Connecting Design and Fabrication through Algorithms

Current and Future Prospects for AEC

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Connecting Design and Fabrication through Algorithms: Current and Future Prospects for AEC

Algorithmic Design (AD) tools enable the creation of geometrically complex architectural shapes that might be challenging to manufacture. This paper presents an overview of recent design-to-fabrication processes based on AD. It reflects on how AD can help overcome fabrication limitations and enhance the connection between architectural geometry, material, and manufacturing, approximating design exploration and construction.

After analysing the literature on AD-based design-to-fabrication processes, the research identifies methodological trends, showing that AD is often used to increase (1) design flexibility, (2) tool interoperability, and (3) control over design manufacturing. It also reveals that custom and standard algorithms are equally used at early-stage design tasks, but that custom algorithms are markedly more used at later stages, where the amount of data and level of detail are higher. The research concludes with a critical reflection on the still-existing design-to-fabrication barriers and proposes future research directions.

Keywords: algorithmic design; architectural design; digital models; design-to-fabrication; design materialization.

1. Introduction

Architecture is about designing and constructing spaces that improve human experience and adapt to ever-changing social and environmental demands. To that end, the practice has always embraced the latest technologies, triggering new design approaches and methodologies. One recent example is Algorithmic Design (AD), a design approach based on algorithms [1] that increases design efficiency and flexibility, expanding both creative thinking and construction possibilities. However, compared to many other economic sectors that experienced significant productivity improvements through the adoption of computational strategies by the end of the 20th century [2], the Architecture, Engineering, and Construction (AEC) sector was slower in making this transition [3–5]. This might be explained by the sector's fragmented nature [6,7], its traditional heavy reliance on manual processes [8], and the uniqueness of both its problems and products [6,8]. Another explanation is the still low investment in learning and integrating AD into practitioners' daily routines. This hesitation stems, in part, from the significant changes that AD entails in terms of design conception, representation, and production [2,6,9,10], together with its large training times and small immediate return [11].

To promote the integration of AD in AEC, several companies, such as Front, AECOM, SmartGeometry, and Ghery Technologies (currently Trimble), were formed in the late 90s and early 00s. By adopting more advanced design approaches [11], these companies provided specialized services for designing and constructing less conventional geometries. Similarly, some design studios, such as Skidmore, Owings & Merrill (SOM), Zaha Hadid Architects (ZHA), Grimshaw, and Foster+Partners, also started to integrate AD within their practice, developing in-house algorithmic strategies to support the development of innovative design solutions [11].

In the last decades, the adoption of AD has been visibly increasing in AEC, particularly because of its ability to deal with the practice's increased complexity and efficiently coordinate the architects' creative nature with performance and feasibility constraints. The geometric freedom allowed by AD has, nevertheless, promoted the design of unprecedented shapes [2,12] that defy traditional construction methods [4,10,13,14]. Fortunately, AD also provides the support needed to fabricate such shapes [15], which would otherwise be not viable to produce [2,12,14]. By increasing architects' control over manufacturing processes and improving communication with other specialists, AD leverages the involvement of architects in design-to-fabrication processes, approximating design exploration and fabrication [5,10,13,14]. Together with more advanced manufacturing technologies, such as Digital Fabrication (DF) tools, AD opens the possibility of materializing nonstandard building elements almost without human intervention [10,12], creating new opportunities for AEC.

This paper presents an overview of recent design-to-fabrication workflows based on AD, particularly those addressing less conventional geometries. Following a literature review, the paper identifies methodological patterns and algorithmic trends and reflects on how AD has been closing the gap between design exploration and fabrication. It concludes with some final considerations on the identified barriers and a proposal towards design-to-fabrication workflows with smoother transitions between geometry exploration, materialization, and fabrication.

2. Methodology

This research aims to investigate the role of AD in supporting design-to-fabrication processes of novel and unconventional architectural geometries. To that end, two research questions were posed, namely *How AD has been changing the relationship between architectural geometry and manufacturing?* and *What barriers are still hindering the use of AD in design-to-fabrication processes?* To address these questions, the research adopted the following methodological steps.

2.1. LITERATURE SELECTION

The research started with the selection of literature from three main bibliographic sources – Science Direct, Scopus, and CuminCAD – within the time frame between 2010 and 2022. To narrow the scope of the search, only articles with three or more of the following keywords were selected: Architecture, Design, Digital Fabrication, Manufacturing, Algorithmic Design, Building Design, Generative Design, and Parametric Design. This originated a sample of 723 potentially relevant studies. Based on an analysis of their titles and abstracts, the sample was then filtered to contain the works that aligned with the scope of this research, reducing the original number of studies to 237. Figure 1 organizes the studies by publication type (pie chart) and shows the frequency with which different design and fabrication terms appear in their titles and keywords (bar chart). The pie chart shows a clear prevalence of conference papers in the selected literature, corresponding to 71% of the works. This might be explained by the tendency of this type of publication to focus on processes and workflows from practical examples, closely aligning with the topic of this research. Journal articles, on the other hand, tend to emphasize more on theoretical methodologies and frameworks, often deviating from the scope of this research.

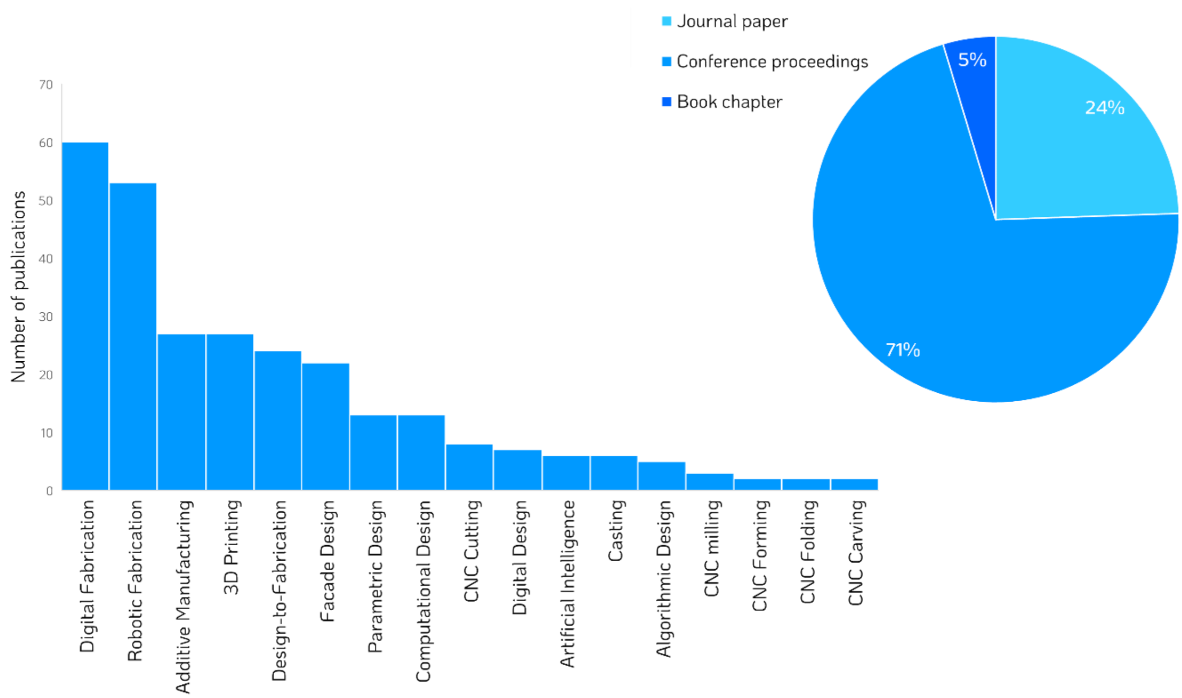

Figure 1. Selected literature: on the left, the frequency of use of different design-to-fabrication terms in the selected works' titles and keywords; on the right: the 237 works organized by publication type.

2.2. Data Collection and Organization

The second step addressed the analysis of the selected literature, placing particular emphasis on the AD strategies used to (1) automate the conversion of geometry into fabrication data, (2) support the transition between design and fabrication stages, and (3) coordinate architectural and manufacturing requirements. The studies that did not provide details about any of these topics were not considered at this stage, further reducing the initial sample to 110 (Figure 2).

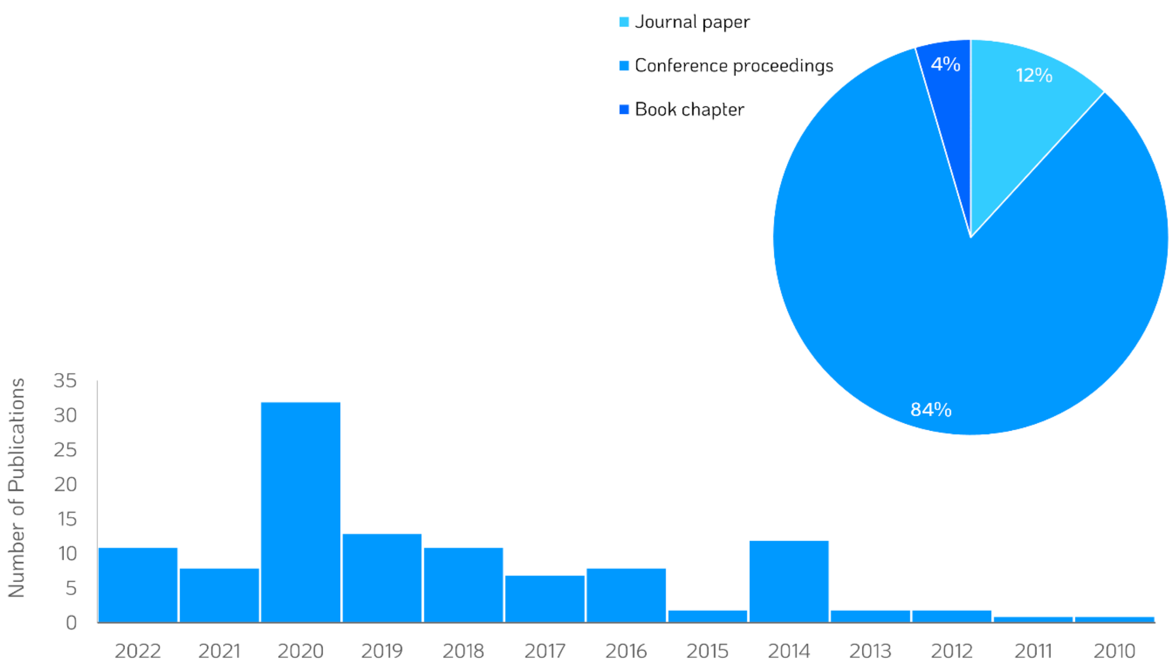

Figure 2. Literature considered for analysis organized by (1) year (bottom/left) and (2) publication type (top-right).

2.3. Literature Analysis

The third step entailed the thorough reading of the previous sample and the organization of a chronological database summarizing each study research context and aim, along with the AD and manufacturing strategies used. The analysis of the database allowed us to identify methodological patterns and frequent design-to-fabrication challenges. It also enabled us to reflect on the merits and limitations of different AD methodologies in converting less conventional shapes into architectural products. The results of this stage are discussed in Sections 3 and 4.

2.4. Discussion

The last research step entailed a critical reflection on the findings of the previous stage and a proposal to enhance the transition between architectural design and fabrication, approximating creative exploration and design materialization. The outcome of this stage is presented in Section 5. After answering the research questions, the paper concludes that the integration of AD in design-to-fabrication workflows strengthens the relationship between design exploration and fabrication, allowing for more efficient and more accurate production of nonstandard architectural products. Even so, the findings also reveal the need to further improve current design-to-fabrication workflows, particularly in converting abstract geometries into specific data for production.

3. Design-to-Fabrication Workflows

The advent of new digital technologies impacted both architectural design and fabrication fields. On the one hand, digital design tools make the design process more efficient and more accurate. On the other hand, new manufacturing technologies, such as DF, make it possible to convert digitally produced shapes into architectural products. With the emergence of AD, architects gained new capabilities in terms of design exploration, simulation, and fabrication, facilitating the development and production of unconventional building elements. This section examines the literature on design-to-fabrication processes based on AD, identifying usage trends in terms of (1) AD tools/libraries and (2) programming languages (PLs).

3.1. AD Tools and Libraries

According to the literature, Grasshopper [16] is the most used AD tool in design-to-fabrication processes, with 56% of the studies mentioning its use (Figure 3). The preference for this tool is because of (1) its ease of use, requiring almost no programming skills to obtain interesting results, (2) its cost-free nature, (3) the extensive support of its online community, and (4) the availability of standard plugins tailored for different design tasks, such as design exploration (e.g., Dendro [17], LunchBox [18], MetaHopper [19], and Weaverbird [20]), structural simulation and optimisation (e.g., Kangaroo [21], Karamba [22], Millipede [23], and RhinoVault [24]), and fabrication (e.g., FURobot [25], HAL Robotics Framework [26], Jeneratiff Digital Fabrication Library [27], Kuka Prc [28], Machina [29], Robots [30], and TACO [31]).

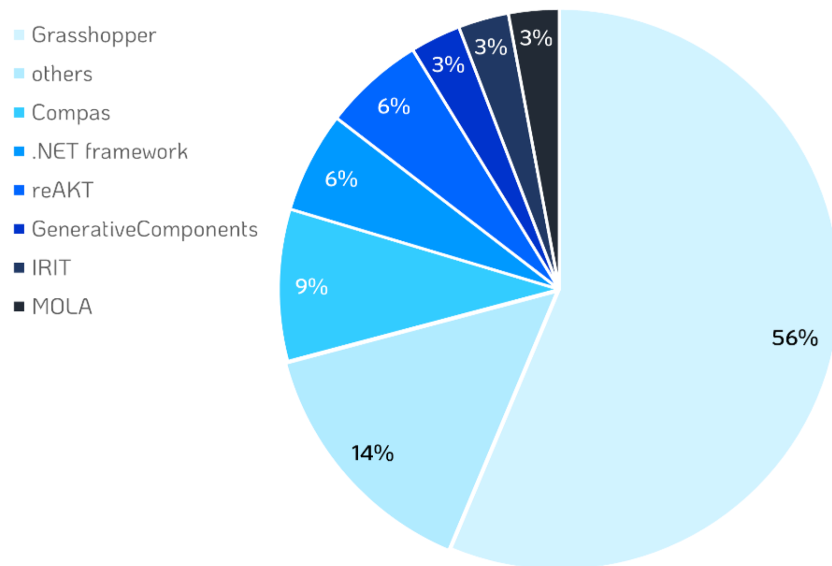

Figure 3. Trends of use of different AD tools and libraries in the selected literature.

Based on the literature, COMPAS computational framework [32] is the second most used AD tool, with 9% of the works using its fabrication extensions compass_fab, compass_slicer, and compass_rrc. It is followed by .NET framework [33] and AKT II's in-house interoperability toolkit Re.AKT [34], both appearing in 6% of the studies; and then Generative Components [35], IRIT modelling environment [36], and MOLA library [37], a lightweight CD library developed at ETH for mesh manipulation and slicing, all appearing in 3% of the studies. The remaining 14% includes, among others, Dynamo [38], the visual programming tool of Revit [39]; RobotStudio [40], ABB's programming and simulation tool for robotic applications; Potterware [41], a design application for 3D Printing ceramics; Plethora [42], SolidWorks' [43] extension for real-time manufacturability feedback and automatic pricing; and DesignScript [44].

The literature also shows that multiple AD tools are often used in design-to-fabrication processes, particularly because of the tools' technical specificity and narrow scope of application. For example, in [45], the authors used (1) Grasshopper to manipulate the design of a reinforced ribbed floor slab and extract sections for fabrication, and (2) COMPAS computational framework to slice the geometry for fabrication and generate the robotic motion paths. Another example is the method applied in [46] for 3D printing shell formworks, which benefited from COMPAS computational framework and several Grasshopper plugins, namely Karamba, to calculate the formworks' principal stress lines; Dendro, for mesh creation and preparation for 3D printing; Millipede, for topology optimisation; and FURobot, for programming KUKA's robotic arm. A last example is the robotic sketching workflow presented in [47], which combined Grasshopper, to generate both the printing paths and RAPID code for the robotic 3D printer (using Robots), and RobotStudio, to debug, simulate, and upload RAPID code.

3.2. Custom Algorithms

In addition to the available AD tools and libraries, the literature evidences the frequent use of custom algorithms, especially to (1) extend the tools' modelling capabilities, (2) handle the information complexity resulting from different design-to-fabrication requirements, or even (3) support the sharing of different file formats and specialised models between tools.

One example is the design and robotic assembly method presented in [48], where custom Python scripts were implemented in the COMPAS computational framework to (i) geometrically explore and detail different metal structure configurations, (ii) perform structural optimisations, and (iii) generate robotic paths for manufacturing. Another example is the facade design of the Edmond and Lily Safra Center for Brain Sciences [49], which combined (i) Grasshopper, to shape the facade pattern units (neurons) and structurally analyse and rationalize the resulting design, and (ii) Python, to extract data from different files, generate the facade design centrelines model, integrate structural and manufacturing constraints in the design process, and generate different facade patterns and details (Figure 4).

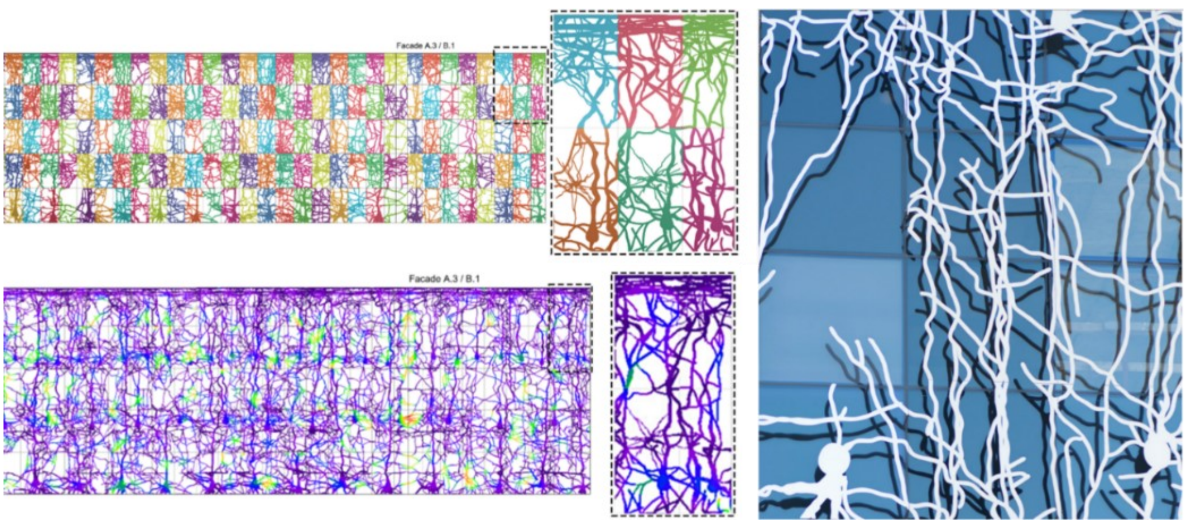

Figure 4. *Top left: panel typologies identified with different colours; Bottom left: Structural analysis of the panels; Right: final facade screen (from* [49]*).*

The last example is the real-time geometry to G-code compiler presented in [50] to simplify geometry preparation for fabrication and the conversion of CAD models into manufacturing machine instructions. In this case, in addition to using .NET framework and Grasshopper, the authors developed C# scripts to support surface patterning routines, remove redundant structural elements, create notch joints, and convert the obtained geometries into G-code (Figure 5).

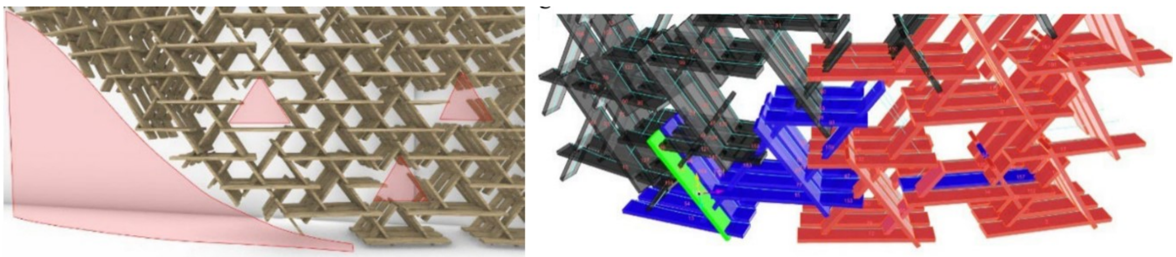

Figure 5. Pattern generation and transformation (left) and virtual model indicating the fabrication and assembly sequences (right) (from [50]).

Figure 6 presents the most used PLs in the literature to implement custom algorithms. It shows that Grasshopper is the most used visual Programming Language (PL) (53%) and Python the most used textual PL (20%). These are followed by C#, which was used in 9% of the works, and C++ and VBA, both mentioned in 4% of the studies. With 3% of occurrence, we have GenerativeComponents, RhinoScript, and MATLAB. The remaining 4% includes PLs like DesignScript, JAVA, Processing, and F#.

In visual programming, Grasshopper is the most popular PL because of the reasons mentioned in Section 3.1. In textual programming, the preference for Python is explained by (i) its simplified syntax, which facilitates its learning and use; (ii) its active online community, which provides extensive technical support and contributes to the ever-growing number of ready-to-use Python libraries; and (iii) the fact that most design tools and programming interfaces support this language. For example, both Grasshopper and Dynamo provide components to interpret Python scripts, namely GhPython and Python node, respectively, and AutoCAD [51], CATIA [52], Rhinoceros 3D [53], SolidWorks, and Blender [54] all provide programming interfaces supporting Python.

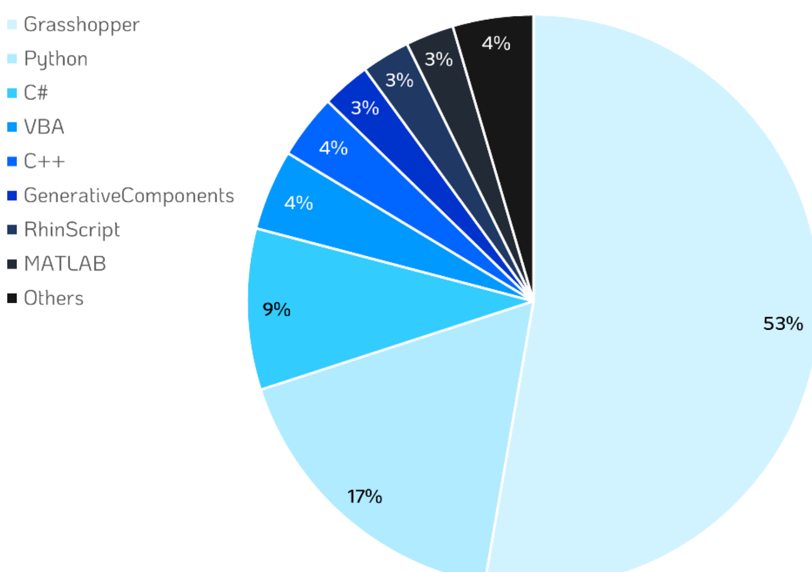

Figure 6. Trends of use of different programming languages in the analysed literature.

4. METHODOLOGICAL PATTERNS

This section analyses the trends of applying AD in different design-to-fabrication tasks. Table 1 presents the tasks that were more often supported by AD in the literature and Figure 7 shows their frequency by category.

Table 1. Design-to-fabrication tasks supported by AD (left) with the corresponding research (right).

Task	Research
2D Drawings Production	[10,55,64–73,56–63]
Data Exchange	[49,55,74–83,57,84–90,58,60,61,63,66,69,70]
Data Visualization	[47,63,92–97,68,71,74,77,79,86,90,91]
Design Detailing	[49,50,70,76,81,82,85,86,89,98–100,55,101–106,58–61,65,66,69]
Design Exploration	[10,45,63–66,68–70,72–74,48,79–83,85–87,89,91,49,92,94–97,99–101,103,104,50,105–114,55,115–124,58–61]
Design Rationalization	[60,63,105,106,120,121,123,125–128,66,68–70,83–85,88]
Formwork Detailing & Generation	[60,90,118,119,126,94,96,97,101,103,104,112,115]
Machine Code Generation	[47,50,106,110,112,121,122,128–132,63,133,76,77,79,86,92,95,100]
Manufacturing Data extraction	[10,55,69,70,76,81,83,85,86,97–99,56,100,105,106,115,116,119,121,123,131,133,57,58,63–65,67,68]
Manufacturing Data Production	[10,48,68–70,72,73,75–77,82,83,55,85,90,95,98–100,105,106,115,116,56,119,121,128,131,134,57,58,60,62,63,66]
Manufacturing Control	[47,48,76–79,81,82,86,90–92,49,93,94,96–100,103,104,106,59,107,109,110,118,120,126,131,133,135,136,60,137,63,64,73–75]
Manufacturing Simulation	[47,59,93,94,97,104,106,118,120,126,131,133,60,135,136,63,74,76,77,79,91,92]
Material Simulation	[64,71,79,97,109,121,122,138]
Preparation for Manufacturing	[10,45,66–73,85,86,50,89,90,96,97,99,100,105,106,109,116,55,118,119,121,127,128,130,131,56,57,62–65]
Production Feasibility & Cost	[49,64,99,103,109,118,124,126,134,70,81,85,86,89,90,96,97]
Production Time	[63,81,90,96,97,99,118]
Structural Simulation	[48,49,76,80,82,83,86,87,89,93,95,96,57,97,98,100,101,104,107,114,120–122,58,124,127,128,133,134,137,139,64,65,69,70,72,74]
Mesh Manipulation	[48,49,85,89,90,96,97,105–107,111,112,50,117,118,120–124,127,128,134,63,66,69–71,83,84]
Surface Patterning & Panelling	[10,49,80,83–85,88,89,91,94,100,104,50,105,106,108,111,112,114,115,117,120,123,63,124,128,134,64,66,68,69,71,73]
Templating Data	[10,55,67,70,86,118,121,127,56–58,60,61,63,64,66]
Tool Communication	[47,49,64–66,68–70,74,76–78,50,79,81,83–89,93,55,99,104–106,109,122,128,129,133,136,56–58,60,61,63]
Tool Path Generation	[45,47,91,94,99,100,106,109,110,113,116,123,48,126–131,133,135–137,63,138,140,141,65,71,74,77,79,90]

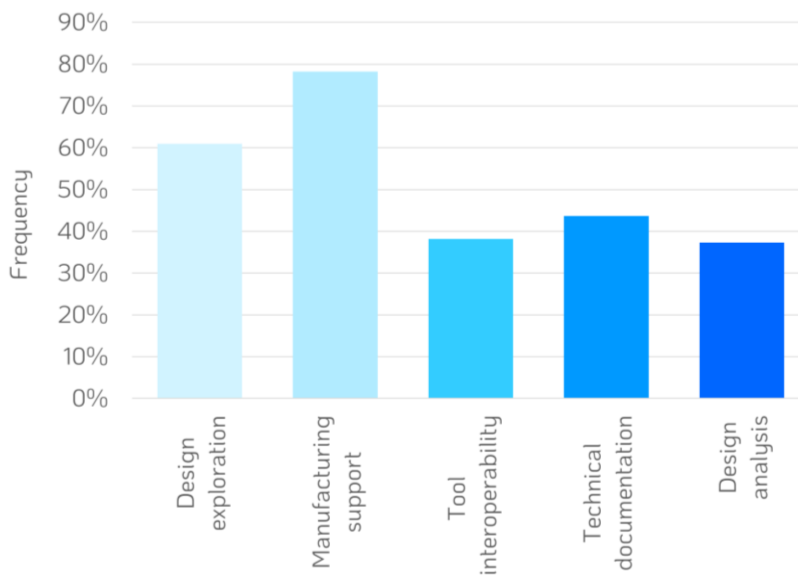

Figure 7. Frequency of different design-to-fabrication tasks supported by AD.

4.1. Design-to-Fabrication Tasks

According to Figure 7, AD was predominantly used to support manufacturing processes (78%): e.g., to simulate CNC machines' motion; predict potential clashes, collisions, and production inconsistencies; and provide visual and/or numerical feedback on the manufacturing process in near real-time. The simulation of robotic movements in Rhinoceros 3D using KUKA Prc Grasshopper plugin [133] and TwinCAT motion control software [93] are two examples. Another example is the preview of brick positioning and assembly in non-standard masonry structures [95].

Moreover, AD facilitated design rationalization and the assessment of the solutions' feasibility, automating cost and machining times estimations. The surface subdivision strategy applied in [126], to ensure that freeform panels could be produced from a single block of material, is one example where AD increased production efficiency while minimizing material waste (Figure 8 Top). Other examples include the process applied in [67] to simplify the falsework construction of an undulating surface, and the novel approach presented in [97] to estimate machining time and material use for different fabrication techniques (Figure 8 Bottom).

AD also simplified the production of manufacturing and construction data, automating, for instance, (1) tool path and machine code generation (G-code and RAPID) directly from 2D or 3D architectural shapes; (2) design detailing according to fabrication and assembly constraints, such as beams [134], panel flanges [63], screws [76], bolts [59], connectors [89], notch joints [50], and assembly labels [66];

and (3) the production of custom formwork/mould parts and details for concrete freeform columns [101], node connections [112], and facade panels [96].

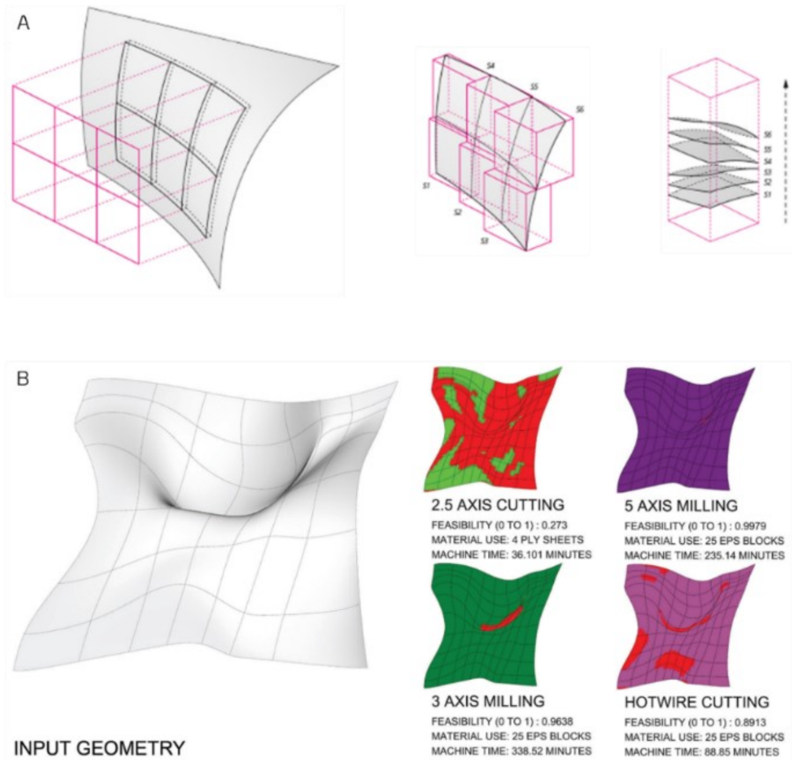

Figure *8. A. Layered mould strategy to simplify panels production and reduce material waste (from* [126]*); B. Evaluation of the fabrication feasibility of a design through different manufacturing techniques (from* [97]*).*

Figure 7 also shows that AD was also frequently used (61%) to support design exploration processes, particularly the creation and geometric manipulation of different architectural elements, such as columns [100,101,142], bricks [79,116], slabs [45,104], facade elements [49,55,63], surface patterns [89,94,118], and mesh configurations [73,120,128]. The generation of different knitting patterns for a concrete waffle shell using the COMPAS_knit toolkit [115] and the development of multiple panel sizes and patterns for an acoustically-driven surface [105] are two examples (Figure 9). Other examples include the segmentation of doubly curved surfaces into planar timber elements of different sizes and shapes using an agent-based modelling algorithm [106], and the generation of different tiling patterns on doubly curved shell structures [128,134] (Figure 10).

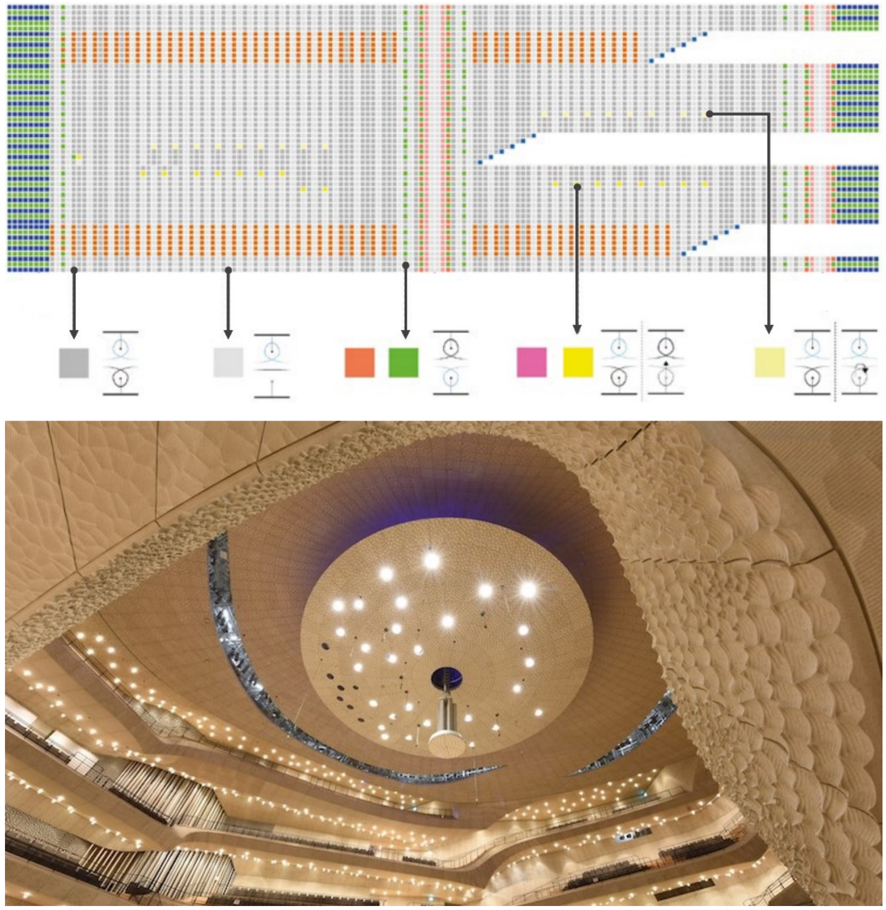

Figure 9. *Top: Conversion of a knitting pattern into machine instructions - each colour represents a different knitting action (source:* [115]*); Bottom: Acoustic panels of the Grand Hall of the Elbphilharmonie Hamburg (from:* [143]*).*

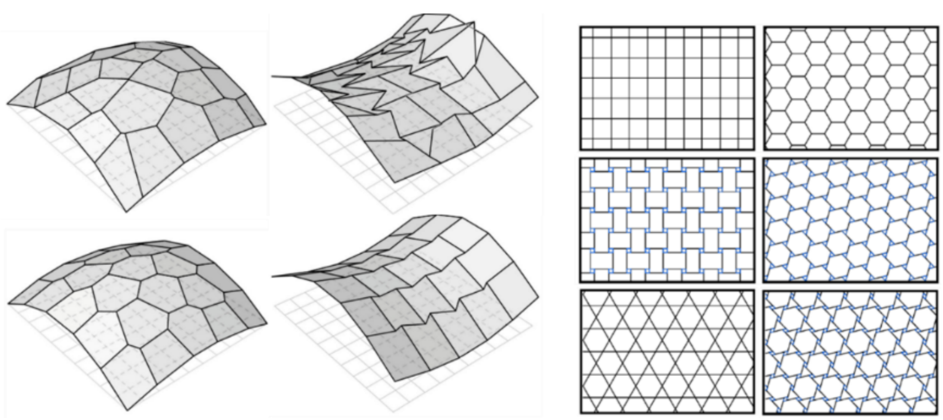

Figure *10. Left: Agent-based modelling approach for subdividing complex, doubly-curved geometries using planar elements (from* [106]*); Right: the translation technique to create nexorades on mesh surfaces using planar panels (from* [134]*).*

Based on Figure 7, AD was also often used (44%) to support the preparation of designs for manufacturing, automating, for instance, the extraction of construction data, such as material quantities [64], and number [81], size [69], and position/orientation of different building elements [70] (Figure 11 left). Other AD applications include the generation of 2D technical drawings fitting custom templates [55] (Figure 11 right) and machine dimensions [118,121], and containing the necessary data for different manufacturing techniques, such as steel [68] or precast concrete fabrication [60], CNC cutting [10,65], or weld assembly [66].

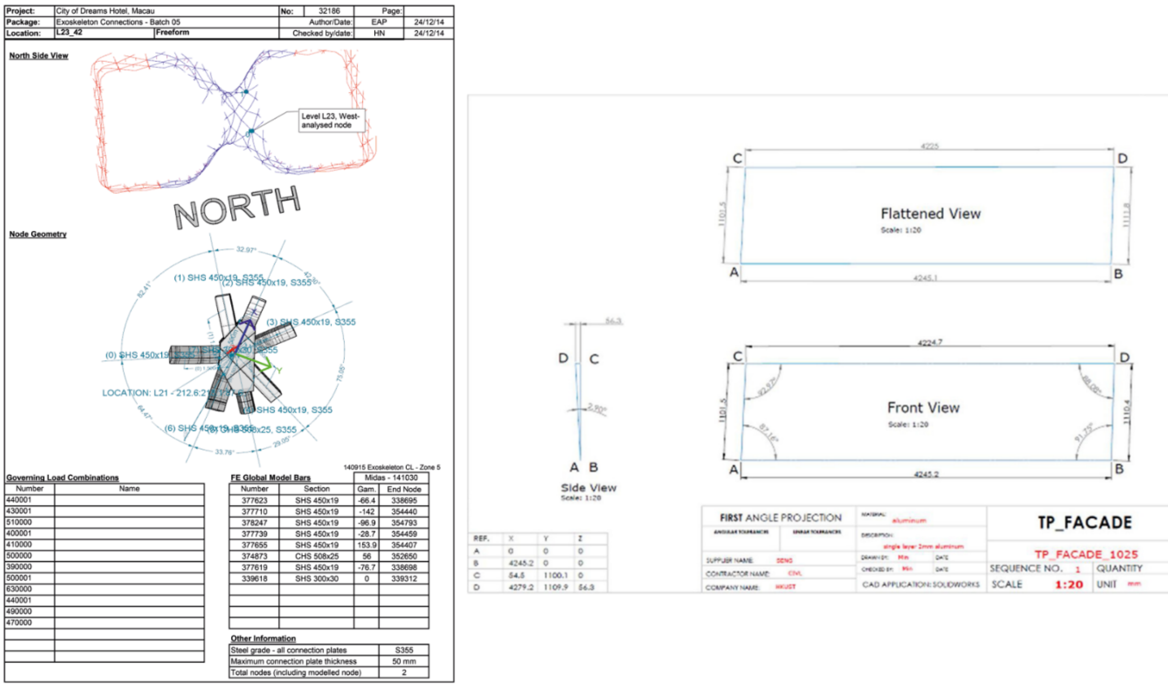

Figure 11. *Left: Technical documentation of a connection node transferred from Grasshopper to an Excel template (from* [70]*); Right: the result of automatically extracting data from a BIM model to an Excel database using Dynamo, and its subsequent integration onto a drawing template using a custom plug-in for SolidWorks (from* [55]*).*

Additionally, AD was often used (38%) to increase tool interoperability and coordinate different specialized data and requirements. For example, several studies mentioned using AD to exchange data more easily between different design tools, automating the time-consuming and laborious conversion of files through formatting conventions, while minimizing potential information losses and translation errors. The use of Re.AKT in [81,83] are two examples where AD allowed for a complete design-to-manufacturing workflow based on real-time interoperable models, fluidly connecting different modelling, analysis, and fabrication environments, such as Rhinoceros 3D, Microstation [144], Sofistik [145], and SAP [146] (Figure 12). Another example is the use of parametric models in [87] to support feedback loops between different specialists and achieve the desired level of interdisciplinarity between architecture and engineering.

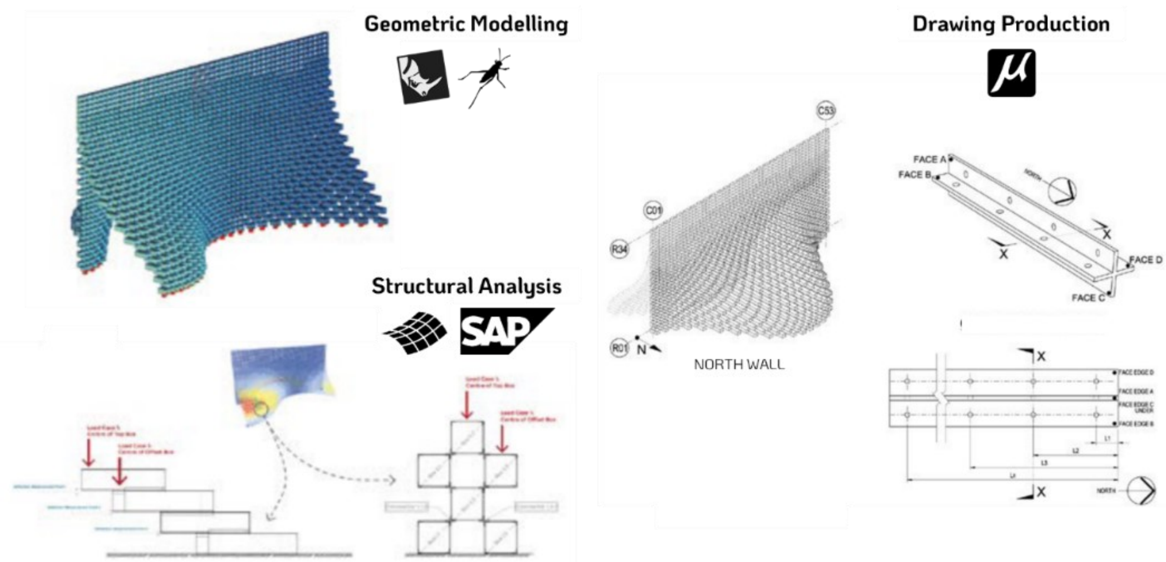

Figure 12. Workflow supported by Re.AKT interoperability toolkit in Serpentine Pavilion 2016 (adapted from [81]

Lastly, AD was also applied (37%) to support design analysis and optimization routines, such as performing form-finding processes for different origami-inspired portable shelters [98] or searching for structural configurations minimizing vertical deflections [57]. Additionally, several studies used AD to simulate material behaviour, as is the case of the custom middleware developed in [91], to adapt and predict the outcome of robotic carving processes based on real-time analyses of materials state; the custom algorithm used in [79], to plan toolpaths based on material behaviour; and the Grasshopper-based tool applied in [71], to inform designers about the overall material organization and the impact of biological parameters on the design of fibre-based structures.

4.2. Algorithmic Trends in Relating Architectural Geometry and Fabrication

To compare the trends of using predefined or custom algorithms in design-to-fabrication processes, Figure 13 organizes the literature of Table 1 according to the type of AD strategy used in each task. The works where it was not clear which AD approach was used were classified as “unknown”.

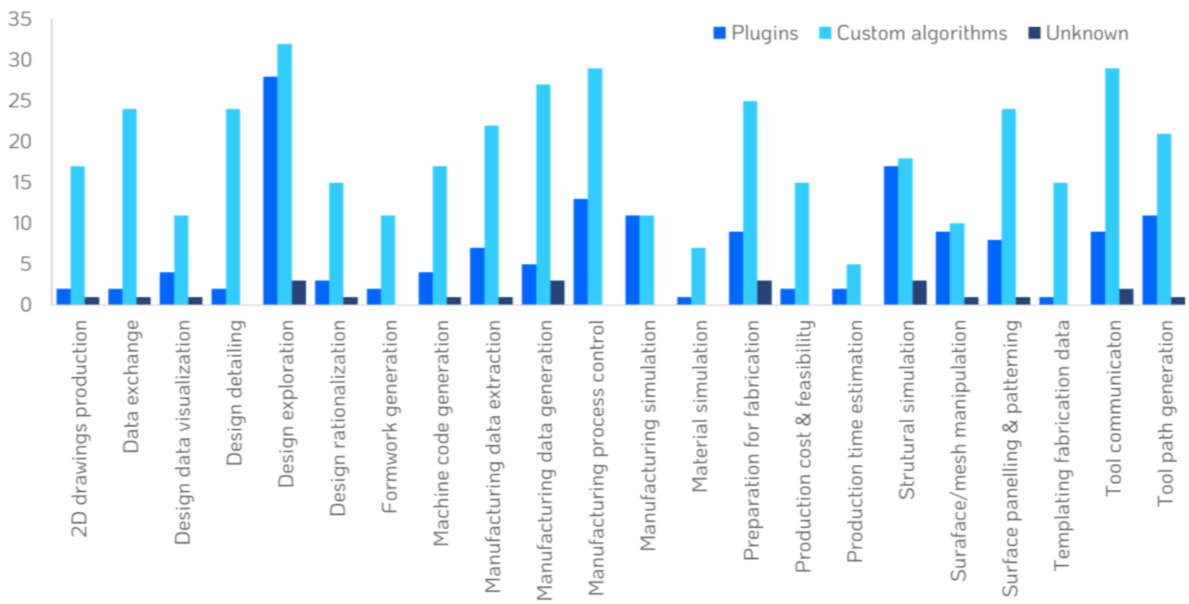

Figure 13. Trends of using predefined and custom algorithms in design-to-fabrication tasks.

4.2.1. Preparation for Fabrication

Figure 13 shows that, in general, custom algorithms were more frequently used than predefined ones, particularly in preparing designs for fabrication. For example, 94% of the studies applied custom algorithms to automate the templating of manufacturing data; 85% to support the production of technical drawings; 92% to simplify design detailing; 85% to produce 3D models of formworks/moulds for manufacturing; and 77% to automate machine code generation.

The BIM-based framework presented in [55] is one example where custom algorithms were implemented in SolidWorks and Dynamo to (1) automatically extract 2D views from 3D models, (2) standardize and adapt the 2D drawings to fit specific templates, and (3) annotate and label facade panels technical drawings for fabrication. Another example is the robotic process described in [131], which uses a custom C# algorithm for Grasshopper to convert NURBS surfaces into fabrication data, automatically generating layered robotic paths on the received surface to achieve the desired surface thickness (Figure 14 Top). The workflow adopted in [104] to fabricate novel slab systems is another example that extends commercial CAD tools, such as Rhinoceros 3D. In this case, custom algorithms were used to further detail the 3D model, e.g., to add structural connections for facade mullions, create openings for facade brackets, pipes, and cabling, and generate formwork data, such as labels and connection and lifting details (Figure 14 Bottom). A last example is the design-to-production method proposed in [123], which entailed the development of a custom toolset for Grasshopper, namely Design with Elastica, to segment and convert doubly curved surfaces into planar curves describing robotic movements.

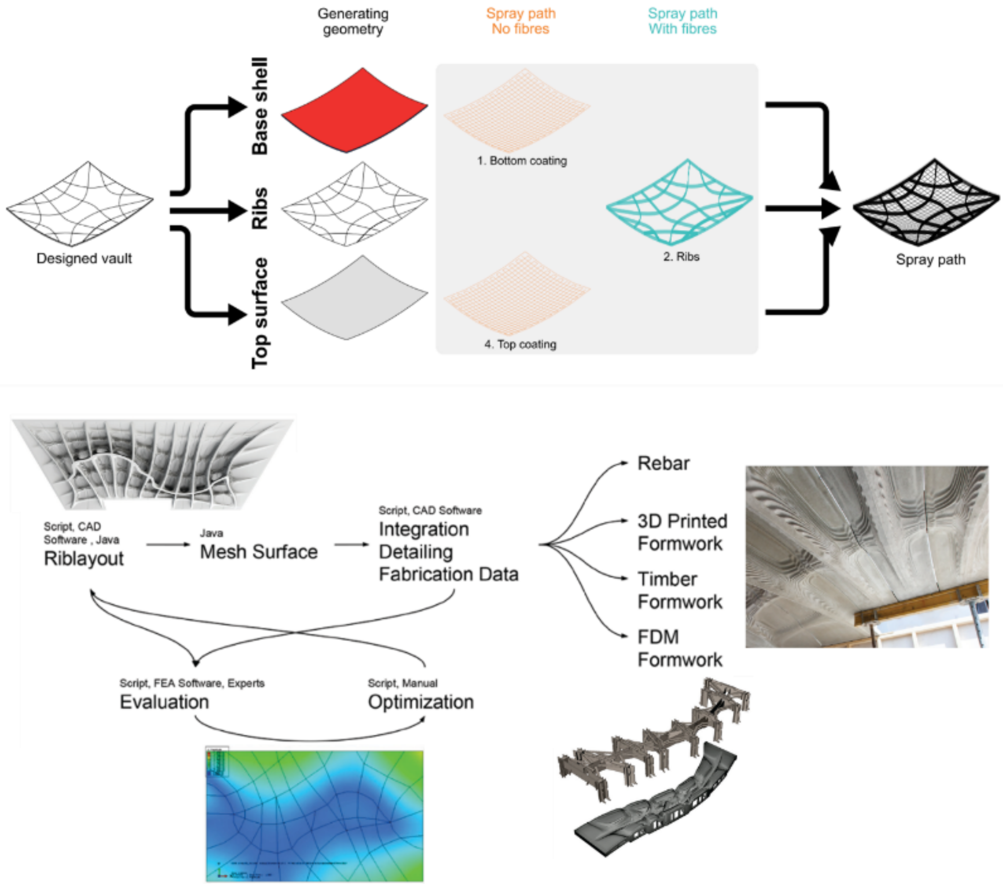

Figure 14. *Top: the robotic concrete spraying process implemented in C# in Grasshopper (from* [131]*); Bottom: fabrication-aware design workflow based on Java and Grasshopper extensions (adapted from* [104]*).*

4.2.2. Tool Interoperability

Based on the literature, data compatibility was also more often improved through custom algorithms. 89% of the studies mentioned their use to translate and exchange data between different file formats and tools, and 73% to support import and export operations between tools. The mesh-to-BIM method proposed in [84] is one example where a custom algorithm was developed to automate the transfer of freeform meshes from Rhinoceros 3D into Revit. Another example is the design-to-fabrication workflow applied in Morpheus Hotel facade structure [70], which required several custom algorithms to link different design, simulation, and fabrication tools. The Kirk Kapital Headquarters [88] is another example where software interchange barriers were surpassed through custom algorithms, originating the in-house AD platform PyRAPID [147]. A last example is the workflow presented in [63], which leveraged the communication and collaboration between designers and fabricators through a custom C++ library.

4.2.3. Design Rationalization

As shown in Figure 13, custom algorithms were also more frequently applied in design rationalization routines, 79% of the studies mentioning their use.

One example is the process applied in the roof structure of the Shenzhen Bao'an Airport Terminal 3 [85,148], where custom algorithms were implemented in Rhinoceros 3D and Excel to coordinate (i) design intent, in this case, creating a honeycomb cladding pattern with smoothly varying perforations (Figure 15 Top); (ii) performance criteria, such as daylight and energy gains, and (iii) feasibility, controlling, for instance, the planarity of individual glass units, the size of joint spaces, and the occurrence of potential clashes with the remaining structure. The design rationalization of the Louvre Abu Dhabi's cladding structure [149] is another example that benefited from custom algorithms, in this case, to reduce the number of bar types of the cladding structure without neglecting its aesthetics (Figure 15 Bottom-left). The last example is the method applied in the Future of Us project in Singapore [68] to balance a complex architectural intent with the need for simple fabrication and assembly processes. In this case, custom algorithms were used to shape and decompose the freeform surface into differently patterned tiles (Figure 15 Bottom-right), whose position depended on shading, structural, and installation requirements [150].

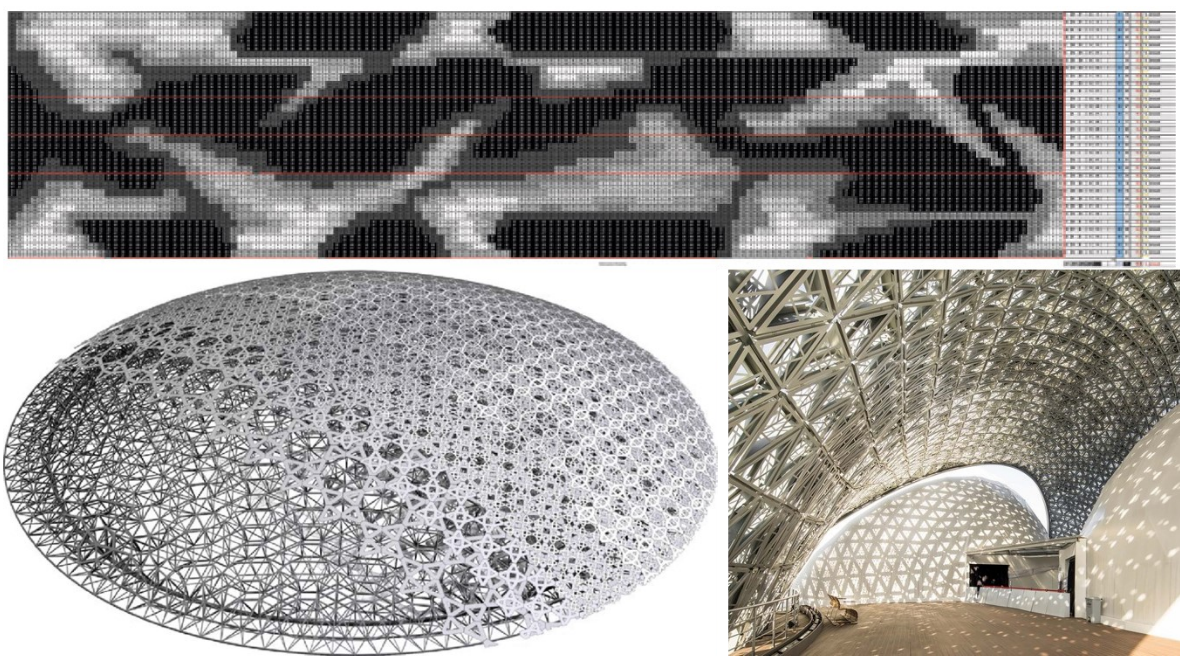

Figure *15. Top: Allocation of 60 000 panel types for Shenzhen Bao'an Airport's cladding structure (from* [148]*); Bottom left: Louvre Abu Dhabi cladding layers (from* [151]*); Bottom right: Inside view of the Future of Us pavilion cladding panels (from* [68]*).*

4.2.4. Manufacturing Control

Figure 13 also evidences a preference for custom algorithms over predefined ones to control design manufacturing, with 88% of the studies mentioning their use in cost estimation routines and 73% to support manufacturing data visualization.

One example is the design tool proposed in [99] to explore facade designs made of wood panels considering production costs and assembly times (Figure 16 left). Another example is the method presented in [90] to translate complex facade shapes into moulds, informing in near real-time about the machining times and material usage of the chosen fabrication strategy. The last example is the parametric construction system Cork re-Wall described in [64] to design and fabricate partition cork/wood wall systems for building renovation projects. In this case, custom C# algorithms were used to subdivide walls into structures and panels considering (1) production costs, (2) structural efficiency, and (3) assembly simplicity.

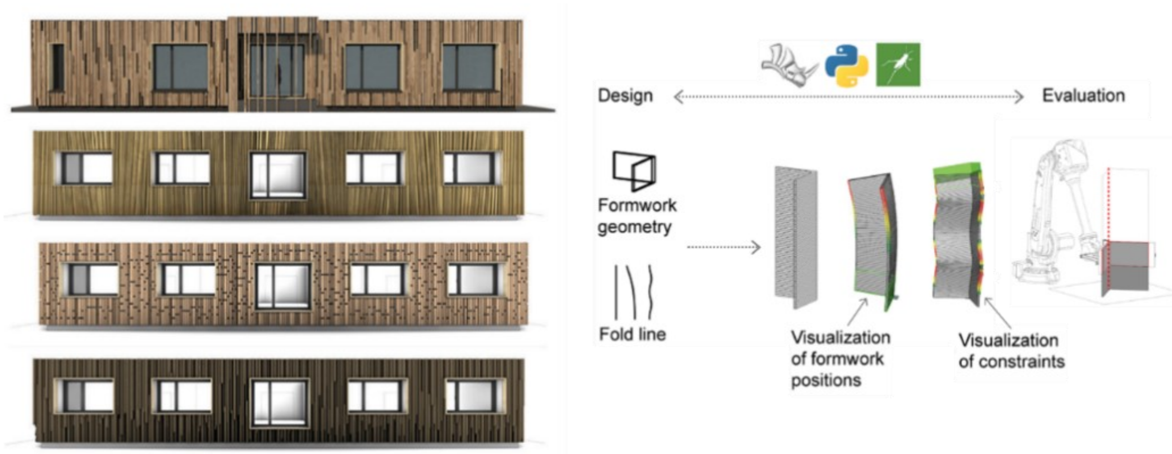

Figure 16. *Left: Fabrication-aware design exploration of different wood-based facades (from* [99]*); Right: visualization of the slipping process and the output geometry based on the formwork shape and fold curve (adapted from* [77]*).*

Examples of custom algorithms to support data visualization in design-to-fabrication processes include the Python extensions implemented in Grasshopper to (1) track the position and rotation angle of individual wood lamellas [92], and (2) visually assess the fabrication feasibility of slip-casting fabrication processes using different formwork configurations and fold curves [77] (Figure 16 right). Another example is the C++ extensions supporting the visual inspection of thousands of different surface panels along with their respective positions, angle deviations, and opacity levels [63].

5. Relating Design Complexity and Algorithms

In this section, we reflect on the relationship between algorithmic trends and the complexity of the design process. The analysis builds on previous insights (Section 4) and considers four factors: (1) the volume of data, (2) the number of performance criteria, (3) the design's level of detail, and (4) the technicality of the tasks performed. It also considers the design's level of abstraction, which has an inverse correlation with the previous factors and thus with design complexity: designs with higher levels of abstraction are more simplified (i.e., containing fewer data and specifications) and more detached from specific instances.

Figure 17 illustrates the relationship between the above-mentioned factors (lilac, pink, purple, and blue curves), the complexity/abstraction of different design stages (black and grey curves), and the trends of using standard and custom algorithms (green and yellow curves). It reveals a direct relationship between the four factors, the design complexity, and the propensity for custom algorithms; and an inverted correlation between the factors, the design's level of abstraction, and the use of standard algorithms.

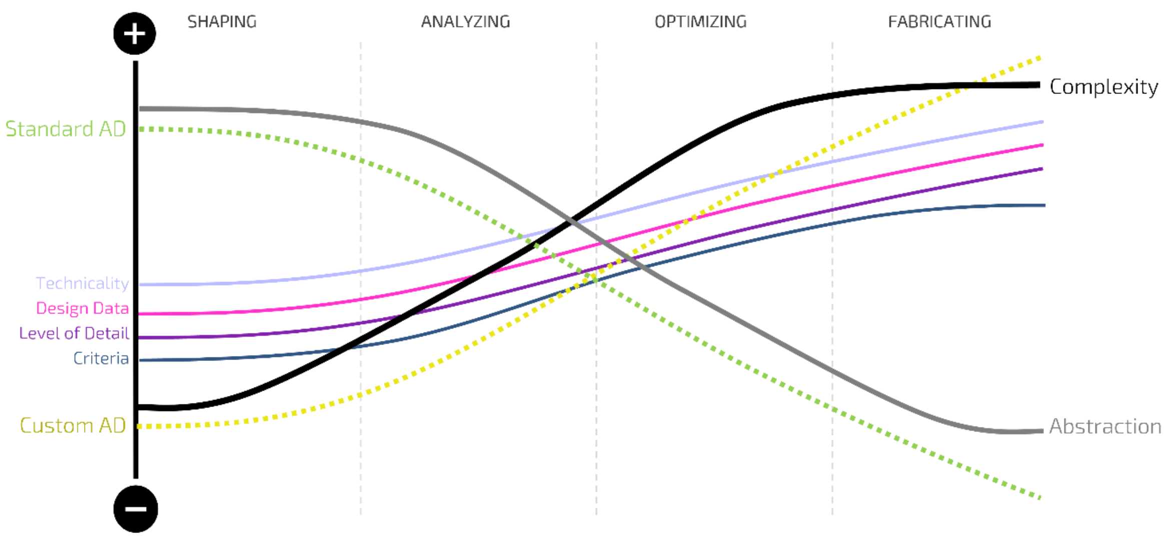

Figure 17. Relationship between design complexity/abstraction and the use of standard and custom algorithms: the more abstract the design, the more frequent the use of standard plugins; the more detailed the design, the higher the use and the size of custom algorithms.

In Figure 17, we show that standard algorithms are more frequently applied at initial design stages, where the design's level of abstraction is still high (grey curve), and its complexity is low (black curve). This happens because early design stages typically involve the geometric exploration of architectural shapes with little detail. Additionally, in these stages, design tasks tend to be more intuitive, technically less demanding, and less dependent on technical criteria. This is visible, for instance, in the geometric exploration process of both the Serpentine Pavilion 2016 [81] and the Healing Pavilion [80], where the resulting parametric models did not yet consider structural and fabrication criteria.

In contrast, when the design evolves, the prevalence of custom algorithms becomes markedly clear. This is explained by the increased complexity of later design stages, where the tasks become technically more challenging and costly, requiring more powerful and more specific algorithmic strategies.

This is especially evident in designs involving less conventional creative intents and architectural geometries because most design tools are tailored for standard geometries and thus must be extended through custom algorithms.

MATSYS' Shell Star pavilion [152] is one example where custom Python scripts were used to optimize and prepare the catenary-like structure for fabrication, making its 1500 individual cells as planar as possible, and unfolding and producing cell flanges and labels automatically (Figure 18 top-left). Another example is the work of THEVERYMANY, where custom Python scripts describe the steps and instructions guiding the entire design-to-fabrication process, along with the existing morphological relationships: in [73], for instance, AD automated the testing of different surface shapes and patterns for self-supporting doubly curved surfaces (Figure 18 top-right), as well as the preparation of the surfaces for manufacturing, automating their panelling and the production of fabrication drawings and assembly supporting schemes. One last example is the design and construction of the Buga Wood Pavilion [76], which required extending a custom agent-based environment with Python and C# bindings. In this case, custom algorithms allowed the design team to develop a central AD model containing all the data needed for manufacturing the 376 bespoke hollow cassettes and supporting feedback loops between the pavilion shape and its fabrication setup (Figure 18 bottom).

Figure *18. Shellstar by Matsys + Riyad Joucka (©Dennis Lo); Marc Fornes/THEVERYMANY, Vaulted Willow, Edmonton, Alberta, Canada (from* [73]*); Buga Wood Pavilion (from* [76]*).*

6. Design-to-Fabrication Workflows

The correlation between custom algorithms and design complexity is also evident in large-scale architectural projects. As these projects typically involve large amounts of data, various context-specific requirements, and expensive design models, they often require custom algorithms [153]. This section elaborates on the design-to-fabrication workflow of six architectural projects that address complex and unconventional design problems mostly through custom algorithms. The aim is to identify methodological trends, recurrent challenges, and the advantages and limitations of the applied AD strategies.

6.1. Architectural Projects

The first project is SoFi Stadium [63], whose roof structure has over 46 000 m^2 of surface area and is composed of approximately 35 000 unique panels (Figure 19). In this project, a custom C++ application was applied in panelling, patterning, and defining the fabrication data of the stadium's roof structure, replacing representational drawings as the primary means of data sharing with a computational database that automatically generated different file formats for different design, documentation, fabrication, and construction purposes. Instead of relying on thousands of 2D drawings describing individual panels, the custom application was based on text-based files containing all the panels' geometric data, which could be then automatically translated into machine instructions by the manufacturers.

After tessellating the stadium surface modelled in Rhinoceros 3D and extracting the nodes' centre points using Grasshopper, the application stored each panel data into new panel objects containing all details about the panels' spatial location, corner positions, edges, and fastener positions. Additionally, the application automated the panels' perforation pattern based on the grayscale values of a global design image, originating text files with the panels' geometric descriptions. Moreover, the application also provided visual support to the searches made on the resulting text file, displaying not only each panel in detail with its respective position on the overall surface highlighted, but also the roof structure area, angle deviations, and panel opacity levels. Lastly, the custom application also supported the definition and structural analysis of thousands of connection nodes for the roof's unique panels [63].

Figure *19. The porous canopy of SoFi stadium composed of approximately 35 000 anodized aluminium panels with different perforation patterns (from* [63]*).*

The second project is Little Island [60], a deck structure on the river of Hudson River Park composed of unique tulip-shaped precast concrete elements, whose irregular, curved surfaces posed several challenges from design to construction. In this project, the outside surface of these elements was modelled using a parametric script, whose base rules were initially defined by the design team (Mathews Nielsen Landscape Architect in collaboration with Heatherwick Studio) and were later refined in collaboration with structural engineers (Arup), who developed additional algorithms to ensure the deck was structurally stable and easy to fabricate through traditional formworks.

Given the limitations of conventional design approaches to deal with the geometric complexity of this project, the team adopted an open 3D modelling approach fusing design and construction models. Custom algorithms were used to surpass the challenges resulting from the deck's unconventional geometry, as well as to leverage both the communication between different specialists and the coordination of specialized design routines. For example, the structural team extended the architects' script (the one defining the deck geometry) to perform the structural calculations needed to design the rebars, connection plates, and embeds of the precast elements. They also implemented custom algorithms to generate the surfaces of all precast elements, the stainless-steel components, and the rebars for the petals and column heads of the tulip-shaped elements. The result was a set of 3D models with all the design elements in their final locations and an arrayed version of the 3D models with the components projected in the 2D plane. This allowed the fabricators to automate the creation of 2D sections and 3D views of each tulip-shaped element, simplifying the production of precast concrete shop drawings for fabrication. During this process, custom algorithms were developed to convert design data into a format suitable for manufacturing, such as .txt and .csv, as well as to check the resulting toolpaths, providing data about production times and CNC cutting sequences.

The third example is Kuwait International Airport [56], which was designed by Foster+Partners and engineered by Arup. The geometric complexity and scale of this project made the design team adopt a project-specific naming convention and numbering for all documents, digital models, and drawings. This allowed the team to automate and organize the design workflow while ensuring data control and accuracy. Custom algorithms were developed to support the desired semi-automated 'Integrated Design Approach' coordinating geometry, engineering, and digital modelling from design to fabrication. According to the authors, this was "the only way to provide the efficiency and the flexibility needed and to overcome the lack of interdisciplinary communication between specialised software" [25, p. 87], such as Rhinoceros 3D, AutoCAD, Revit, Tekla, Navisworks, SOFiSTik, and Excel, allowing, for instance, the parametric modelling and structural evaluation of different elements to drive their modular detailing.

To overcome the lack of interoperability between structural models, BIM models, and CAD drawings, the structural team developed a parametric central data model of the airport's freeform megastructure in Rhinoceros 3D, where almost all the elements were defined using C++, C#, and Grasshopper. Since all relevant project information was defined in this central data model (e.g., the dimensions, materials, and quantities of different components, such as beams, cables, connections, etc.), it could be shared with different specialists to develop sub-models, serving as a unique source of information for the entire team. For example, structural components for calculations in SOFiSTiK, BIM models for project coordination in REVIT, and both models and 2D drawings for production could all be extracted from this central model (Figure 20 top).

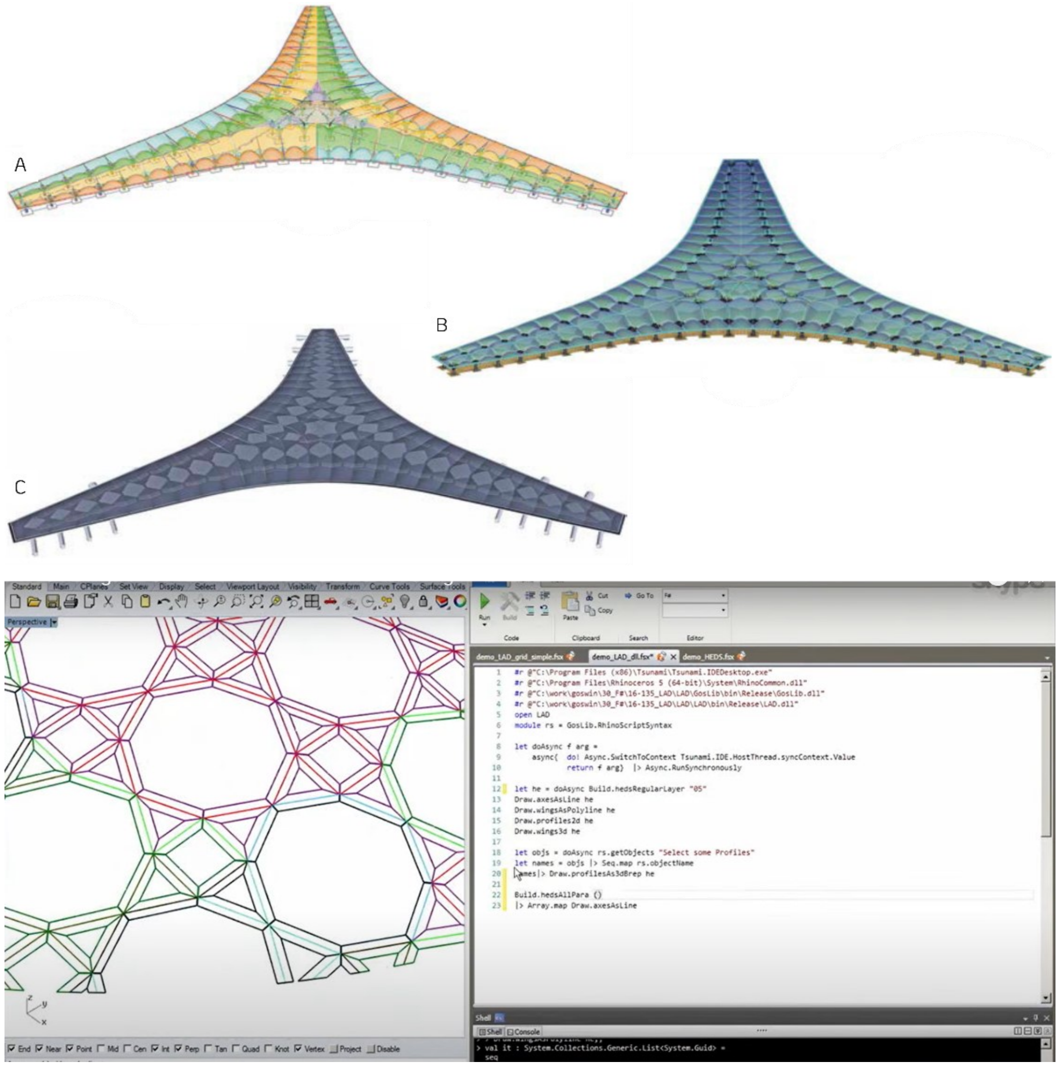

Figure 20. Top: Kuwait International airport Terminal 2: the roof structure central model (A), FE model (B), and BIM model (C) (adapted from [154]*); Bottom: Louvre Abu Dhabi steel elements organized by layer (left) and the F# source code (right) (from* [155]*).*

A similar scenario occurred in Louvre Abu Dhabi's complex cladding structure [69], whose design-to-fabrication was mostly driven by custom algorithms in close collaboration between different specialists, such as architects, structural and lighting engineers, and CAD-to-CAM specialists. In this project, custom algorithms were used to parametrically define the cladding's complex structure and coordinate aesthetics with structural and lighting criteria. The result was a central parametric model describing the geometry and pattern of the museum's cladding structure through abstract elements, such as points, lines, and vectors, as well as its structural elements (Figure 20 bottom).

To convert the wireframe model into a 3D structure, which was important to visualize the museum's cladding geometry and generate CAD drawings, the parametric model was hosted in Rhinoceros 3D using a F# plugin implemented in TSUNAMI. This facilitated the coordination of geometric rules with performance and construction constraints, allowing the team to balance the cladding's geometric exploration with (1) its structural evaluation, assessing its self-weight, cost, and buildability using ANSYS [156] and ROBOT [157], (2) the museum's shading requirements, adapting the cladding pattern to meet the transparency map set, and (3) the structure's feasibility, greatly reducing the number of different elements [69]. Additionally, the central parametric model supported the design detailing of the museum's cladding structure, as well as its preparation for fabrication: for example, it automated the production of manufacturing drawings with all elements labelled and nested, and the extraction of detail drawings, quantities, and cost estimations. The central parametric model was also critical to make the construction of such a complex structure real, supporting the cataloguing of its different elements and the management of both installation and assembly processes.

The next project is the Gilder Center for the American Museum of Natural History [84], in New York, designed by Studio Gang Architects. To overcome the challenges resulting from importing NURBS shapes from CAD to BIM environments, the team applied a mesh-to-BIM workflow that allowed them to efficiently and accurately transfer the museum atrium's complex shape from Rhinoceros 3D to Revit, integrating all geometric and technical data needed for subsequent documentation and production. The workflow started with the mesh preparation in Rhinoceros 3D, followed by its derivation using custom tools combining Grasshopper, RhinoCommon library, Triangle.NET, and Plankton .NET library. Then, the team used OpenNURBS and NetDXF libraries to translate the mesh into a format compatible with REVIT, in this case DXF. They also developed a custom add-in for REVIT's .NET API to extend its importing and exporting capabilities, allowing the team to assign additional data and attributes to the imported shapes, such as material, performance, and manufacturing information, while transferring them. This enables the team to effectively produce technical documentation for each design speciality, leveraging design coordination and project delivery.

The last project is Canary Wharf Crossrail Place [66] in London, whose lattice roof is composed by a triangular timber grid with inflated ethylene tetrafluoroethylene (ETFE) cushions that provide a dynamic appearance to the structure. In this project, the design team (Foster+Partners) used custom algorithms to establish the multiple geometric relationships defining the roof's complex structure, facilitating the generation and assessment of different shape configurations, while synthesizing the design into a set of logics that could be then understood by both timber specialists and fabricators.

To support the iterative design and analysis loops, the structural team (Wiehag) linked CAD and structural analysis models in a parametric way through an Excel data hub containing geometric, structural, material, and logistics information about the project. Custom algorithmic extensions were developed to (1) generate the lattice roof geometric configuration in Excel, (2) perform structural analyses using Rstab, and (3) generate the roof's structural elements in the CAD platform directly from the Excel data hub. Additional algorithms were implemented by the structural team to automate the inspection, planning, glueing, and pressing of the timber beams, as well as to translate Excel data into machine instructions.

Similarly, the ETFE cladding experts (se-austria) used custom scripts to support the ETFE cushions fabrication planning, automating the generation of (1) 11 000 cushion patterns, (2) 1 560 shop drawings for the ETFE cushions welding assembly, and (3) the positions of 8 500 brackets connecting the ETFE elements to the timber structure. Additional algorithms were developed to generate fabrication files containing manufacturing instructions, such as cutting, milling, and drilling paths, and assembly marks indicating the elements' ID, orientation, and welding position. Custom algorithms were also implemented to leverage on-site production logistics, supporting the provision of lists for suppliers with specific packing and delivery instructions. As, in this project, all specialists used the same approach and shared data via Excel and 3D models, it was possible to improve design communication and collaboration and thus achieve higher levels of refinement.

6.2. Comparing Workflows

This section elaborates on the previous design-to-fabrication workflows, identifying methodological trends and reflecting on their advantages and limitations in terms of design precision, flexibility, scalability, and interoperability. Figure 21 illustrates the two most marked procedural trends in the analysed examples. In the first one (top scheme), several independent ADs are developed by different team elements, originating various algorithmic descriptions of the same design that suit different purposes (e.g., shape exploration, performance evaluation, or manufacturing preparation). In the second workflow (bottom scheme), a single central AD is developed by the whole team, integrating the data needed by all specialities. In both cases, the amount of information embedded in the AD model can vary: it may only contain geometric aspects of the design, or it can include a high level of information that obviates the need for BIM models. The Louvre Abu Dhabi [69] and the Morpheus Hotel [70] are two examples where the AD model contained all the data to drive the design process from shape exploration to manufacturing, and no BIM model was needed.

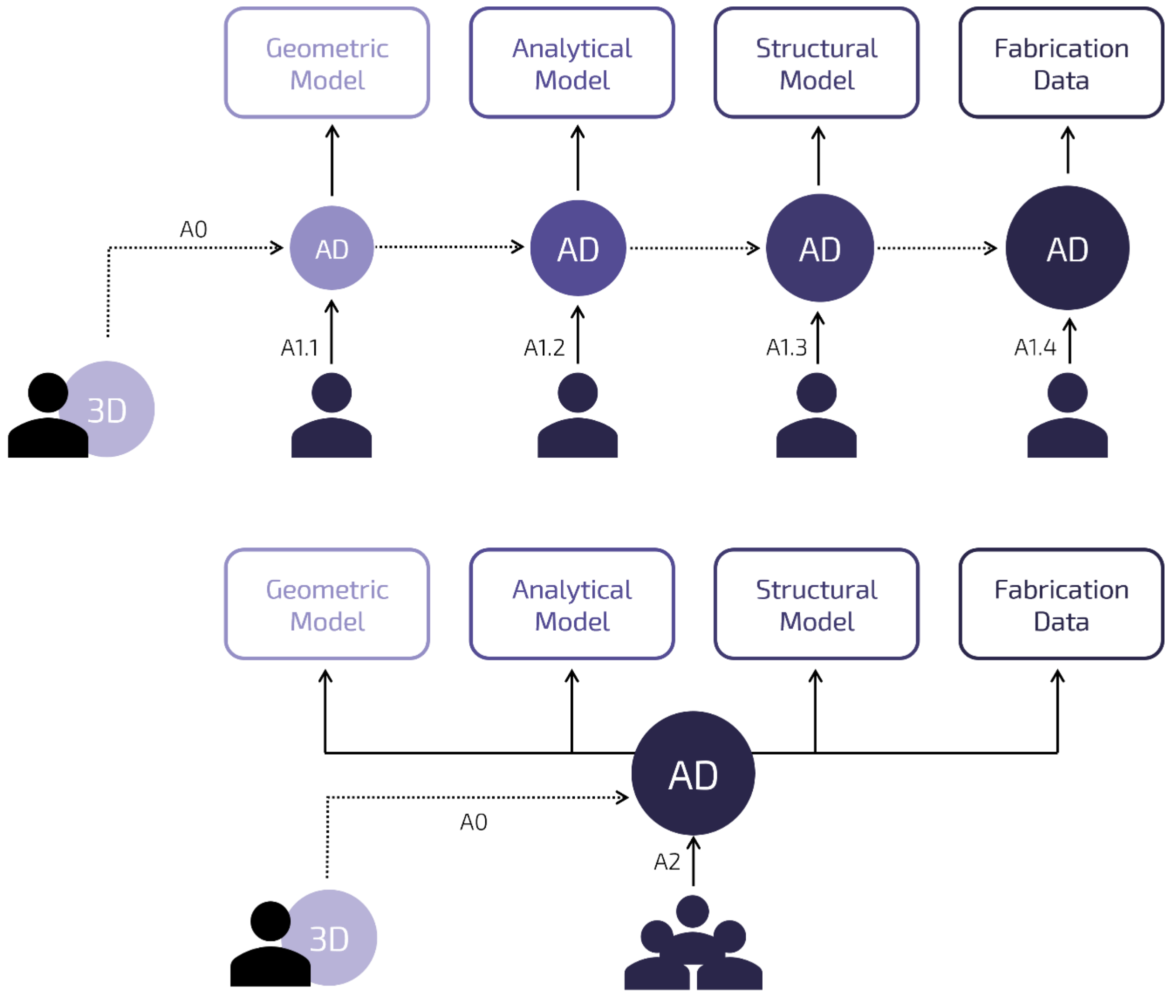

Figure 21. Two design-to-fabrication workflows based on AD. Top: An existing 3D model is inspected through algorithms (A0), originating an AD model that can be further extended and parametrically manipulated, or the architect directly creates the AD model from scratch (A1.1); in both cases, the AD is then extended by different team members for analysis (A1.2), structural preparation (A1.3), and fabrication (A1.4). Bottom: A central AD model is either created from an existing 3D model (A0) or developed from scratch, and is then gradually enriched with geometric, analysis, structural, and fabrication data by the whole team (A2).

The two design-to-fabrication workflows illustrated in Figure 21 can start by (1) inspecting an existing 3D model of the design using algorithms to obtain the corresponding AD, i.e., the algorithms describing the 3D model (arrows A0), or (2) implementing the AD from scratch (arrows A1.1 and A2).

The first scenario occurred, for instance, in SoFi Stadium [63] and Gilder Center [84], where the 3D models of the stadium's roof structure, in the first case, and the museum's atrium, in the second, were converted into algorithms to make its production feasible. In the case of the SoFi Stadium, the resulting AD corresponded to the roof structure's panel nodes and supported subsequent design tasks, such as the patterning and detailing of the panels, the definition of fabrication data, and the visualization of the panels' geometric characteristics, opacity level, and location on the overall surface. In the Gilder Center, the obtained AD integrated the atrium's geometric description with the data needed for its subsequent integration into the museum's BIM model.

The second scenario occurred in the Kuwait International Airport [56] and the Louvre Abu Dhabi [69], where almost all building elements were developed through algorithms. The resulting ADs were then used as a basis for subsequent design processes, including structural design and analyses as well as the labelling of elements.

After obtaining the initial AD model, the team can adopt two strategies: each specialized team develops its own AD model from the initial one (Figure 21, top scheme), or everyone works on the same AD model (Figure 21, bottom scheme). In the first strategy, each team considers only the requirements related to its scope of intervention in the project, creating specific AD models containing either the architects' creative intent (arrow A1.1), or the design's environmental performance (arrow A1.2), or its structural performance (arrow A1.3), or the available manufacturing technology (arrow A1.4). In the second strategy, each specialist changes the AD model shared by the team to introduce various types of data from design to fabrication and adjust the design to the conceptual/technical requirements it must meet (arrow A2).

Canary Wharf Crossrail Place [66] is an example of the first strategy as different design, timber structure, and cladding specialists developed their own algorithmic methods to surpass the design challenges faced. Another example is Little Island [60], where engineers and fabricators independently extended the AD developed by the architects (the one defining the deck structure's shape) to solve their specific challenges. As in this scenario, different experts typically produce or adapt an existing AD according to the tasks to perform, the result is often a collection of independent specialized AD models that need to be coordinated to avoid design inconsistencies and outdated information. For example, in Little Island [60], the coordination between different specialities was achieved by importing the generated 3D models into Navisworks for clash detection and information reference.

Regarding the second strategy, Louvre Abu Dhabi [69] is an example of a collaborative design process where different specialists all contribute to the development of a central master model from design to fabrication. In this project, the design team (Ateliers Jean Nouvel and HW Architecture) and both structural (Buro Happold) and climate (TransSolar) engineers worked on the same model to find a balance between the multiple interrelated constraints, such as aesthetics, structure self-weight, cost, and cladding opacity. As the process evolved, the central parametric model was further enriched with additional design data, later supporting design detailing, manufacturing preparation, and structure installation.

Comparing both workflows (Figure 21 top and bottom schemes), the use of multiple and sometimes unrelated ADs requires greater coordination between specialities because every time one AD changes, the others must be immediately updated, and the changes checked to ensure they are feasible. For example, in Little Island [60], structural engineers extended the architects' AD to check whether the changes made to the deck structure were viable, guaranteeing a balance between design intent and structural efficiency. Similarly, the fabrication team developed their own AD to check the toolpaths developed by the engineers and ensure accurate production planning and scheduling.

Moreover, as independent ADs often result from solving specific challenges that arise within each design speciality, they are often poorly structured and have little to no relationship with each other. In contrast, using a master AD model ensures the design is always up to date because all stakeholders work on the same AD and thus any modification to the design is automatically propagated to all its specialized versions. This scenario occurs in Louvre Abu Dhabi [69], where the changes made by each design speciality were always supplemented and validated through physical simulations, and in Canary Wharf Crossrail Place [66], where, although specialized ADs were independently developed by different teams, the data generated was always shared via a central data hub, ensuring it was always updated.

Additionally, as the use of a central master model requires the development of a structured AD from the beginning of the project that can coordinate the requirements of different specialities, the resulting design-to-fabrication workflow is often more efficient, flexible, and accurate. Despite requiring greater organization and initial investment, this scenario is often more suitable to deal with large-scale and geometrically complex designs, as is the case of Louvre Abu Dhabi, Kuwait International Airport, and Canary Wharf Crossrail Place. Without a central master model, it would have been difficult, or nearly impossible, to manage (i) the amount of technical data involved in these projects, (ii) the geometric complexity and uniqueness of the elements to produce, and (iii) the constant interactions between different specialities, which actively contributed to the projects' development and realization. In these projects, the use of a central parametric model allowed the team to achieve higher levels of design refinement in terms of geometry, performance, and structure [66]. It also led to a reduction in manufacturing costs, enhanced fabrication precision, and simplified assembly and installation processes [56,63,69] by eliminating the need for manual interventions [66].

Table 2 summarizes the design-to-fabrication tasks automated by AD in the previous projects. It shows that custom algorithms were applied in all projects to support design detailing and to integrate construction data. It also shows that almost all projects used custom algorithms to coordinate shape exploration and structural analysis routines, as well as to automate the production/extraction of manufacturing data. Although only two projects entirely automated the production of 2D drawings for manufacturing through AD, almost all of them provided the data needed for fabricators to extract technical documents easily and accurately. Similarly, despite only two projects using AD to directly support logistic tasks, such as onsite delivery and assembly processes, the information available in almost all projects' AD models allowed for improving these tasks.

Table 2. Summary of six large-scale design-to-fabrication processes extended by custom algorithms.

	SoFi Stadium	Little Island	Kuwait International Airport	Louvre Abu Dhabi	Gilder Center	Canary Wharf Cross rail
Master Model	✓		✓	✓		✓
Shaping		✓	✓			✓
Patterning	✓			✓		
Structural analysis	✓	✓	✓	✓		✓
Environmental analysis				✓		
Rationalization				✓		
Detailing	✓	✓	✓	✓	✓	✓
2D views/section		✓		✓		
Manufacturing data	✓	✓	✓	✓	✓	✓
Logistics Instructions				✓		✓
Design data	✓	✓	✓	✓	✓	✓

7. From Architectural Geometry to Fabrication through Algorithms

The use of AD in design-to-fabrication workflows has been growing because of its ability to provide design flexibility and control over manufacturing processes, increasing design precision, facilitating data coordination, and automating repetitive and time-consuming operations. As AD might require a non-trivial programming effort, there is a tendency to use predefined plugins or libraries encapsulating algorithmic descriptions and making their application more intuitive. Despite making AD more user-friendly, this solution however compromises the algorithms' expressiveness, especially when these are implemented in visual programming languages, such as Dynamo and Grasshopper, whose limited scalability hinders the development of large-scale designs. Moreover, by converting abstract algorithms into specialized plugins we restrict not only their degrees of freedom but also their scope of application, narrowing the diversity of tasks and tools supported. As a result, exploring different design possibilities in design-to-fabrication workflows requires the designer to frequently switch between different plugins, resulting in a time-consuming and error-prone process where the AD is consistently changed or even restructured.

Additionally, responding to the variability and context-specificity of architectural design usually (if not always) requires restructuring or even extending standard plugins with custom algorithms, a task that requires programming experience. The literature shows that, in these situations, the tendency is to implement text-based algorithmic extensions rather than visual ones. This is explainable by the lack of abstraction mechanisms of most visual programming environments, compromising their scalability and expressiveness, as well as their limited extension mechanisms, which typically rely on a general-purpose text-based programming component as an escape hatch. It is often the case that these custom algorithms developed for a specific project later give rise to standard plugins or AD libraries for others to use (e.g., [123]). As, in these cases, the original algorithm was developed for a particular context and its structure was hardly planned, it is submitted to a standardization process that reduces its degrees of freedom but generalizes and simplifies its use. This brings us back to the earlier point that this process reduces the expressiveness and flexibility of the abstracted algorithms. However, if this was not done, their reuse in other contexts and design problems would be far from trivial.

7.1. How AD has been changing the relationship between architectural geometry and manufacturing?

The literature shows that AD has allowed architects to increase their design flexibility and efficiency, enabling not only the exploration of novel geometries but also their realization. It also shows that AD has increased architects' control over design-to-fabrication processes, improving their perception of the physical outcome of their design intentions and promoting their active participation in manufacturing activities. This brings creative and construction processes closer together, giving rise to design approaches where design exploration and aesthetics consideration are guided by manufacturing and material principles.

For example, in Table 2, the workflows resulting from a central AD model – SoFi Stadium, Kuwait International Airport, Louvre Abu Dhabi, and Canary Wharf Crossrail Place – were able to automate several design tasks, from design to construction. As the level of design complexity of these projects required the coordination of large amounts of data and unconventional design requirements, the teams adopted a central AD model to reduce:

- the time and cost of the design-to-fabrication process, reducing the number of iterations between specialists and avoiding repetitive work;

- error accumulation and outdated information, propagating the changes made by different teams in real-time and constantly updating the design;
- the time and effort spent in repetitive performance evaluation, design detailing, technical documentation, and data extraction tasks.

It should be noted that the adoption of a central AD model requires initial investment as well as good coordination between specialized teams to ensure all relevant data is provided efficiently and accurately. In smaller-scale projects, where AD is used only for one-off tasks, as is the case of the Gilder Center, the investment required to develop and maintain a central model may not pay off. In these cases, the algorithms developed are only used by their creator teams to solve specific problems, the results being later shared with the other teams through graphs, tables, technical drawings, or even 3D models.

7.2. What barriers are still hindering the use of AD in design-to-fabrication processes?

Most standard algorithms have a wide scope of application but cannot fully respond to the specificity and complexity of architectural design problems. First, because they are designed to address generic problems and, second because they are frequently implemented using visual programming languages and thus present limited scalability and performance [63]. This also explains why visual programming strategies are more frequently applied at early design stages or in small-scale projects.

In contrast, custom algorithms often support the context-specificity and complexity of architectural design but also present a narrow scope of application. This is because these algorithms are frequently designed to address very specific design problems, particularly those that standard algorithms cannot solve. Although custom algorithms can be reused outside their creation context, their application almost always requires adjustments to their structure, which takes time and above all demands programming experience.

Table 2 shows that the need to extend mainstream design tools via custom algorithms was ubiquitous in all projects. Standard algorithms were not sufficient to solve the challenges faced during the design-to-fabrication process and ended up being extended with custom algorithms. Figure 13 endorses this view: except for manufacturing simulation, custom algorithms were more often applied than standard algorithms in all design tasks, and significantly so in most cases. This may be explained by (i) the reduced ability of standard algorithms to deal with more complex problems, large amounts of data, and multiple design requirements; (ii) the generalist nature of their features and parameters, which hardly respond to the specificity of both creative and construction processes; and (iii) their limitations in interoperating with multiple tools simultaneously.

Another issue is the lack of portability of most AD strategies, whether standard or custom. Even using AD, the literature evidences the still fragmented nature of most design-to-fabrication workflows, which continue to require adjusting and extending the solutions to fit different manufacturing and construction scenarios. For example, when selecting a plugin specialized in design manufacturing, the structure of the AD evolves according to the requirements of such plugin. If, in the meantime, the designer wants to test a different fabrication strategy, he or she will not only have to select another plugin, but also change both the structure and content of the developed AD program to meet the specificities of the new plugin. This means that when switching between various plugins, whether specialized in geometric exploration, performance evaluation, or fabrication, several changes to the AD must be made.

To achieve smooth design-to-fabrication workflows, design teams must develop ADs that can flexibly and continuously handle various types of information, design requirements, and specialized tasks, from design conception to construction. Ideally, this requires describing an AD in a generic and more abstract way initially and then adapting it according to the requirements of the selected materials and manufacturing technology, among other criteria.

7.3. Prospections on Design-to-Fabrication Methodologies

To smooth the transition between design-to-fabrication strategies, it is necessary to deliver AD tools that allow for direct control over geometry materialization and fabrication processes and provide appropriate algorithms for different surface finishing, material properties, and manufacturing techniques.

A possible solution is to provide a system that allows users to fix the intended fabrication strategy but not the manufacturing tool. It is then the system's responsibility to adapt the developed AD according to the specificities of the different fabrication engines used. To achieve such behaviour, the system must abstract different fabrication strategies as well as link the designs' geometric and material characteristics with the technical requirements of different manufacturing tools.

Another possibility is a system allowing abstracting the fabrication strategy to use (i.e., keeping it partially undefined) and, based on the design's geometric and material characteristics, suggesting different manufacturing scenarios. This would allow the designer to explore several fabrication strategies and simulate the result of producing the developed solution with, for instance, different materials, surface textures, and stereotomy.

In either case, it is necessary to define an AD-oriented methodology (1) identifying the best methods for each fabrication strategy; (2) automating the extraction and manipulation of fabrication data for each one; (3) converting fabrication data according to the manufacturing engine used; and (4) allowing for graphically displaying both the operation and outcome of different fabrication strategies using different materials and manufacturing engines. Additionally, the methodology should provide solutions supporting the decomposition of complex geometries into smaller and/or simpler elements that can be produced with the available resources, whether machinery or building materials, and easily transported and assembled.

These suggestions require an exhaustive study of the computational methods that deal with each manufacturing strategy, as well as the digital and analogue means to achieve the expected results. Clearly, that study will raise additional questions and answers regarding a better exploration of AD in the context of design-to-fabrication.

8. CONCLUSION

New technologies have been triggering new design approaches that are changing the way architects design and construct buildings. Algorithmic Design (AD) is a prominent example that extends the flexibility and efficiency of architectural practice, enhancing creative thinking and design space exploration. By facilitating the development of less conventional solutions, these approaches challenge current fabrication and construction methods, motivating the search for novel design-to-fabrication strategies.

In this paper, we investigated the impact of AD in design-to-fabrication processes, approximating the exploration and fabrication of less conventional architectural designs. We presented an analysis of 237 scientific papers on this subject, identifying methodological patterns and algorithmic trends (e.g., most used AD tools and libraries in design-to-fabrication workflows and tasks more often supported by algorithms). The result was a categorisation of design-to-fabrication tasks where the use of AD was most prominent. For each of them, the tendency to use standard and custom AD strategies was identified. For example, the analysis revealed a clear prevalence of custom algorithms over standard ones in data exchange, design detailing, and generation of manufacturing data, among other activities, and a more balanced ratio in tasks related to shape exploration, mesh manipulation, and manufacturing simulation.

After reflecting on the previous findings, we correlated the algorithmic trends found in design-to-fabrication processes with design complexity/abstraction. We then analysed six architectural projects where AD was critical throughout the entire process. Building upon this, two design-to-fabrication workflows were proposed, one based on a central AD model shared by the whole team and another where different AD models are built by different team members. Lastly, we discussed the advantages and limitations of each workflow as well as their correlation with the projects' level of complexity.

Overall, the research revealed the potential of AD to leverage design-to-fabrication processes. In addition to strengthening the relationship between architectural geometry and fabrication, the use of AD facilitated design collaboration and communication between architects and engineers. The gained insights allowed us to answer the two research questions driving this study, namely *How AD has been changing the relationship between architectural geometry and manufacturing?* and *What barriers are still hindering the use of AD in design-to-fabrication processes?* They also inspired our final considerations and solutions for more efficient and smoother design-to-fabrication workflows.

The analysis presented in this paper provides valuable insights, but it also presents a few limitations that may influence the findings. The first one is the imbalance in the types of scientific publications within the selected literature, with a clear prevalence of conference papers. This could potentially introduce a bias capable of distorting some of the results. Another limitation lies in the tendency to only publish results falling outside the norm. Therefore, there is a risk of underestimating the prevalence of industry practices grounded in standard algorithms. Nevertheless, as the paper focuses on design-to-fabrication processes of unconventional architectural shapes, the bias is thus minimized.

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Declaration of Interests

None.

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