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# DIGITAL MANUFACTURING TAXONOMY FOR ARCHITECTURE

## TAXONOMÍA PARA LA FABRICACIÓN DIGITAL PARA LA ARQUITECTURA

## TAXONOMIA DA FABRICAÇÃO DIGITAL PARA A ARQUITETURA

**Figure 0.** HF1 | CoBLOgó. Source: Sperling & Herrera Polo (2015)

## ABSTRACT

This article presents the Taxonomy for Digital Fabrication (TDFab+Arch), a tool developed to categorize and compare projects materialized through digital fabrication. In this article, TDFab+Arch has been applied to the Homo Faber (HF) catalogs, which bring together digital fabrication projects in Latin America from 2015 to 2022, and a comparison has been made between the techniques used by these projects. The structuring of the taxonomy was based on systematic literature reviews that identified criteria in the design processes, resulting in four categories: "design aspects," "machinery," "materials," and "surface topology." The methodology used in this article is "constructive research" as described by Kasanen et al. (1993) and Lukka (2003), which involves three phases of the process: understanding the project, proposing a solution, and validating the taxonomy. This methodology facilitates an understanding of the application of the taxonomy as a mode of classification, contributing to the advancement of knowledge in the field. The article presents the projects through text and images, making it easier to identify relevant aspects. TDFab+Arch stands out for its flexibility and versatility, making it suitable for cataloging project design. The taxonomy generates various visualization types, allowing designers to explore the criteria according to their specific needs. Qualitative content analysis and the structuring of the taxonomy were essential for organizing the techniques, materials, and equipment involved in digital fabrication, promoting a clearer understanding of the field. As a result, TDFab+Arch allows the designer to explore the criteria from different perspectives and gain a more comprehensive understanding of the projects. The taxonomy is an adaptable and customizable tool, allowing users to understand the criteria used in the development of each project.


**Keywords:** taxonomy, digital fabrication, project classification, Homo Faber


## RESUMEN

Este artículo presenta la Taxonomía para la Fabricación Digital (TDFab+Arch), una herramienta desarrollada para categorizar y comparar proyectos materializados a través de la fabricación digital. En este artículo, la TDFab+Arch se aplicó a los catálogos de Homo Faber (HF), que reúnen proyectos de fabricación digital en América Latina entre 2015 y 2022, y se realizó una comparación entre las técnicas utilizadas por estos proyectos. La estructuración de la taxonomía se basó en revisiones sistemáticas de literatura que identificaron criterios en los procesos de diseño para la estructuración en cuatro categorías: formas para fabricación digital, maquinaria, materiales y topología de superficie. La metodología utilizada en este artículo es la «investigación constructiva» de Kasanen et al. (1993) y Lukka (2003), que se ha dividido en tres fases del proceso: comprensión del proyecto, propuesta de la solución y validación de la taxonomía. Esta metodología ayuda a comprender la aplicación de la taxonomía como modo de clasificación y contribuye al avance de los conocimientos en la materia. El artículo presenta los proyectos mediante texto e imágenes, lo que facilita la identificación de los aspectos relevantes. La TDFab+Arch destaca por su flexibilidad y versatilidad, lo que la hace ideal para la catalogación del diseño de los proyectos. La taxonomía genera distintos tipos de visualización, lo que permite a los diseñadores explorar los criterios en función de sus necesidades particulares. El análisis del contenido cualitativo y la estructuración de la taxonomía fueron esenciales para organizar las técnicas, materiales y equipos implicados en la fabricación digital, promoviendo una comprensión más clara del campo. Como resultado, TDFab+Arch permite al diseñador explorar los criterios desde diferentes perspectivas y obtener una comprensión más exhaustiva de los proyectos. La taxonomía es una herramienta adaptable y personalizable, que permite a los usuarios comprender los criterios utilizados en el desarrollo de cada proyecto.


**Palabras clave:** taxonomía, fabricación digital, clasificación de proyectos, Homo Faber


## RESUMO

Este artigo apresenta a Taxonomia para Fabricação Digital (TDFab+Arch), uma ferramenta desenvolvida para categorizar e comparar projetos materializados por meio da fabricação digital. Neste artigo, a TDFab+Arch foi aplicada aos catálogos Homo Faber (HF), que reúnem projetos de fabricação digital na América Latina entre 2015 e 2022, e realizada uma comparação entre as técnicas utilizadas por estes projetos. A estruturação da taxonomia foi baseada em revisões sistemáticas de literatura que identificaram critérios nos processos de projeto para a estruturação em quatro categorias: "formas para fabricação digital", "maquinário", "materiais" e "topologia das superfícies". A metodologia utilizada neste artigo é a "pesquisa construtiva" conforme descrita por Kasanen et al. (1993) e Lukka (2003), que envolve três fases do processo: compreensão do projeto, proposição da solução e validação da taxonomia. Essa metodologia auxilia o entendimento da aplicação da taxonomia como modo de classificação e contribui para o avanço do conhecimento na área. O artigo apresenta os projetos por meio de texto e imagens, facilitando a identificação de aspectos relevantes. A TDFab+Arch destaca-se pela flexibilidade e versatilidade, podendo ser utilizada tanto no processo projetual quanto na catalogação de projetos. A taxonomia gera diferentes tipos de visualização que permitem que os projetistas explorem os critérios conforme suas necessidades. A análise qualitativa de conteúdo e a estruturação da taxonomia foram essenciais para organizar as técnicas, materiais e equipamentos envolvidos na fabricação digital, promovendo uma compreensão mais clara do campo. Como resultados, a TDFab+Arch permite que o projetista explore os critérios a partir de diferentes perspectivas e tenha uma compreensão mais abrangente dos projetos. A taxonomia é uma ferramenta adaptável e personalizável, permitindo que os usuários entendam os critérios utilizados no desenvolvimento de cada projeto.


**Palavras-chaves:** taxonomia, fabricação digital, classificação de projetos, Homo Faber

## INTRODUCTION

This article presents the Digital Fabrication Taxonomy for architectural scale projects materialized through digital fabrication. It offers categorization with well-defined criteria to aid understanding and comparison between projects. The taxonomy, which was named TDFab+Arch, was developed as part of doctoral research. The application of TDFab+Arch enables the design of digital fabrication processes and categorization of various projects. The taxonomy is a theoretical and methodological framework, hosted in the Notion platform (an online tool) for project classification and documentation. Therefore, it is a tool for project registry and comparative analytical support.

This article aims to describe the development of taxonomy and its application in projects from the Homo Faber (HF) catalogs: HF1.0 (Sperling & Herrera Polo, 2015), HF2.0 (Scheeren et al., 2018), and HF3.0 (Herrera et al., 2023), which house digital fabrication projects published between 2015 and 2022 in Latin America. These catalogs were chosen because they curate projects that detail techniques, processes, and results, facilitating analysis. TDFab+Arch is based on two systematic literature reviews that identified criteria addressed in digital fabrication design processes, permitting an enriching comparative analysis. Thus, the projects in the HF catalog are analyzed using the "constructive research" methodology of Kasanen et al. (1993) and Lukka (2003). The steps include characterizing the materialized projects using digital fabrication techniques, applying the taxonomy, and comparing the projects to discuss the techniques employed. As a result, relevant criteria emerge for laboratories in Latin America, promoting debates, new collaborations, and applications in different contexts, thus guiding trainee designers. The taxonomy and tool aim to promote debate, develop new criteria, expand applications, and guide trainee designers by systematizing the criteria used in the catalogs.

## THEORETICAL FRAMEWORK

This article analyzes the application of the TDFab+Arch taxonomy to the HF catalog. The taxonomy, which systematizes design aspects such as materials, machinery, and surface topology, is used here to organize the cataloged projects and enable comparisons that reveal particularities of the Latin American context. This approach links the design process to regional feasibility criteria while exploring the development of the HF catalog itself. To overcome the temporal limitations of the state of the art, taxonomy proves to be a flexible tool capable of contextualizing new discussions in the field, whether temporal, technological, or geographical.

### Digital fabrication in Latin America

Digital fabrication in Latin America follows a different trajectory, emerging from the academic context before being consolidated in architectural practice. This contrasts with the Global North, where the evolution went from industry to architecture. This dynamic has created a culture of personal fabrication and a diverse ecosystem of local initiatives integrating digital technologies into their projects (Herrera, 2024). In South America, interest in complex forms and complexity theories has led to digital fabrication being recognized as a means of computational transition, initially in the academic environment, enabling the creation of scaled prototypes (Scheeren, 2022). While in the Global North, digital manufacturing evolved from practice and the use of tools such as CAD and CAM.

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In contrast, South America's development was driven by the theoretical knowledge acquired by researchers trained abroad, who were often disconnected from industry and manufacturing (Herrera, 2024). Over the last 20 years, the region has seen few significant technical advances, with initiatives primarily focused on the individualized use of technologies, rather than introducing innovations in materials, geometries, or integrated systems (Scheeren & Sperling, 2024).

Digital manufacturing in North and South America presents marked contrasts. In the North, there is economic and political stability; the sector is driven by the military, government, and industrial funding, focusing on full-scale construction and with broad integration between industry, academia, and computer culture. In the Global South, there is economic dependence and instability; the sector is sustained by academic and private funding, resulting in modest laboratories and small-scale projects with an impact limited to academic design and restricted curricular integration (Herrera, 2024).

Herrera (2024) notes that global production in digital fabrication has progressed in a complementary manner, integrating academic and practical experiments to disseminate knowledge. In Latin America, SIGraDi has been the primary vehicle for discussion and exchange on digital fabrication since 1998. To understand Latin American production in this context, this article uses the Homo Faber catalog, which features digital fabrication projects produced over the last two decades, to demonstrate the application of TDFab+Arch as a tool for cataloging and comparing projects, as well as assisting in future projects.

## Homo Faber catalog

The Homo Faber project began in 2014 with the aim of mapping and categorizing digital fabrication initiatives in Latin America. The first exhibition, Homo Faber 1.0 (Sperling & Herrera Polo, 2015), provided a conceptual and technological basis for the subject, becoming a reference in the region and consolidating the material as a key point in the Latin American scenario. In 2018, the second edition, "Homo Faber 2.0: Politics of the Digital in Latin America" (Scheeren et al., 2018), expanded this mapping to include new initiatives from various regions. The third edition, "Homo Faber 3.0: Appropriation of Digital Fabrication from Latin America" (Herrera et al., 2023), consisted of a series of exhibitions organized by several Latin American universities. These exhibitions were supported by research and publications that integrated a network of researchers and creators, allowing for a comprehensive view of digital fabrication practices in Latin America. The project contributed to the growth and consolidation of laboratories and research networks in the region, highlighting local initiatives and their applications in architecture, design, and art (Herrera et al., 2023).

These catalogs cover the two decades of implementation and development of digital manufacturing technologies in Latin America, fostering a network of collaboration between professionals, academics, and institutions in the region. The publications present productions of architecture, furniture, household utensils, jewelry, and musical instruments. Each object cataloged contains detailed manufacturing information, including processes and materials used (Scheeren, 2022; Herrera et al., 2023).

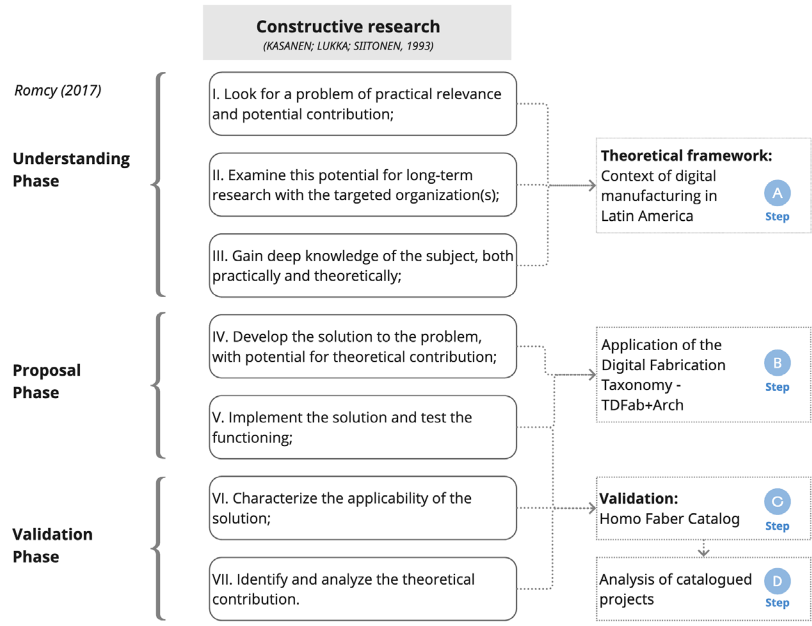


**Figure 1.** Methodological guidelines Source: Prepared by the author in 2024.

In this research, the Homo faber catalogs are considered the most comprehensive, systematic, and continuous efforts to register research and design advancements in Digital Fabrication in Latin America. Its use in research also acknowledges limitations resulting from its inherent editorial process and the maturation of theoretical discussions on the subject. Thus, we also understand the impact of furthering gaps in scope by only selecting projects from these catalogs that resulted in materialized objects, thereby excluding social or theoretical experiments on digital fabrication. The purpose of this approach was to evaluate the effectiveness of the criteria established and the capabilities of the TDFab+Arch tool.

# METHODOLOGY

This article employs the "constructive research" method proposed by Kasanen et al. (1993) and Lukka (2003), which begins by identifying a problem and proposing a solution to it. The process is divided into three phases: understanding the project, proposing a solution, and validating the taxonomy based on the HF cataloging. It aims to classify the materialized HF projects using TDFab+Arch. The research began with understanding the problem and identifying contributions to digital fabrication, followed by applying the taxonomy to validate and assess its potential for cataloging digitally materialized projects. The study thus advances knowledge by creating and validating a theoretically grounded taxonomy corroborated by scientific literature (Figure 1).

## Categorization of criteria for TDFab+Arch

Through a rigorous systematic literature review, the criteria outlined in the taxonomies were subsequently categorized into groups. This grouping also registers, as per the literature review, the multiple authors who explore the selected criteria in their research. These are groups that encompass key elements of the design process (design elements), types of digital fabrication for material realization as detailed by Iwamoto (2009) and other prevalent methods, techniques

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and strategies for generating surfaces (surface topology), the size of the object (small, medium, large, and extra-large), and the equipment necessary for the architectural object's manufacturability. These criteria were further segmented and allocated within these categories, as illustrated in Table 1.

**Table 1.** Criteria and authors
Source: Prepared by the author.

| Criteria | Authors |
|---|---|
| Scale | |
| Small | Pupo (2008), Griz et al. (2017), and Bax & Trum (2002) |
| Medium | |
| Large | |
| Extra Large | |
| Digital fabrication techniques | |
| Folding | Iwamoto (2009), Dunn (2012), Capone & Lanzara (2018), Capone & Lanzara (2019) and Lanzara (2015) |
| Sections | |
| Tessellation | |
| Conforming | |
| Surface Topology | |
| Double curvature | Capone & Lanzara (2018), Capone & Lanzara (2019) and Lanzara (2015) |
| Free form | |
| Simple curve | |
| Machinery | |
| Additive Processes \| 3d Printer | Bax & Trum (2000), Bax & Trum (2002), Trum & Bax (1996), Sass & Botha (2006) and Vrouwe (2018), Austern et. al (2018) |
| Subtractive Processes \| Laser Cutting | |
| Subtractive Processes \| CNC Router | |
| Robotics | |
| Materials | |
| Wood / Plywood | Bax & Trum (2002), Chua et al. (2003), Austern et al. (2018), Ashby (2013), Agudelo (2017) and Vrouwe (2018). |
| Steel | |
| Fabric | |
| Concrete | |
| Cob / Straw | |
| Ceramic / Masonry | |
| Carbon Fiber | |
| Biomaterials | |
| Plastic / PLA | |
| Design Aspects | |
| Performance (environmental and structural) | Ashby (2013) and Sass & Botha (2006) |
| Waste | Ashby et al. (2019) |
| Time - Cut, machine, and assembly | Bax & Trum (2000), Sass & Botha (2006), Austern et al. (2018) |
| Transportation | Sass & Botha (2006), Austern et al. (2018), Griz et al. (2017), and Ashby et al. (2019), |
| Parameterization / BIM | Vrouwe (2018), Gebhardt (2011), Dunn (2012), and Cooper (2001) |
| Modulation | Griz et al. (2017) and Sass & Botha (2006) |
| Connections / Fitting | Griz et al. (2017), Chua et al. (2003), Bax & Trum (2002) |
| Stability | Trum & Bax (1996) |
| Assembly and Disassembly | Austern et al. (2018) and Sass & Botha (2006) |
| Cost | Austern et al. (2018), Ashby et al. (2019), and Bax & Trum (2000) |
| Tool path | Griz et al. (2017) |

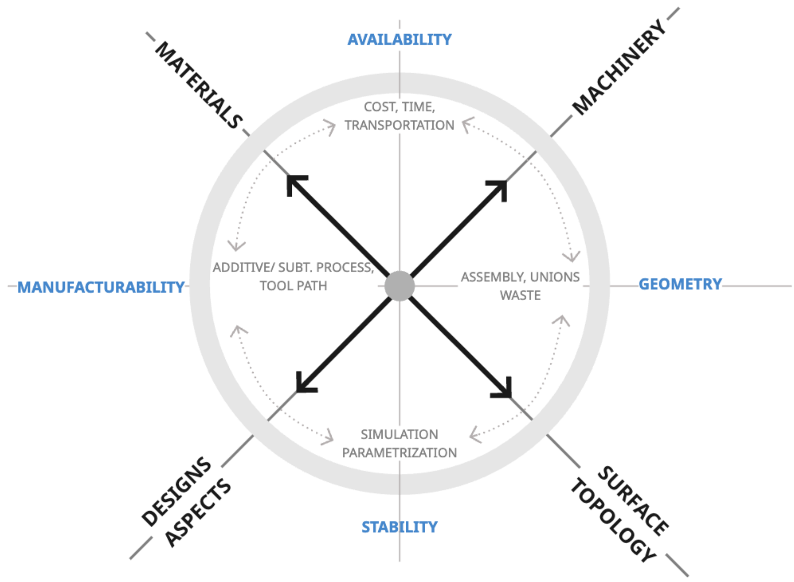


**Figure 2.** TDFab+Arch. Source: Prepared by the author in 2023.

TDFab+Arch is structured in a circle to reflect its cyclical application. The circle features four categories along the diagonal axes: "forms for digital fabrication," "machinery," "materials," and "surface topology." The "design aspects" criteria are arranged in blue around the circle and gray inside. The criteria are organized radially along diagonal and perpendicular axes, allowing designers to access the project from various points, such as machinery, materials, or design aspects. This approach requires understanding scale, surface type, and digital fabrication. This structure guides designers in decision-making, allowing flexible access along the axes, with arrows indicating bi-directionality. The taxonomy and the proposed tool aid the creative process and inform decisions. The inclusion of "arch" emphasizes its architectural focus, while the plus symbol (+) suggests applicability in other fields, such as engineering and design (Figure 2).

The application of taxonomy in the Homo faber catalogs served as an ideal cross-section to validate this effectiveness, as justified above, allowing graphic indicators to be drawn up that reflect the designers' concerns when creating the prototypes. The taxonomy application process highlighted the importance of the criteria in the hierarchical and relational understanding between them.

## DEVELOPMENT

TDFab+Arch results from methodological development and the theoretical-conceptual framework, including systematic literature reviews, qualitative content analysis, taxonomy structuring, and validation. The information section includes data on the Homo Faber project catalog, such as origin, responsible laboratory, project name, author, and date of publication. In the third section, the designer must define the scale of the object: small scale covers portable objects, such as stools and chairs; medium scale applies to objects that can be moved or lifted by one individual, such as tables and; large scale refers to larger and heavy objects that require two people or equipment to be moved or handled, such as full size beds and wall panels. Finally, extra-

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large scale refers to autonomous structures, such as pavilions and buildings, which require infrastructure for assembly. In the context of the taxonomy, scale influences the choice of materials, the precision of equipment, and the feasibility of the project, as well as proportions and the relationship with the environment.

In the fourth section, the criteria for digital fabrication are selected, including shapes, surface topology, machinery, materials, and design aspects. Each category can be accessed and filled in independently by selecting the triangle in the TDFab+Arch tool table.

In this section, "shapes for digital fabrication" are covered, including serial planes, tessellation, and forming and bending (Iwamoto, 2009), which allow an object to incorporate various techniques. The "surfaces topology" is discussed, including double curvature, simple form, and free form (Lanzara, 2015). The machinery used in digital fabrication, including additive and subtractive processes, is also examined, with images and examples of the equipment. The section analyzes the materials used in the projects, distinguishing between "one material", which uses a single type of material, and "different materials", which involves several.

## Taxonomy applied in architectural projects

This topic covers three sections that analyze the similarities and differences between the criteria of the projects cataloged in the HF and those of TDFab+Arch. Interaction with the taxonomy enables the identification of project aspects through text, images, and videos. These analyses help to improve the tool, identify its limitations, and explore new opportunities for creation and materialization.

### *HF | Scales and geometry*

This section analyses projects of different scales: small, medium, large, and extra-large, establishing a relationship between the TDFab+Arch criteria and their application in materialization. Examples such as "Mapped Empathy" by Guto Requena and "Bancapar" demonstrate this relationship using a single material: metal for Bancapar and plywood for Mapped Empathy. Both employ subtractive processes with CNC milling machines and use serial planes to construct free forms, with Bancapar achieving its shape by cutting into a plate and Mapped Empathy exploiting the malleability of the materials (Figure 3 and Figure 4).

The projects described are large-scale and are influenced by the availability of machinery, which affects the choice of materials, cost, time, and transportation. Stability, guaranteed by the joints, is crucial on this scale. Parameterization was used to define the curves based on simulations. These criteria concern various aspects of digital manufacturing. Thus, there is a synthesis in the projects, structured based on the criteria established by the taxonomy (Table 2).

**Figure 3.** HF2-Mapped Empathy. Source: Scheeren et al. (2018).

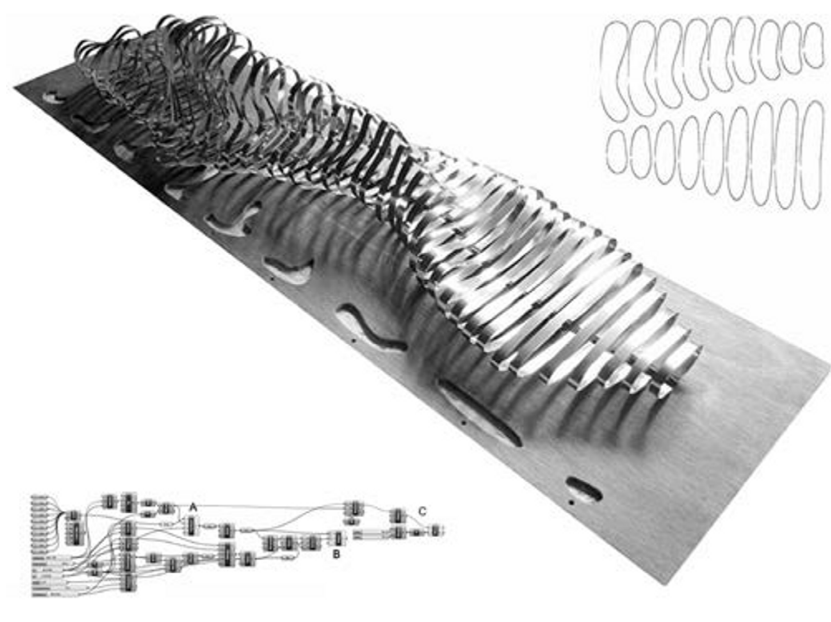


**Figure 4**. HF1-BANCAPAR Source: Sperling & Herrera Polo (2015).

### *HF | Manufacturing processes, surfaces, and materials*

By focusing on additive and subtractive manufacturing processes, it is possible to apply them in a complementary way in a project. In the "Artisanal Digital Tile Fabrication" example, the subtractive process serves as the basis for the additive one. Molding allows shapes to be created from cut pieces, highlighting the interdependence between the processes. This integration demonstrates how digital fabrication explores various approaches, leveraging the unique characteristics of each method to create creative and practical solutions in project materialization (Figure 5).

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| Criteria | Sub-criteria | Application |
|---|---|---|
| 1. Scale | 1.3 Large | Both are large-scale projects |
| 2. Digital Manufacturing Techniques | 2.2 Sections | Use of serial planes |
| 3. Surface Topology | 3.2 Free Form | Freeform curves with complex geometry |
| 4. Machinery | 4.3 Subtractive Processes | CNC milling is used to cut sections |
| 5. Materials | 5.1 Wood / Plywood | "Mapped Empathy" uses plywood |
| | 5.2 Steel / Metal | "BANCAPAR" uses metal |
| 6. Design Aspects | 6.1 Performance (Structural) | Structural performance and stability are considered |
| | 6.3 Time – Cut, Machine, and Assembly | Time is affected by scale and process |
| | 6.4 Transportation | A large size influences transportation |
| | 6.5 Parameterization / BIM | Curves defined by parametric simulation |
| | 6.7 Connections / Fitting | Stability ensured through joinery |
| | 6.10 Cost | Cost influenced by machinery and scale |

**Table 2.** Scales and geometry – taxonomy Source: Prepared by the author.

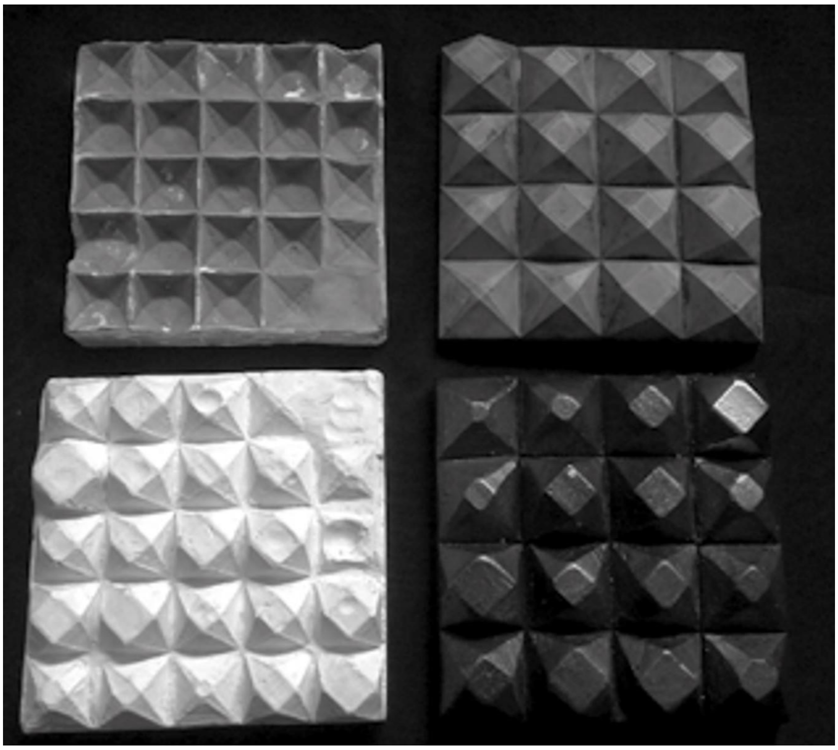

**Figure 5.** Artisanal Digital Tile Fabrication Source: Scheeren et al. (2018).

The manufacturing process can use concrete, clay, and 3D printer filaments, resulting in curved parts with single, double, or free-form designs. For large-scale objects, large shapes or fittings are required between smaller pieces. When linking digital manufacturing techniques with joints, there is an affinity between serial planes, forming, tessellation, and bending. Some elements can be formed without fittings, simply by shaping and stacking, as seen in the Onion Lab's "Helix Sculpture" (Figure 6).

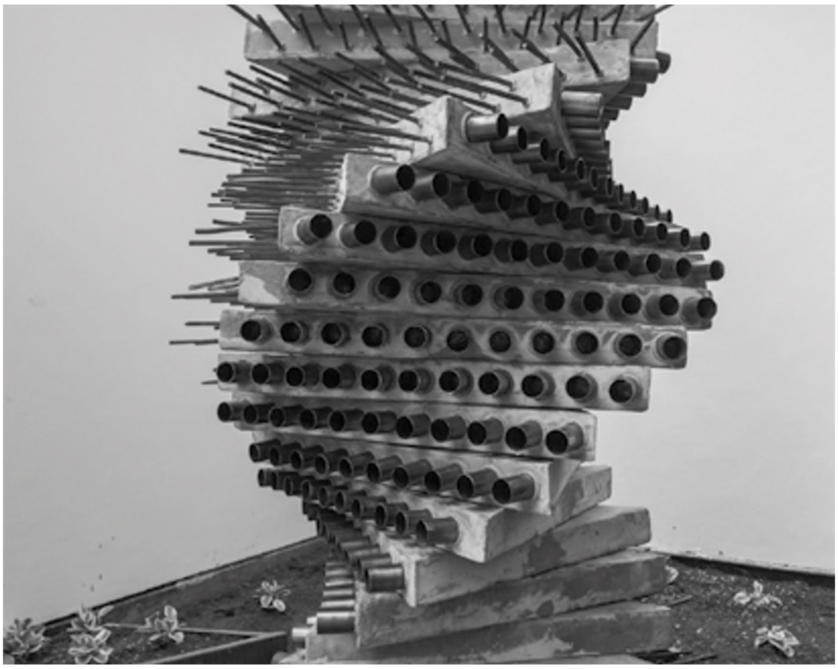

**Figure 6.** Helix sculpture Source: Scheeren et al. (2018).

**Figure 7.** Lounge for Brazilian Venture. Source: Scheeren et al. (2018).

**Figure 8.** Funicular Shells. Source: Scheeren et al. (2018).

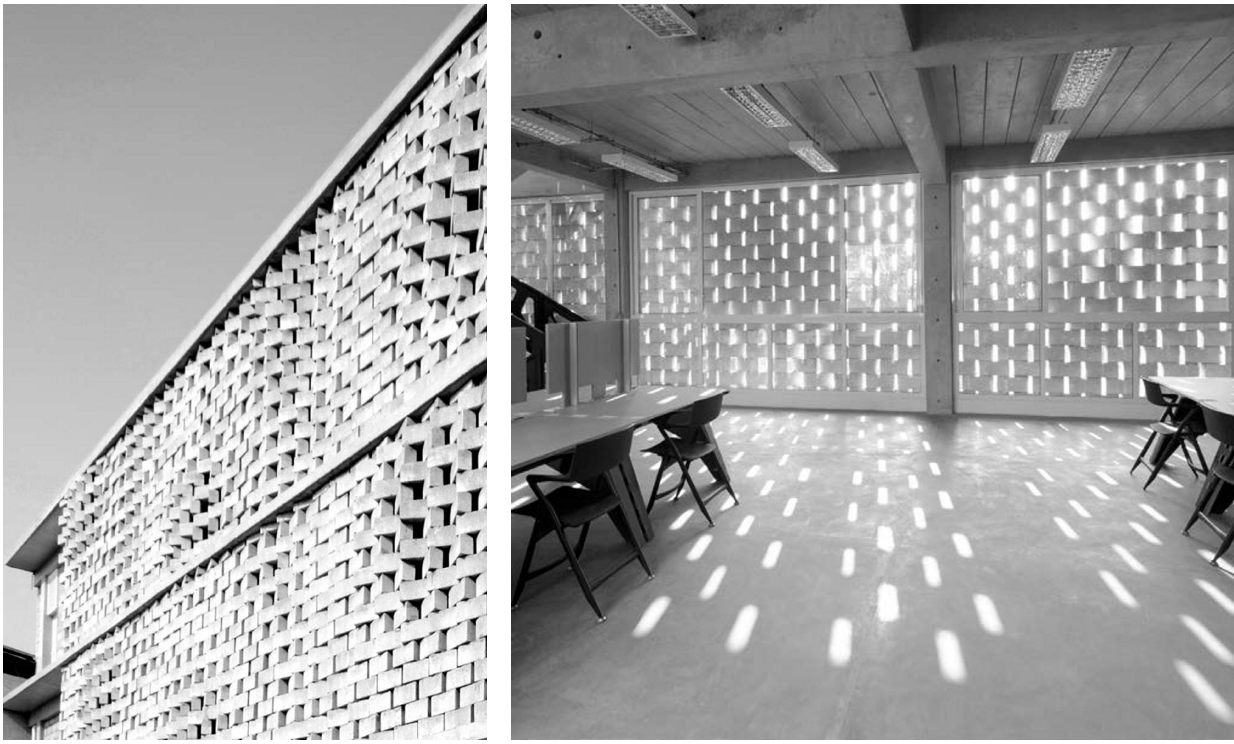

**Figure 9.** HF1 | CoBLOgó. Source: Sperling & Herrera Polo (2015).

In TDFab+Arch, manufacturing processes impact other key factors, including materials, machinery, and surface topology. These influences are verified through the Homo Faber projects discussed. Combining two or more techniques in an object can affect its scale and complexity, requiring an assessment of cost, benefits, and connectors for stabilization. Contouring techniques can be applied in the subtractive process, as in sculptures. In the "Lounge for Brazilian Venture" project, topologies based on digital sculpture were used to create the surfaces of sofas and niches, with an algorithm in parametric software to automate the preparation of the files. The 3D model was sectioned according to the depth of the CNC milling machine, with pieces cut, numbered, and grouped for transportation. These pieces served as the basis for applying resin and fiberglass, combining subtractive and additive processes (Figure 7). The "Funicular Shells" project used modeling, CNC manufacturing, and assembly of funicular-shaped pavilions, analyzing their structural behavior through simulations. The analysis involves the object's scale, stability, and connectors, with the surface topology being influenced by the manufacturing technique used (Figure 8).

The projects mentioned also demonstrate a connection between the different criteria addressed in the Taxonomy. This connection begins in the category of surface topology and runs through the criteria relating to materials, machinery, forms for digital fabrication, stability, and additive and subtractive processes. This interaction between the criteria affects cost, time, transportation, assembly, joints, and waste generation.

To create double-curved or free-form shapes, it is common to use subtractive processes with fittings. Using machinery such as robots or material deposition to build curves is possible, but the stability and connection between parts must be considered. Another layer of complexity is added with the simulation and performance, both environmental and structural, of the project's assembly process. This example can be seen in the "CoBLOgó" project, where a monolithic concrete piece is developed to form a free-form façade. The arrangement of the pieces was dictated by computer simulations of environmental performance, as shown in Figure 9.

In this example, TDFab+Arch begins by selecting concrete as the material and its manufacturing process, which influences the computer simulations that help define the surface's topology. Additionally, machinery availability is taken into account when assembling the parts. This process illustrates the interaction between the different TDFab+Arch criteria in registering a complex scenario, where the choice of material, geometry definition, and the appropriate use of machinery are crucial to the project (Table 3).

**Table 3.** Manufacturing processes, surfaces, and materials taxonomy. Source: Prepared by the author.

| Criteria | Sub-criteria | Application |
|---|---|---|
| 1. Scale | 1.3 Large | All projects are medium to large-scale; complexity and assembly require this classification |
| 2. Digital Manufacturing Techniques | 2.1 Folding | Present in shaping (e.g., Helix) |
| | 2.2 Sections | Used in the Lounge project (for CNC) and the Helix Sculpture |
| | 2.3 Tessellation | Present in Helix, Tiles, and Funicular Shells |
| | 2.4 Conforming | Tile forming through molds; concrete shaping in CoBLOgó |
| 3. Surface Topology | 3.1 Double Curvature | CoBLOgó and Funicular Shells |
| | 3.2 Free Form | Lounge, Helix, CoBLOgó |
| | 3.3 Simple Curve | Tiles project |
| 4. Machinery | 4.1 Additive Processes | Tiles and CoBLOgó |
| | 4.3 Subtractive Processes | Lounge project and Tiles |
| | 4.4 Robotics | Potential use for material deposition (mentioned as a possibility for curved forms) |
| 5. Materials | 5.4 Concrete | CoBLOgó and Tiles |
| | 5.6 Ceramic / Masonry | Tiles |
| | 5.9 Plastic / PLA | 3D printing filaments mentioned |
| 6. Design Aspects | 6.1 Performance (Environmental & Structural) | CoBLOgó and Funicular Shells use simulation to inform design |
| | 6.2 Waste | Efficiency considered in material usage and the production process |
| | 6.3 Time – Cut, Machine, Assembly | CNC and additive methods impact duration |
| | 6.4 Transportation | Lounge project pre-grouped pieces for transport |
| | 6.5 Parameterization / BIM | Lounge and CoBLOgó use parametric modeling and simulation |
| | 6.6 Modulation | Tiling patterns and part segmentation (Lounge, Tiles) |
| | 6.7 Connections / Fitting | Helix (stacking), CoBLOgó (modular assembly) |
| | 6.8 Stability | Required in all due form and scale; ensured via joinery or simulation |
| | 6.9 Assembly and Disassembly | Lounge and Helix are assembled modularly |
| | 6.10 Cost | Affected by process choice (CNC, 3D print, concrete molding) |
| | 6.11 Tool Path | CNC routing (Lounge, Tiles), automated file generation via parametric modeling |

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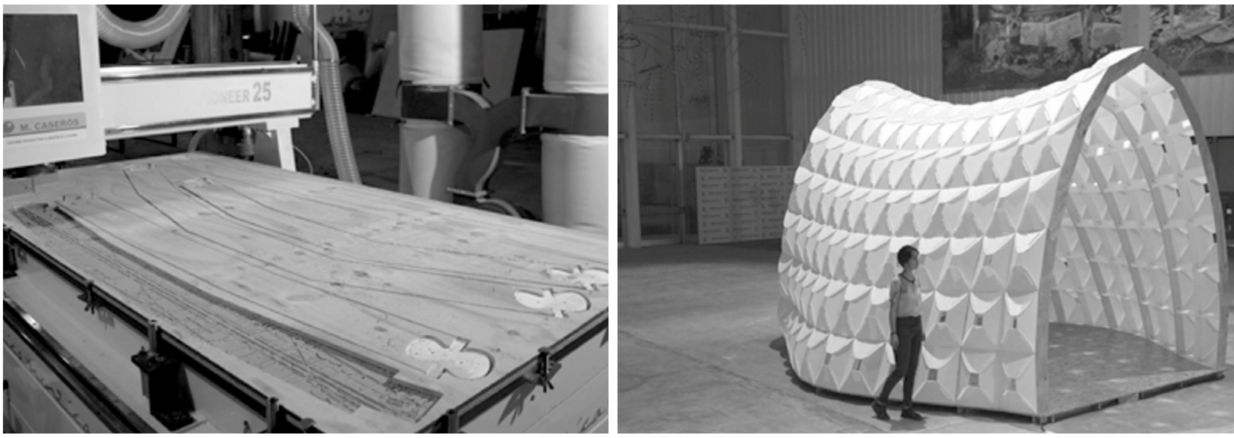

**Figure 10.** Furetsu. Source: Scheeren et al. (2018).

## HF | Joints and materials

An example of a project that explores joints and materials is "Furetsu", which uses a lightweight material to create parts with highly curved surface topologies or free forms. The project uses materials such as plywood sheets, acrylic, and metal, and employs CNC routers and laser cutters to create folds and tessellations within these materials. In addition, this technique can be used as a nesting method that facilitates the bending of the shape or even through the geometry of the pieces themselves. These strategies are illustrated in Figure 10.

In this project, a lightweight material was used to manufacture independent parts that were cut separately. These parts were superimposed on a pyramidal structure and connected by a rigid frame cut using a CNC milling machine. In digital manufacturing, joints play a crucial role in uniting materials and shapes, providing stability to the parts. The final shape of the pavilion is achieved through two simultaneous digital fabrication techniques: folding and tessellation, which are applied to flat pieces to create a double-curved shape. Computer simulations generated this complex geometry, allowing the pavilion to be easily assembled and disassembled, and for it to be mobile and reused.

In the discussion about scale and joints, we see that in small pieces, fittings are unnecessary, as the objects tend to be self-supporting or massive. The project "A Walking City; Archigram Unique vs Reproducible" was made using two types of materials, classified as multi-material in the context of TDFab+Arch. In the prototype, the shape was achieved by fitting the plywood pieces together. In the second experiment, the model was made monolithically without the need for fittings (Figure 11).

The project was conceived with consideration of the available machinery, establishing a relationship with the appropriate materials for Digital Fabrication. At the same time, attention was paid to assembling the parts and ensuring their structural stability. As for the joints between parts of the same object, two types relate to the criteria formulated: when the joints are made from the same material as the object, as in the case of wooden/plywood objects with saddle

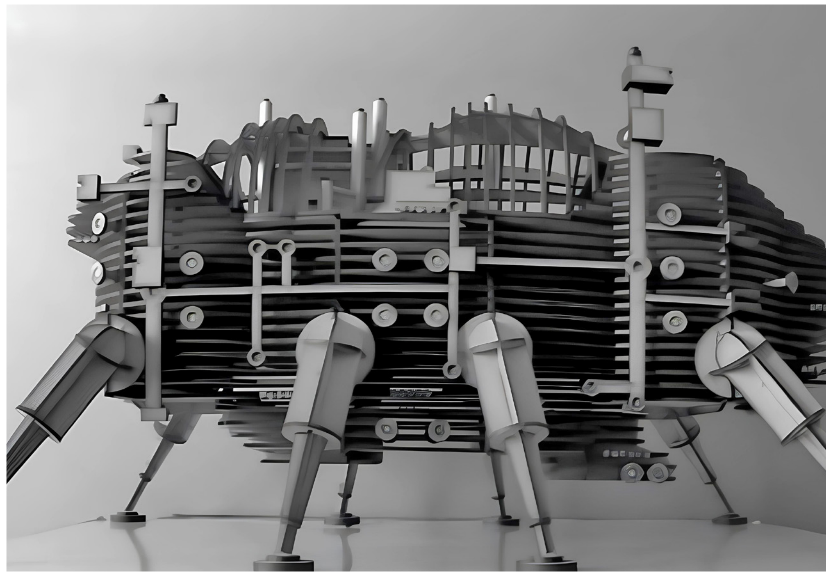

**Figure 11.** A Walking City. Source: Sperling & Herrera Polo (2015).

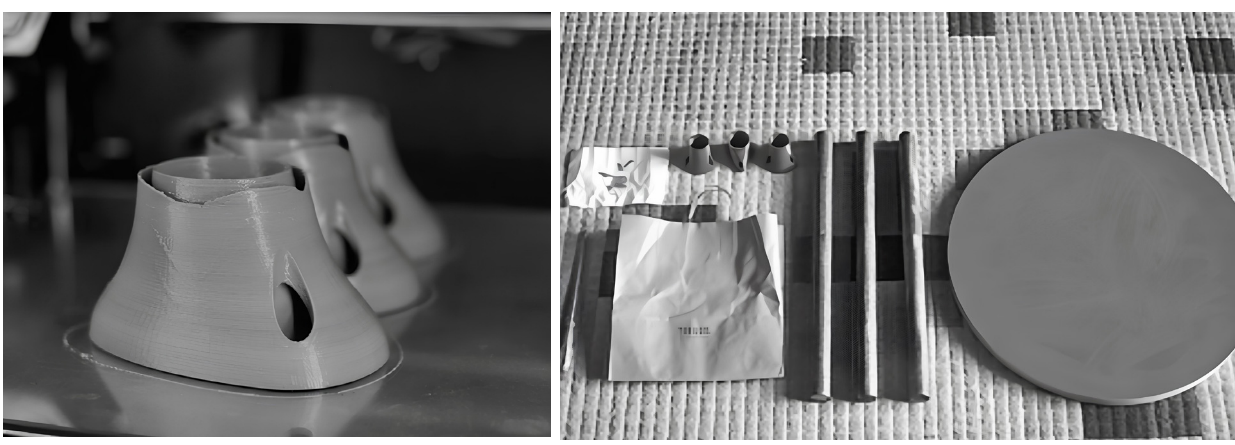

**Figure 12** - HF2 | 360 Furniture. Source: Scheeren et al. (2018).

fittings for serialized plans; and when the joints use different materials, as in the case of plywood objects and screw and nail fittings or 3D printed objects. This is the case with the "360° Furniture" project, a line of furniture that integrates everyday objects with 3D printing technology. This approach allows production to be customized to the user's preferences (Figure 12).

The function of the joints in furniture assembly characterizes this project. Through parameterization, these joints were optimized and tailored to meet specific needs. The assembly process uses a 3D printer to produce the joints, which enable the connection between plywood cut using subtractive processes and the furniture's cylindrical wooden legs.

### Case Study Syntheses - HF

The case studies examine different materials, fabrication techniques, and scales, illustrating how digital tools impact the geometric complexity, assembly logic, and material performance of each proposal (Table 4). Projects such as

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| Criteria | Subcriteria | Application |
|---|---|---|
| 1. Scale | 1.1 Small / 1.3 Large | "360° Furniture" and "Walking City" involve small objects; "Furetsu" is a large-scale pavilion |
| 2. Digital Fab. Techniques | 2.1 Folding | Used in "Furetsu" to enable surface shaping |
| 3. Surface Topology | 2.3 Tessellation | Enables curvature in "Furetsu" |
| | 3.1 Double Curvature | Achieved in "Furetsu" |
| | 3.2 Free Form | Both "Furetsu" and "Walking City" exhibit complex forms |
| 4. Machinery | 4.2 Subtractive Processes | Used in "Furetsu" and possibly in "Walking City" |
| | 4.3 Subtractive Processes | Used to cut plywood and structure in "Furetsu" and "360° Furniture" |
| | 4.1 Additive Processes | Applied in "360° Furniture" to produce joints |
| 5. Materials | 5.1 Wood / Plywood | Common to all projects |
| | 5.9 Plastic / PLA | 3D printed components in "360° Furniture" |
| | 5.2 Steel / Metal | Used in "Furetsu" |
| | Multi-material | "Walking City" (monolithic + joinery versions) |
| 6. Design Aspects | 6.1 Performance (Structural) | All projects consider structural stability |
| | 6.3 Time – Cut, Machine, Assembly | Simplified assembly via CNC cuts and simulation in "Furetsu" and joints in "360° Furniture" |
| | 6.4 Transportation | "Furetsu" is mobile; disassembly is enabled |
| | 6.5 Parameterization / BIM | Used to design and adapt joints in "360° Furniture" |
| | 6.6 Modulation | Present in serialized planar cuts ("Furetsu", "Walking City") |
| | 6.7 Connections / Fitting | Key focus in all three projects (wood joints, mixed-material joints, printed connectors) |
| | 6.8 Stability | Achieved through connection strategies and design simulation |
| | 6.9 Assembly and Disassembly | Prioritized in "Furetsu" and "360° Furniture" |
| | 6.10 Cost | Influenced by the number of parts, fabrication techniques, and joint type |
| | 6.11 Tool | CNC and laser cutting strategies used for optimization |

**Table 4** Joints and materials
Source: Prepared by the author.

Mapped Empathy and Bancapar exemplify large-scale constructions using subtractive processes (CNC milling) and serial sections to achieve freeform geometries. In contrast, Furetsu and 360° Furniture highlight the role of joints and material behavior in medium and small-scale projects, using both subtractive and additive processes. The Walking City and Lounge Venture emphasize modularity, mobility, and performance-oriented design, often shaped by the available machinery and parametric modeling. As a tool for recording and supporting comparative analysis, the exploration of TDFab+Arch enables the construction of diverse interpretations of case studies. Examples of byproducts are presented in Table 5, which consolidates the main criteria observed in each case, focusing on material choices, processes, geometry, assembly methods, project scale, performance considerations, and the use of parameterization.

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| Project | Material | Process | Geometry | Assembly | Scale | Performance | Parameterization |
|---|---|---|---|---|---|---|---|
| Mapped Empathy | Plywood | Subtractive (CNC) | Freeform, serial sections | Stability through joints | Large | Time, Cost, Transport | Curve-based simulation |
| Bancapar | Metal | Subtractive (CNC) | Freeform, serial sections | Stability through joints | Large | Time, Cost, Transport | Curve-based simulation |
| Tile Fabrication | Concrete, ceramics | Molding, 3D printing | Double curvature, tessellation | Modular assembly with joints | Medium | Structural performance, time | Parametric simulation |
| Furetsu | MDF | CNC cutting (sectioned layers) | Freeform surfaces | Assembly by stacking parts | Large | Structural stability | Parametric scripting |
| 360° Furniture | PLA (3D printed) | Additive (3D printing) | Simple curves + joints | Direct printed connectors | Small | Cost, Time | Joint-specific scripting |
| Walking City | MDF + Arduino | CNC cutting + electronic assembly | Simple modular forms | Mountable components | Small | Transport, Modularity | Not mentioned |
| Lounge Venture | Plywood | CNC cutting | Freeform, serial sections | Structural assembly with joints | Large | Structural performance, cost | Geometric parameterization |

**Table 5** Synthesis of cases
Source: Prepared by the author.

This research analyzes through the developed taxonomy how digital fabrication techniques shape the development of an architectural object at various scales. Through case studies ranging from prototypes to pavilions, it demonstrates how fabrication methods, materials, and assembly strategies define the outcome of a project. These examples illustrate the fundamental interplay between geometry, structural performance, and the capabilities available within digital workflows. Although the current focus is on the construction process, the taxonomy opens avenues for future research on the function and occupation of spaces, broadening the understanding of how these systems can be inhabited. Additionally, the tool can be used to identify emerging trends in the Global South by analyzing specific projects. Its potential will be reinforced by the continuous expansion of its database, consolidating its role as a guide for research and design practice.

## CONCLUSIONS

The TDFab+Arch digital manufacturing taxonomy is a flexible and versatile tool that can contribute to optimizing the design process of digital manufacturing and cataloging projects. This paper covers several aspects of the research methodology, including the Systematic Literature Review (SLR), qualitative content analysis, and the structuring and application of the Taxonomy for Digital Fabrication in Architecture (TDFab+Arch). Through these approaches, it was possible to define potential advances in the field of digital fabrication at the architectural scale.

SLR provided a theoretical basis for the research, identifying and refining the study and developing the taxonomy. The qualitative content analysis enabled a

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more in-depth investigation of the articles collected through the coding carried out by TDFab+Arch. This analysis provided a comprehensive understanding of the concepts related to digital fabrication and the needs and challenges designers face.

Thus, the objective of this article was achieved, with the structuring of the taxonomy being a fundamental step in organizing and categorizing the essential elements of digital manufacturing. Moreover, in applying the taxonomy, various techniques, materials, equipment, and design aspects are involved in the process. This structuring contributed to a more detailed and systematic understanding, facilitating the application of TDFab+Arch and the development of digital manufacturing projects. The tool emerged from the development and integration of all the discussed components. It constitutes a theoretical-methodological framework, built on the Notion platform (digital tool) for project classification and documentation. Consequently, it serves as an instrument for project registration and comparative analytical assistance. TDFab+Arch has the potential to assist in the design process and can be used as a guide from project conception to materialization or as a tool for classifying digital fabrication projects. The name of the tool suggests an emphasis on architecture, but this does not limit its use. The types of visualization available in the Digital Fabrication Taxonomy offer designers different ways to visualize and explore the criteria entered into the tool. It is important to note that the designer is encouraged to explore multiple types of visualization by switching between them as needed. Each view has specific advantages and contributes to understanding and organizing the criteria.

The tool's flexibility and the ability to apply filters enable users to select the visualization that best suits their preferences and needs at any time. This possibility improves the tool's interactivity, allowing the designer to explore the criteria from various perspectives and gain a more comprehensive understanding of the projects. The Digital Manufacturing Taxonomy is an adaptable and customizable tool, allowing users to choose the visualization that best suits their needs at any given time.

Continued application of the TDFab+Arch to future catalogs and as a design tool will allow for a better understanding of the contextual elements that contributed to the decision-making processes leading to different solutions. Comparative studies through the taxonomy's categories are made possible, as well as structured reviews of similar processes, techniques, geometries, and materialities. This is a critical element for accelerating the production of significant contributions to the field and flattening learning curves for future generations of designers and researchers alike.

## AUTHORS' CONTRIBUTIONS CRediT

Conceptualization, BF and CN; Data curation, BF and CN; Formal analysis, BF and CN; Acquisition of funding, BF; Research, BF and CN; Methodology, BF and CN; Project administration, BF and CN; Resources, BF and CN; Software, BF and CN; Supervision, CN; Validation, BF and CN; Visualization, BF and CN; Writing - original draft, BF and CN; Writing - revision and editing, BF and CN.

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