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DIGITAL FABRICATION IN ARCHITECTURE THE TRANSFORMATION OF DESIGN PROCESSES

Engy Fawzy Ahmed [a*]

[a] Architecture, Thebes Academy, Cairo, Egypt, engy.fawzyahmed@gmail.com

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ABSTRACT

Digital Fabrication is a process that utilizes machines to create physical objects directly from digital data through additive or subtractive methods. Originating in the 1950s due to post-war technological advancements, it has become a transformative force in architecture and construction, seamlessly integrating design and fabrication.

More than just a tool for model-making, Digital Fabrication enables the production of full-scale structures using cutting-edge technologies and emerging materials. By leveraging specialized software and techniques, it allows architects to design highly complex forms that go beyond traditional construction methods.

This process fosters a dynamic, reciprocal relationship between design and material, where real-time experimentation and testing refine the outcome. Today, design and fabrication are nearly simultaneous, enabling rapid prototyping, laser cutting, and mock-ups to validate and enhance architectural concepts. The iterative nature of this approach ensures efficiency, innovation, and material optimization.

Given its impact on the industry, Digital Fabrication is now an essential skill for architects. Educating future professionals in these technologies is as crucial as the integration of computers in architectural practice, ensuring continuous advancement in design and construction methodologies.

KEYWORDS: Digital Fabrication -Computer-Aided Design (CAD) - Computer-Aided Manufacturing (CAM) - Parametric Design - Generative Design - Algorithmic Architecture - Fabrication Technologies - Digital Construction - Meshes and Geometries.

OBJECTIVES

This study explores digital fabrication as an emerging technology, emphasizing its transformative impact on architectural design processes. It advocates for integrating digital fabrication into architectural education, highlighting its importance in training and professional qualification.

Through case studies, the research presents the tools, principles, and methodologies that define digital fabrication as a design approach. Following a chronological framework, it examines its origins, key pioneers, and technological evolution, showcasing current applications and potential (Figures 1-3).

Fig. 1. Frank Gehry Disney Concert Hall.

Fig. 2. Applications, Technicolor Bloom.

Fig. 3. Applications, Cellular Tessellation.

1 INTRODUCTION

1.1 History of Architectural Design and Fabrication

Architectural projects fundamentally involve two key actions: designing and building. Advances in technology, the widespread use of computers, and the development of sophisticated modeling software (Fig. 4) have revolutionized architectural design, enabling a seamless connection between digital and physical realms with greater speed, efficiency, and precision.

Modern digital architectural methods focus on integrating material and form to create increasingly complex structures (Fig. 5). Digital fabrication plays a pivotal role in this transformation by merging design and construction into an interactive, iterative process.

Design Intelligence and the New Economy, describes this shift as a process where fabrication itself becomes an act of knowledge creation. The traditional boundaries between thinking and making, designing and fabricating, and prototyping and final production are blurred, fostering a dynamic and non-linear approach to innovation. [1]

This paradigm shift establishes a dual design process where designing and fabricating exist on the same level, reinforcing a new direction in architecture that prioritizes experimentation and continuous evolution (Fig. 6).

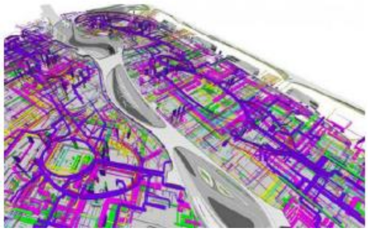

Fig. 4. 3D modeling

Fig. 5. Project realized through complex geometries

Fig. 6. Filmmaker, Gran city

1.2 Fabricating Architecture in the Digital Era

Digital fabrication in architecture is a relatively new yet rapidly evolving phenomenon that has become a fundamental aspect of contemporary design over the past 15 years. It encompasses all material fabrication processes driven by digital techniques and software, utilizing both subtractive (Fig. 7) and additive methods. [2]

While CAD (Computer-Aided Design) systems (Fig. 8) have been employed for over 50 years in engineering—especially in automotive and aerospace industries—architecture has only recently begun to leverage these tools for transforming design into fabrication. Components are now modeled digitally and mass-produced through prototyping (Fig. 9), bridging the gap between design and physical construction.

Fig. 7. Object created by materi subtraction

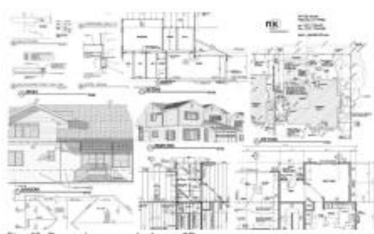

Fig. 8. Project presented in 2D

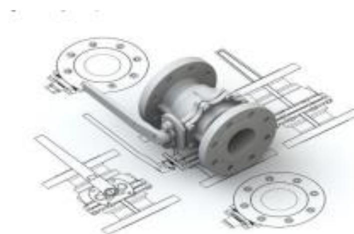

Fig. 9. 3D model superimposed on 2D model

2 METHODS AND TECHNIQUES IN DIGITAL FABRICATION

2.1 Generation of CAD geometries

CAD (Computer-Aided Design) software is widely used in architecture schools and studios as a design tool for creating digital representations of objects. Introduced in Spain in the late 1980s from Germany, CAD replaced hand-drawn drafting by enabling efficient editing, copying, and modifying of designs. Its main advantages include intuitive operation, compatibility with multiple platforms, and seamless integration with other digital tools, enhancing design efficiency. [3]

In digital fabrication, scale is a critical factor, as machine limitations must be considered. However, CAD's 3D modeling capabilities are limited in accuracy, leading to the use of NURBS (Non-Uniform Rational B-Splines) and meshes for complex geometries.

A notable example is the Dublin House project by Amanda Levete Architects, where sunlight analysis influenced the design, dynamically shaping a curved, perforated roof with glass inserts to enhance natural light and ventilation. (Figures 10-12).

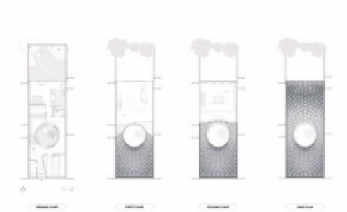

Fig. 10. Plans of the house in Dublin

Fig. 11. Three-dimensional development for the study of light

Fig. 12. Final model made thanks to the previous study

2.2 Generation of NURBS geometries

NURBS (Non-Uniform Rational Basis Spline) is a mathematical model used in computational design to generate and represent curves and surfaces (Fig 13-15). with precision. Developed from mathematical studies in 1946, NURBS is based on polygonal formulas and offers advanced control through control points, forces, and nodes. (Fig 16). This system allows designers to create complex geometries from simple volumes and facilitates seamless integration with Computer Numerical Control (CNC) machines. [4]

NURBS is the digital equivalent of drafting splines, which were flexible strips of plastic, wood, or metal used to draw complex curves in ship hulls and airplane fuselages. These splines were shaped and held in place using weights, mirroring how NURBS curves are manipulated digitally.

Fig. 13. Program used for 3D modeling, Rhinoceros

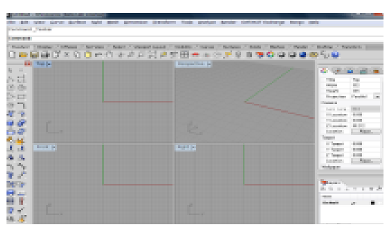

Fig. 14. Rhinoceros program interface

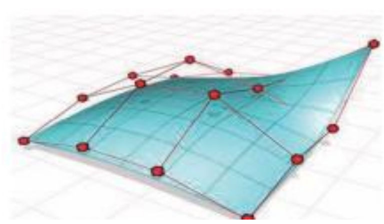

Fig. 15. Development of the elements that form NURBS

2.3 Geometry generation Meshes

Meshes are a fundamental method for generating complex surfaces in 3D modeling, consisting of vertices, edges, and faces that define an object's polyhedral geometry. Polygonal meshes, typically structured with triangular or quadrilateral polygons, function as an irregular grid used in digital modeling. (Fig 16-18).

Meshes enable various geometric operations, including Boolean functions, smoothing, and simplification. They are extensively applied in computer graphics, supporting collision detection and ray tracing. Beyond CGI visualization, meshes are crucial in finite element analysis (FEA) for structural and physical simulations in architectural and engineering applications. [4]

Fig. 16. Program used to model with meshes

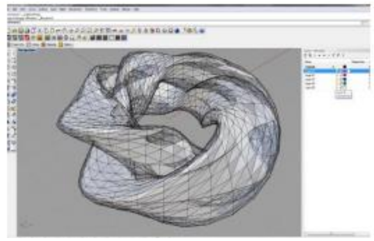

Fig. 17. 3D modeling made with a triangular mesh

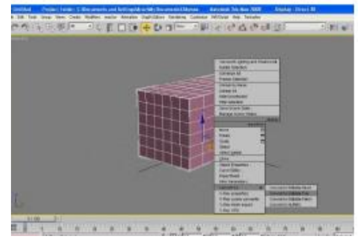

Fig. 18. 3Dmax interface for creating 3D models

2.4 Generation of geometries curvilinear formations

Advancements in digital design and CAD/CAM technologies have enabled the creation and fabrication of complex curvilinear geometries. Architects now explore fluid facades and spatial formations, integrating design and fabrication for precision and efficiency. This seamless workflow has revolutionized architecture, making previously unattainable forms achievable. (Fig 19-20). [5]

Fig. 19. Curvilinear formation

Fig. 20. Zaha Hadid, Nordpark Cable Railway

3 DIGITAL DESIGN STRATEGIES

3.1 Principles of Digital Fabrication: Cutting

Cutting is the most common digital fabrication process due to its efficiency and accessibility. It is a two-dimensional operation, constrained by the machine's dimensions and material width. Various cutting techniques optimize this process: (Fig 21). [6]

- Laser Cutting: Uses an infrared laser beam and pressurized gas (CO_2) for precision and versatility.

- Plasma Arc Cutting: Generates a high-temperature plasma beam via an electric current through gas to cut materials. . (Fig 22).

•	Water Jet Cutting: Utilizes high-pressure water jets mixed with abrasives for precise, material-efficient cuts. . (Fig 23).

Fig. 21. Model made using Laser cutting

Fig. 22. Cutting with Plasma Arc

Fig. 23. Cutting with Water

3.2 Principles of Digital Fabrication: Subtracting

Subtractive fabrication removes material from a solid volume to shape the desired element, with waste either discarded or recycled. Using a rotating drill, this process operates along the X, Y, and Z axes, enabling greater complexity than 2D laser cutting. (Fig 24-26). [7]

Advanced four- and five-axis systems allow drill rotation for more intricate geometries. Key advantages include:

- Scalability for larger elements.
- Versatility with a wide range of materials.
- Precision due to low tolerance levels.
- Efficiency in mass production of large components.

Fig. 24. Cut produced by CNC

Fig. 25. Model made in wood

Fig. 26. 5D subtraction of Metallic material

3.3 Principles of Digital Fabrication: Adding

This process, known as "Rapid Prototyping," differs from traditional manufacturing by building up layers of the same material to form the desired design. All additive manufacturing methods rely on converting three-dimensional models into sequential two-dimensional layers, which are then processed cumulatively by the machine. (Fig 27-29). [8]

3.3.1 Key advantages of this technique include:

• Direct fabrication from digital models eliminates the need for molds, making it ideal for producing unique products.

• The precise material deposition enables the creation of complex geometries, including internal voids.

• Machines used for this process are typically enclosed, allowing installation in compact spaces without special requirements.

• No specialized fabrication expertise is required to operate these machines, making the technology widely accessible

Fig. 27. 3D Printing

Fig. 28. 3D Printing of complex geometry

Fig. 29. 3D Printing of a utopian project

4 APPLICATIONS OF DIGITAL FABRICATION IN ARCHITICTURE

4.1 Design Tactics: Introduction

Digital fabrication in architecture goes beyond using computers as tools; it integrates creativity and technology throughout the design and construction process. Traditionally reliant on mass production and standardized components, architecture now benefits from digital experimentation, enabling innovative spatial design and material exploration. [9]

This approach reshapes the relationship between design and construction, allowing architects to engage directly in fabrication. Rather than providing a fixed methodology, digital fabrication introduces strategic techniques such as sectioning, modularizing, folding, contouring, and forming.

Notable case studies include Studio Gang's Lincoln Park Pavilion, highlighting digital project execution, and Mark Goulthorpe's Hypersurface, which explores interactive, responsive architectural surfaces. (Fig 30-32).

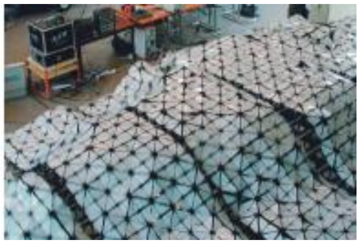

Fig. 30. Top view of panels composing "The HypoSurface"

Fig. 31. Interaction with the hypo Surface

Fig. 32. Detailed view of internal motors for movement

4.2 Design Tactics: Sectioning

Surface creation in architecture can follow a rib-like trajectory or a perpendicular sectioning strategy, (Fig 33). forming a structural grid. Le Corbusier applied this method in the Ronchamp Chapel roof, using unique concrete beams to achieve complex geometry. This approach enables lightweight, precise structures, particularly for curved surfaces. (Fig 34). [10]

William Hesse, a pioneer in digital fabrication, utilized sectioning in his Urban Beach installation (MoMA/P.S.1, 2002), featuring laser-cut steel and PVC to create fluid, open spaces. His methods effectively adapt traditional sheet materials into dynamic three-dimensional forms. (Fig 35).

Fig. 33. Vertical and perpendicular sectioning

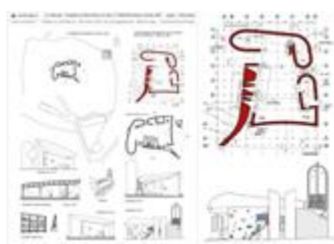

Fig. 34. Sketch by Le Corbusier

Fig. 35. Urban Beach

4.3 Design Tactics: Modulation and Composition

Modulation and composition enable seamless assembly of components, historically seen in Roman mosaics and Gothic windows. Previously labor-intensive, this process is now streamlined through digital technology, allowing instant transitions from 3D models to fabrication (Fig 36). [11]

In digital design, polygonal meshes facilitate efficient construction of complex surfaces using standardized materials like aluminum or wood, reducing costs and time. Precision depends on the chosen system, whether NURBS or meshes (Fig 37).

Buckminster Fuller's geodesic domes exemplify this strategy, utilizing triangular and hexagonal patterns for structural efficiency. Robotic fabrication further enhances accuracy and efficiency in modern applications (Fig 38).

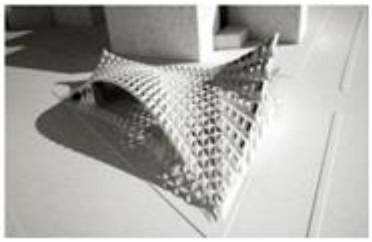

Fig. 36. Project using this technique

Fig. 37. Cellular Tessellation

Fig. 38. Buckminster Fuller

4.4 Folding Tactics in Digital Fabrication

Folding is the simplest way to transform a 2D element into a 3D form, adding structural rigidity and design efficiency. This technique ensures spatial and formal continuity, distinguishing it from other strategies (Fig 39).

Digital fabrication enables precise folding pattern calculations, allowing scaled models to become full-scale prototypes for spatial experimentation. Software as Rhinoceros unfolds 3D designs into cut table profiles, with machines either scoring or perforating materials for easier folding (Fig 40).

Ideal materials for this technique include metal sheets, paper, plastics, and textiles, chosen for their flexibility and resistance to breaking during folding (Fig 41). [12]

Fig. 39. Explanatory book on folding techniques

Fig. 40. Agora Theater exterior view

Fig. 41. Yokohama International Port

4.5 Contour Tactics in Digital Fabrication

Many construction materials, such as stone sheets, laminated wood and composite panels, are transported as flat surfaces. Contouring transforms these 2D materials into 3D forms through a subtractive process (Fig 42).

Digital fabrication has modernized the concept of sculpting, reminiscent of Greek column capitals, by enabling intricate ornamentation using CNC machining with minimal tolerance (Fig 43).

This process requires converting digital models into machine-readable formats using software like MasterCam, RhinoCAM, and SURFCAM, which generate G-Code to guide tool paths with precise positioning and speed control (Fig 44).

Fig. 42. Molds made of EPS, 2” thick

Fig. 43. Finish achieved using contouring

Fig. 44. Greg Lynn, Prettygoodlife.com Showroom

4.6 Forming Tactics in Digital Fabrication

Digital fabrication is widely used across industries, from mobile phones to car bodies and architectural components. Forming enables cost-efficient mass production by generating multiple parts from a limited number of molds, commonly seen in facades, carpentry, and structural elements (Fig 45).

Beyond standardized production, advanced forming techniques explore material properties, such as ultra-thin concrete structures. The process typically involves male and female molds, though in some cases, a single mold suffices, using curing, heat forming, or vacuum forming. Mold fabrication is crucial, requiring the same precision as the final piece (Fig 46).

William Massie, a pioneer in CAD/CAM technology in architecture, explored digital forming at Columbia University. His 1997 project, The Concrete Wall, demonstrated full-scale digital fabrication, with digitally modeled deformed planes shaping the surface (Fig 47). [13]

Fig. 45. Félix Candela, Los Manantiales Restaurant

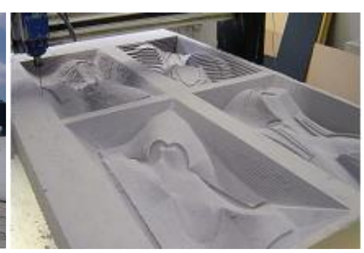

Fig. 46. Mold Creation

Fig. 47. Mold creation for final piece fabrication

5 ADDITIVE MANUFACTURING (3D PRINTING)

5.1 3D Printing Introduction

3D printing is the most well-known additive manufacturing process, enabling rapid production of objects from various materials by layering material incrementally.

The first commercial 3D printer, Stereolithographic (1980s), used liquid polymers solidified by a laser. Each layer was formed as a platform lowered gradually until the final object was completed. Since 3D-printed elements can be fragile, adhesives or binding agents are often used to reinforce the structure. [14]

5.1.1 Currently, there are four main types of 3D printing:

- Laminated Object Manufacturing (LOM): Uses laser-cut layers of paper or plastic stacked to form an object.

- Fused Deposition Modeling (FDM): Melts a plastic filament that solidifies as it cools, layering material to build the object.

- Multi-Jet Manufacturing (MJM): Utilizes a print head that deposits melted thermoplastic wax layer by layer.

- Selective Laser Sintering (SLS): Combines MJM and FDM techniques, using a laser to melt fine metal layers into the desired shape. [15]

5.2 3D Printing in Architecture: Enrico Dini

Enrico Dini, an Italian engineer, pioneered large-scale 3D printing for architecture, pushing the boundaries of experimental construction. Sharing conceptual similarities with Neri Oxman, Dini views 3D printing as a tool to redefine habitable space. He questions why, despite having full control over building geometry, construction methods remain largely unchanged. (Fig 48). [16]

Dini initially explored nature-inspired structures and gained recognition for using 3D printing to create large-scale artificial coral reefs for marine life. This breakthrough led him to realize the potential of 3D printing not only for replicating nature but also for generating new architectural forms. His research then shifted towards full-scale construction using sand as a primary material, earning him the title "The Alchemist of Rocks." (Fig 49).

His patented D-Shape 3D printer enables large-scale printing using innovative materials, marking a significant advancement in digital fabrication and architectural design. (Fig 50).

Fig. 48. Enrico Dini: "The Man Who Printed

Fig. 49. Early Works of Enrico Dini

Fig. 50. D-Shape, Necessary Wiring

6 FUTURE OF DIGITAL FABRICATION IN ARCHITECTURE

6.1 Digital Fabrication in the Future: The Architect's Formation

The rapid expansion of digital fabrication technology in architecture, many universities have incorporated its teaching into their curricula (Fig 51).The majority of these institutions are located in the United States, where technological advancements tend to outpace those in other parts of the world.

Several universities, including Michigan, California, Harvard, Washington, and the Illinois Institute of Technology, offer courses that familiarize students with digital fabrication tools, enabling them to create small-scale models and experiment with new materials.

The University of Michigan (Fig 52-53).has a state-of-the-art digital fabrication lab that utilizes robotic automation for both additive and subtractive manufacturing processes. The lab features six multi-purpose robots operating cooperatively within three modular work cells. These workspaces can be rapidly reconfigured for various tasks, including cutting, subtracting material, or 3D printing. Additionally, the lab is equipped with advanced digitization tools such as 3D scanners, which can capture physical models and translate them into point-cloud data within Rhinoceros software. [17]

Fig. 51. Incorporation of Digital Fabrication Workshops

Fig. 52. Columbia University, Digital Fab Studio

Fig. 53. University of Michigan, Robotic Arm

6.2 Digital Fabrication in the Future: New Materials

Digital fabrication has expanded material applications, from traditional (wood, metal, glass, ceramics) to contemporary (plastics, composites). This technology enables innovative uses, such as 3D printing with sand or structural plastic elements (Fig 54).

Fiber-reinforced composites (glass, carbon, plastic) are emerging as key materials in future architecture, with their influence already evident (Fig 55).

A notable example is the BBVA headquarters in Madrid. It comprises a three-story office building and a central ovoid structure. The façades integrate self-supporting shading elements made of fiberglass-reinforced polyester with an internal metal frame, providing solar protection and a distinctive aesthetic (Fig 56).The ovoid form gives the building a dynamic, ship-like appearance. [18]

Fig. 54. Incorporation of Digital Fabrication Workshops

Fig. 55. Columbia University, Digital Fab Studio

Fig. 56. University of Michigan, Robotic Arm

The RV Prototype House by Greg Lynn (2015) explores emerging materials in architecture. This 1:5 scale model envisions a 150m² adaptable living space with only a 60m² footprint, using carbon fiber and textiles. The design is based on three rotational configurations: 0° for living, 90° for cooking, and 180° for resting (Fig 57).

In 2011, the BMW Guggenheim Pavilion became the first structure to use carbon fiber as its primary framework, leveraging its molecular properties to filter air particles (Fig 58).

On a larger scale, The Kingdom Tower in Saudi Arabia, set for completion in 2018, incorporates carbon fiber cables in its elevator system. These cables are ten times lighter and more durable than traditional steel cables, optimizing efficiency and performance (Fig 59). [19]

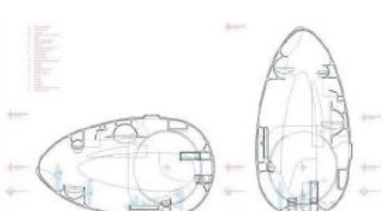

Fig. 57. Variation of Habitable Space

Fig. 58. BMW Guggenheim pavilion

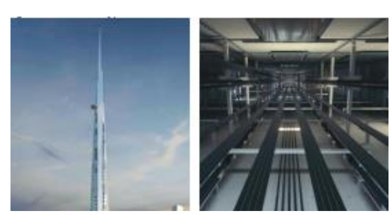

Fig. 59. Kingdom Tower-Elevator Shaft

7 CONCLUSIONS

The impact of digital design and fabrication techniques on architecture is unprecedented. The integration of digitally generated information to produce precise and complex geometries, directly linked to the construction process, is bringing architects back to a central role in building production.

The future of digital fabrication in architecture involves a continuous dialogue of exploration, invention, and application. Since the first Digital Fabrication seminar in Ontario (2004) to the "FABRICATE: Making Digital Architecture" conference in London (2011), the architectural field has recognized the transformative potential of this movement. While there are diverse approaches to employing digital fabrication in contemporary design, its true value lies in how these technologies are applied to enhance architectural processes.

One of the immediate transformations in digital fabrication is the accessibility and mobility of necessary equipment. It is now common for architecture studios to have 3D printers or multi-axis CNC machines integrated into design workflows—tools that were financially and technically out of reach just a decade ago.

Furthermore, many architecture schools have incorporated CAD/CAM software into their curricula, enabling students to explore and push technological boundaries. Digital fabrication methods are already shaping and will continue to influence the design, production, and construction of buildings. The direct relationship and real-time feedback between design and construction using these methods represent a crucial evolution in the architectural discipline.

Digital fabrication represents the most transformative shift in architectural design, redefining methodologies and encouraging non-linear approaches. Its true potential lies in seamlessly integrating material exploration, computational design, and fabrication strategies within architectural projects.

7.1 The creative application of digital tools has bridged the gap between design and construction, offering two key advantages:

• A new generation of designers skilled in both programming and material fabrication, yielding unprecedented architectural outcomes.

• A more interactive and dynamic design-to-production process, enhancing the efficiency of building component fabrication.

Perhaps the most exciting aspect is the interdisciplinary nature of digital fabrication, enabling architects to reclaim their role in material production and construction—fields from which they had become increasingly distanced.

Architectural Digital Fabrication Glossary

• CAD (Computer-Aided Design): Digital tools assisting architects, engineers, and designers in creating precise models and technical drawings.

• CAM (Computer-Aided Manufacturing): A process that bridges digital design with automated fabrication, minimizing manual intervention.

• CNC (Computer Numerical Control): A system that precisely controls machine tools through programmed coordinates, enabling high-accuracy fabrication.

• Laser Cutting: A technique that uses a focused laser beam to cut materials, assisted by pressurized gases like oxygen or nitrogen.

• NURBS (Non-Uniform Rational B-Splines): A mathematical model used in computer graphics for defining complex curves and surfaces with high precision.

• Parametric Design: A design paradigm that utilizes relationships between elements to generate optimized geometries based on algorithmic rules.

• Stereolithographic (SLA): A 3D printing process that uses UV light to cure liquid resin, layer by layer, to create highly detailed prototypes.

• Project Strategy: The structured approach architects use to conceptualize and develop designs, integrating theories, tactics, and form-generation principles.

• Composite Materials: Engineered materials combining two or more substances to achieve enhanced properties such as strength, rigidity, lightweight, or thermal resistance.

• Software: A collection of digital programs and routines that enable computers to perform specific tasks in architectural design and fabrication.

• 3D Modeling: The process of creating a digital mathematical representation of a three-dimensional object, which can be visualized, rendered, or fabricated using 3D printing.

• Tool: An instrument designed for specific tasks in construction, fabrication, or digital modeling.

•Plasma Arc Cutting: A process that heats gas to over 20,000°C, ionizing it into plasma to precisely cut conductive materials through a high-energy arc

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