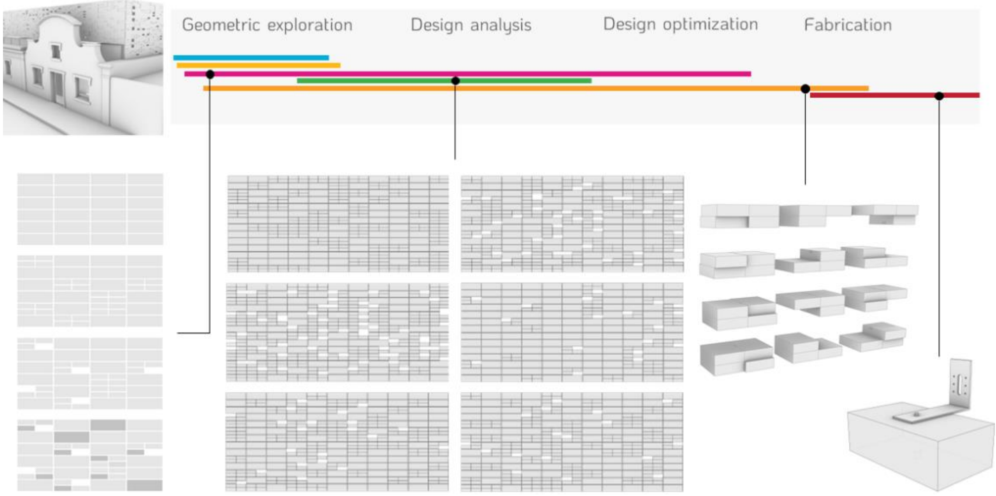

Fig. 13. Design workflow of a brick facade pattern with some key moments of its AD process (from left to right): pattern geometric evolution, aesthetic- and performance-based design exploration, design rationalization, and design detailing.

Regarding the last example, the architects adopted the workflow of Fig. 14, where the different geometry-, performance-, and fabrication-related algorithms all contributed to the design development of a set of unconventional facade panels, from conceptual exploration to manufacturing preparation. In this case study, the aim was to produce a facade design prototype made of different metal panels, whose varying shapes created a visually complex and irregular surface stereotomy and whose different levels of permeability responded to the existing performance requirements.

As illustrated in Fig. 14, the workflow started with the implementation of the design intent, which benefited from geometry-related functionalities, and proceeded with the panels' geometric exploration, coordinating the previous algorithms with performance-related ones. The result was a set of facade panels with the desired geometric irregularity and volumetry and simultaneously presenting different levels of permeability that met the existing shading and privacy needs. The process continued with the integration of additional manufacturing-related strategies, allowing the architects to (1) segment the facade design into smaller parts to facilitate its subsequent assembly and transportation processes; (2) create connection details between the panels, and between the panels and the facade structure; and (3) automatically produce technical drawings for manufacturing (in this case, laser cutting), while benefitting from labeling and nesting strategies to reduce both material waste and assembly complexity.

As it is visible in Fig. 14, the architects also benefited from the available fabrication strategies during the geometric exploration of this case study. By coordinating the design intent with manufacturing constraints, the architects could extend their creative process, not only increasing the range of construction schemes considered, but also gaining a better insight on the impact of each manufacturing scenario on the solution’s aesthetic quality.

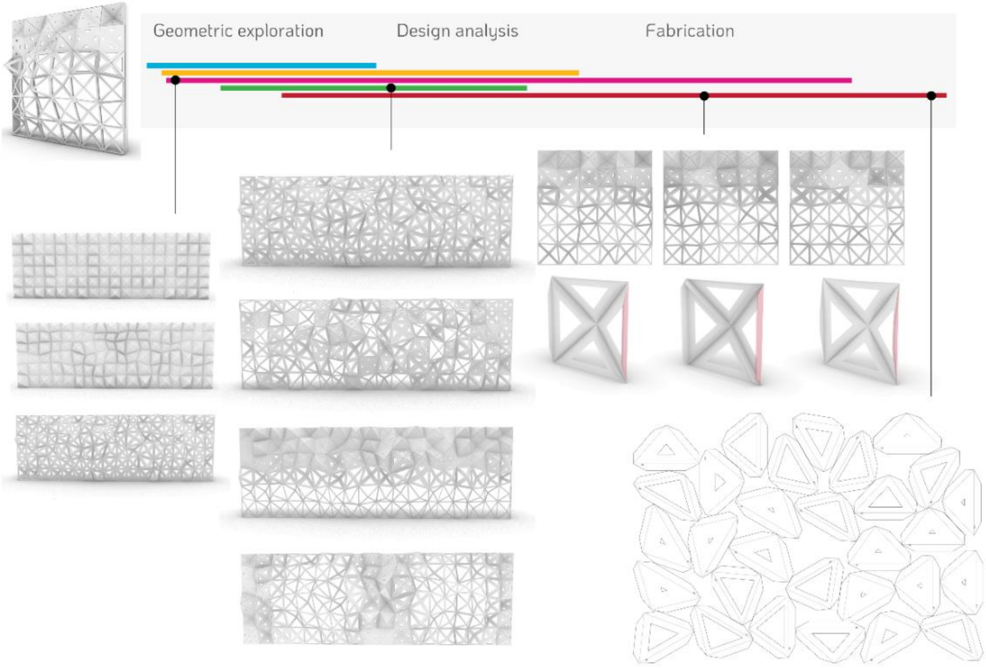

Fig. 14. Design workflow of a facade design prototype with some key moments of its AD process (from left to right): design intent implementation, aesthetic- and performance-based design exploration, design detailing, and manufacturing documentation.

7 Discussion and Final Considerations

Buildings are one of the main contributors to the greenhouse effect, which explains the growing concern about reducing their environmental footprint. Given the great influence facades have on the environmental performance of buildings, their design has been increasingly integrating performance requirements in addition to the traditional aesthetic and functional constraints. Recent computational design strategies, such as Algorithmic Design (AD), have lowered the barriers to the adoption of performance-based design strategies, but their use remains shy in the field mostly because of their technical complexity and level of abstraction.

Nevertheless, to meet the 2030 Agenda’s and Industry 4.0 goals of creating more sustainable built environments, architects must adopt AD strategies. To help such adoption we propose reducing the complexity of AD approaches by structuring a methodology and framework containing different algorithmic strategies that can be easily combined in the development of new design solutions. Given the environmental relevance of building facades, the proposal focuses on this building element, encompassing not only its different stages and requirements but also the variability and diversity of architectural design problems. The aim is to support AD workflows that coordinate aesthetic, performance, and construction requirements in a flexible and responsive way since early design stages, promoting the search for more sustainable solutions.

7.1 Design Workflow

To evaluate the proposal, we applied the framework in a set of case studies developed collaboratively by architects with and without AD skills. Multiple design scenarios were considered, and various design requirements addressed. Based on the results, we conclude that the use of the AD framework improved:

1. The design freedom – given the ease with which architects could select and combine different algorithmic strategies and apply iterative design changes, multiple design variations were tested in all case studies, and a wide range of design scenarios was considered.
2. The coordination between different requirements since early design stages – given the solutions' algorithmic nature and parametricity, the architects could easily apply performance and manufacturing-related principles to drive geometric exploration processes and the other way round, i.e., using geometry-related principles to guide design optimization and fabrication.
3. The architects' decision-making processes – the design freedom combined with the flexible integration of different types of data provided architects with more insight on the quality of the solutions as well as on the impact of their design changes.
4. The design space explored – because of the greater design freedom and coordination between different requirements, architects could devote more time to creative exploration, increasing the range of solutions considered.
5. The quality of the solutions achieved – as the architects' decisions were more informed, they could more easily guide the design development process towards better solutions.
6. The control over design-to-manufacture – the ability to automatically extract technical documentation for manufacturing, combined with the flexibility to test multiple design variations, allowed architects to consider multiple construction scenarios, while assessing the impact each one had on the solution's aesthetic and sustainability.

Despite not considering all possible design scenarios, our proposal was successful in responding to the most common design problems, while adapting to more specific circumstances when needed. In these cases, the developed extensions were then incorporated into the AD framework, becoming available for future use. The possibility to incrementally extend the framework with the results of its practical application is intentional, allowing us to not only increase the range of predefined strategies available, but also refine and adapt the existing ones to real case requirements and constraints.

7.2 Meeting Sustainable Development Goals

Despite the simplicity of the presented case studies, they demonstrate the potential of the proposed methodology and framework to support AD workflows and promote more informed design processes towards more sustainable facade design solutions. As the integration and coordination of different performance requirements is facilitated, architects are left with more time to explore the design space and consider other solutions beyond those initially imagined. This in turn allows architects to gain more control over the design development process, increasing the chances of achieving more sustainable solutions that meet the 2030 SDGs Agenda of making the built environment sustainable in terms of production and consumption [5].

This ability is visible in the first case study, when the architects combined performance analysis results with their aesthetic preferences, ensuring the obtained solutions complied with both the design intent and the performance requirements. Besides guiding the design space navigation towards the architects' preferences, the proposed solution facilitated the analysis of the trade-offs between aesthetic and performance requirements.

The case studies also proved the ability of the proposal to facilitate the concretization of less conventional design solutions, while increasing their production efficiency and sustainability by minimizing both energy consumption and waste. This was demonstrated by the second and third case studies, where the architects gradually reduced the cost and material waste resulting from the solutions' manufacturing without compromising the design intent and performance requirements.

To sum up, we conclude that the proposed AD methodology and framework allowed architects to approximate their creative thinking with the design making, a critical step towards the Industry 4.0 and its goal for sustainable industrialization and production.

Acknowledgements

This work was supported by national funds through *Fundação para a Ciência e a Tecnologia* (FCT) (references UIDB/50021/2020, PTDC/ART-DAQ/31061/2017) and the PhD grant under contract of FCT (SFRH/BD/128628/2017).

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