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Advanced Customization in Architectural Design and Construction

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Chapter 1
Introduction

Abstract *Introduction to Advanced Customization* offers an insight into the future potentials and challenges that the building sector will be facing in the following years. A strong inclination towards innovation in architecture and construction is foreseeable due to vast changes in the realms of computational design and advanced digital fabrication tools. These elements are transforming the socio-economic and cultural conditions of our contemporaneity and have a strong impact on the design disciplines. Advanced customization is the expression of a flexible construction industry seeking to improve building quality and originality through the use of computer controlled tools, integrated together by the experimental research on emergent technologies. The tendency to radical building customization can be seen both as a combination of a *technology push* and *need pull* to satisfy market demands. New methods of collaboration and process development—i.e. Parametric Design and Building Information Modeling (BIM)—are supporting the file-to-factory process with an environment that involves interdisciplinary collaborations and higher levels of integration in the construction of personalized architecture.

Keywords Advanced customization · Computational design · Building information modeling · Intelligent industrial prefabrication · File-to-factory mass customization

1.1 General

This book offers a brief and precise insight into the future potentialities and challenges that the building sector will be facing in the next years.

A strong inclination towards innovation in architecture and construction is foreseeable due to vast changes in the realms of computational design and advanced fabrication tools. These elements are transforming the socio-economic and cultural conditions of our contemporaneity and have a strong impact on the design disciplines. Researchers and designers from all over the world are developing experimental architecture, in prototypes up to the scale of small pavilions, in collaboration

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with industrial producers, and with the use of advanced fabrication machines. This global research has provided the opportunity to analyze, study and share unconventional solutions. Nevertheless, the biggest challenge in the future will be the implementation of these results at the building scale, addressing the complexity and high standards typical of the built environment of our age.

The level of industrialization, as well as the level of innovation, are fundamental drivers of experimentation in the field of AEC (Architecture, Engineering and Construction). The focus of this publication is set on innovative design and construction solutions offered by state-of-the-art tools and machines. This idea is highlighted and explained through a selection of case studies on customization in architecture that are analyzed, from design to realization, considering the full workflow that involves different professional actors, production technologies and software interoperability.

With the final goal to foresee 100 % customized construction, as promoted in the last chapter of the book, the case studies are divided by architectural systems, giving precedence to the most important aspect of the building construction, the interfaces themselves.

Another fundamental aspect of the book deals with the gap between design and manufacturing that has been consistently diminishing in the recent years. This has led to the emergence of novice methods and processes in the building sector, in turn stimulating the collaboration among different professional figures.

1.2 Towards an Intelligent Industrial Prefabrication

Mass customization and personalization are gaining greater relevance, both at the concept phase and the preliminary design development, and in the production and construction phases. Advanced customization allows the introduction of highly specific architectural solutions linked to the ability to utilize flexible digitally controlled machinery and the increasing industrial capacity to change production patterns.

Many building construction systems take advantage of these innovative methods and implement their solutions at various scales and in different functional layers—from structure to shell, from envelope to HVAC systems. Moreover, advanced customization may be utilized to inspire technical solutions that require specific and personalized performance characteristics, as well as influence flexible and easily maintainable buildings.

In the context of architecture and construction, the concept of advanced customization implies a dual meaning. On one hand, it is the expression of a flexible construction industry seeking to improve building quality and originality through the use of digitally controlled tools, and able to integrate research on emergent technologies developed mainly aside of the industrial context by researchers and experimental practitioners. On the other hand, it addresses the necessity for ambitious construction decisions to be taken at an early stage of the design phase, before site operations, ensuring stronger construction management. In other words, the complexity of many contemporary projects provides an opportunity to reconsider the sequence idea-project-site, towards an integrated model in which technological implications become early drivers in the design to construction process.

In recent years, the AEC has been globalizing in response to strong international competitiveness and industrial production needs that must answer to the latest requirements of architects in terms of precision, flexibility and innovation. As a result of these processes, there has been an exponential diffusion of high-level manufacturing techniques to produce building components with improved performance. This tendency is expression of a "technology push", i.e. the inducement of new research products and processes on the design by an industry searching to expand in new markets. At the same time, contemporary architects apply new technological solutions, as consequence of a "need pull" to satisfy market demands and generate profitable interferences with the technological push. In reality, it is difficult to exclusively refer to one or the other model of innovation, but mostly as a combined dynamic: the genesis of a technology can be found in an intermediate position between the necessity to satisfy a need and the availability of solutions for this need. The next chapters of the book give an insight into the concept of advanced customization and a definition of its possible scenarios of application in the fields of architectural design and construction (Paoletti 2009).

1.3 Shifting to a Process Strategy

Advanced customization in architectural design is driven by the use of computational tools and by the integration between the fields of manufacturing and design. Innovative technological solutions are challenging more and more the use of traditional construction choices in the building sector. The new potentialities, supported by the digital advancements of the last decade, depart from the development of a cross disciplinary research that replaces the typical division between product and process.

Advanced customization comes from the industrialization in construction, and has a long history, originating from prefabrication with traditional material, passing from the industrial revolution and arriving at sixties experimentation and the present evolution. During the 18th century, dry assembly in construction was the main practice forerunning the use of "prefabricated" components. The technique was characterized by elements mainly assembled with mechanical interfaces which did not require wet connections. This method has accompanied the evolution in construction and, depending on the historical period, different variations were applied from precursory structures made of stone, wood and local materials to the first use of metals. In fact, pre-industrial techniques for dry assembly were part of a widespread practice of building that had internalized the dry construction process through its material culture.

After the industrial revolutions, dry assembly techniques were outlined as a new paradigm. From a shared heritage of material culture, they became the main driver of a new radical concept of building construction, based on industrialized mass production and repetition leading to both increased quantity and improved product quality.

This phase of evolution reached maturity during the 20th century, and nowadays it is slowly shifting towards a new process of advanced customized industrialization. There are several factors that are supporting the validation of this new phase in building construction: the use of increasingly complex technological interfaces, the intent to characterize architectural language, the search for improved performance and increased levels of flexibility over time, the need to minimize construction time and rationalizing the organization of activities within the site, and last but not least, taking into account the issues related to sustainability and ecology.

The biggest change comes from the dialogue between new manufacturing techniques and advanced softwares for digital modelling and fabrication that are becoming widely accessible. Digital fabrication is a manufacturing process developed firstly within the industrial fields such as automotive and aerospace industry where precision and direct production is requested, and nowadays more and more utilized in the construction sector. It is related to the evolution of digital technologies that enable a more direct interface from the design, thanks to parametric softwares and production modalities, nowadays realized by flexible CNC machines.

Facing the innovative possibilities offered by the know-how deriving from other industrial fields, the problem is not merely to select the appropriate technology for the project, but mostly to define the beneficial conditions to allow the mechanisms of technological transfer. Examples of this can be found in different sectors: from materials (shells, polymers, fibres), to semi-processed products (profiles, accessories for the construction, gluing systems), to components (metallic nets, adhesive tapes), to technologies (led, optical systems). All these elements can be called "pervasive" which means that they are created in sectors of high technology, but are then spread transversally in all sectors, as well as the traditional ones, introducing important changes (Utterback 1996). In the end the possibility to define a series of parametric solutions, from the early design stages, can encourage innovation by supporting the possibility to directly interact with the production chain, change parameters and directly control the construction of a technical solution, conceived as an intelligent prefabrication process.

1.4 New Methods of Collaboration

Another important aspect of advanced customization in architecture and construction is related to a new method of process development—i.e. Building Information Modeling (BIM)—which supports an environment that involves interdisciplinary collaborations among the different figures engaged with a project, allowing a higher level of integration and anticipating possible interferences. This offers a real advantage for the AEC where information in the "supply chain" is fragmented and sometimes missing or repeated in the different phases of the project. Finally, a last theme that has to be underlined is the relationship between advanced customization and construction rules and regulations.

Computational techniques allow the modelling not only of objects, but also of sets of information that can be codified and controlled directly by the designers. To take full advantage of this information is required a BIM platform that involves a diverse group of designers, technical experts, specialty consultants, trades, and project managers, each serving limited and highly specialized functions critical for achieving the project owner's objectives. One result may be a further blurring of the already unclear line between design and construction functions, also changing traditional contract laws, which are scarcely relational. A relational perspective would indeed focuses much more on customs, usage, and behavioral considerations, and much less on legal rules and principles which often constrain innovative construction processes (Paoletti and Tardini 2011).

The digital age enabled a direct digital link between what can be represented and what can be built through "file-to-factory" processes of computer numerically controlled (CNC) fabrication. There is an unprecedented directness with digital design information ready to be used in the construction of buildings. The consequence is that architects are becoming much more involved in the fabrication, as they can efficiently create the information that is translated directly into the control data that drives the manufacturing equipment. A growing number of successfully completed projects, which vary in size and budgets, demonstrate that digital fabrication can offer productive opportunities within schedule and budget frameworks that need not be extraordinary.

References

Paoletti I (2009) Innovative design and construction technologies: Building complex shapes and beyond. Maggioli Editore, Santarcangelo Di Romagna

Paoletti I, Tardini P (2011) Mass innovation. Emerging technologies in construction. Maggioli Editore, Santarcangelo Di Romagna

Utterback J (1996) Mastering the dynamics of innovation: how companies can seize opportunities in the face of technological change. Harvard Business School Press, Boston, Massachusetts

Chapter 2
The Third Industrial Revolution

Abstract The Third Industrial revolution is a growing phenomenon characterized by the diffusion of digital fabrication devices and the consequent democratization of production. An alternative open-source fabrication ecosystem is gradually developing and challenging the actual production logics and, as consequence, the social organization. The discipline of architecture is a protagonist of this revolution. The imminent diffusion of new productive systems, along with the development of advanced software, allow new possibilities to connect the domains of design and construction, and to realize components given a certain (algorithmic) description, and to synthetically describe the physical environment and its behaviours within the digital environment. The role of the designer in this phase is to extend the potential of the CAD/CAM procedures, and re-appropriate the control in the design-to-construction process to once again engage in the actual manufacturing of building construction and provide high performance, tailored architecture. The open network of digital production supports new design collaborations and manufacturing logics which are able to reconfigure the urban organization of the industrial system and the interaction with citizens, as in the experimental planning of Fab City Barcelona. The use of open-source software and hardware opens up new horizons for more transparent and collaborative development of interventions at different scales and throughout the various stages of the projects formation.

Keywords Digital fabrication · Fab city · Fab lab · Open-source architecture · Peer production · Third industrial revolution

2.1 Digital Fabrication in Architecture

Davis (1987) coined the term *mass customization* in the book "Future Perfect", which, for the first time, provided a conceptual framework for a then emergent process that six years later Joseph Pine would define as a combination of both craft and mass production elements (Pine 1992). The central theme of "Advanced

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Customization in Architectural Design and Construction" is the radical aspect of customization, characterized by the use of advanced digitally controlled machinery. This process is contextualized within a revolutionary industrial shift driven by a novel approach in the production of architecture, in which design and construction are gradually bridging the gap.

Fundamental in this perspective is indeed the evolution of digital design and Computer Numerical Controlled (CNC) machines, as the first prototype was developed by MIT and introduced to the market in 1952. During the 1960s the technology entered the aircraft, shipbuilding and automotive industries. In the 1990s architects started using diffused computer-aided design (CAD) software as a representational tool to improve precision and expand the limits of their creations. It was only a decade later when designers and researchers started a profound study of the materialization of digital models into full-scale architecture and of the exploration of probing the ways in which CAD/CAM technologies could support the design process through digital fabrication.

The concept was firstly theorized by William Mitchell in 1977 when he stated that through

> interfacing production machinery with computer graphic systems a very sophisticated design/production facility can be developed (Mitchell 1977).

Later, in the context of the technological evolution during the 1990s, Bernd Streich at the Department of CAAD and Planning Methods at the University of Kaiserslautern published several works on computer-aided techniques for architectural models. In 1991, he introduced the use of stereolithography as a feasible method for digital fabrication. In 1996 Streich co-authored "Computer-Aided Architectural Model Building", the first complete book describing digital fabrication in the architectural design process (Streich and Weisgerber 1996).

Contemporary to the academic studies, but on a practical level, the first architectural office that experimented with a "paperless" process of construction fabrication was Gehry Partners, LLP in the late 1980s. The turning point was in 1992 with the large fish-shaped pavilion project, located at Barcelona's waterfront. The initial phase of the process involved the creation of a physical maquette from which a corresponding digital surface model was generated and then refined to perform structural analysis. The production and assemblage of the full-scale structural components were completely directed by the digital model (Fig. 2.1).

For building contractors, who were used to the production of orthogonal geometries, complex projects seemed unnecessarily difficult to build. Facing this problem, architects began to realize the need to dialogue directly with fabricators in order to see their experimental architecture materialized. Following the seminal example of Gehry, they understood that digital information could be utilized in the fabrication and construction processes to drive CNC machines, without producing drawings, which in turn would save time-consuming activities and reduce possible mistakes due to information transfer (Kolarevic 2003).

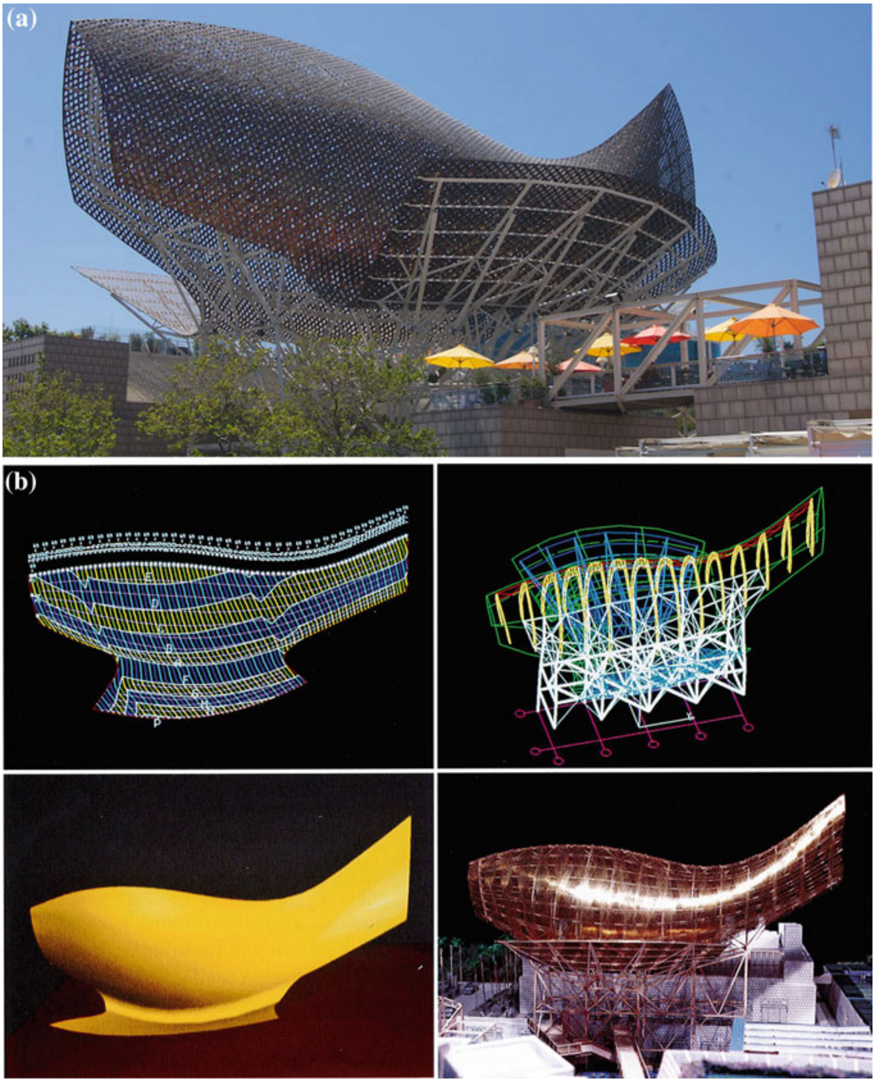

Fig. 2.1 **a** Fish-shaped pavilion developed by Gehry Associated, Barcelona 1992. **b** The pavilion was completely directed by digital models (Mohammed Afana)

2.2 From Numeric Control to Connecting Bits and Atoms

After about 70 years since the introduction of the first CNC tools, digital fabrication machines have evolved greatly through the years and, at the same time, have become more economically accessible as well. With the conjecture of the mass diffusion of this hardware, it is again at MIT that the history of digital fabrication

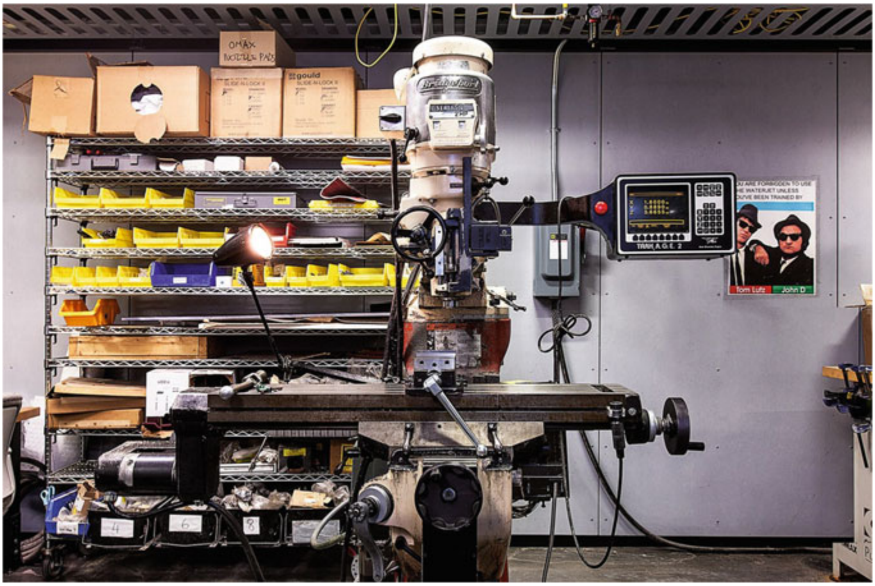

Fig. 2.2 Centre of Bits and Atoms, Massachusetts Institute of Technology (Spencer Lowell)

had an important advancement with the establishment of the Center for Bits and Atoms at the Media Lab, ran by Prof. Neil Gershenfeld (Fig. 2.2). This experimental laboratory was founded with the goal to explore the boundary between computer science and physical science which, inevitably, would be central in the case of digital design, in particular, studying how

> to turn data into things, and things into data (Gershenfeld 2012).

Since its creation in 2001, the Center for Bits and Atoms has had a programmatic interest in investigating a territory that is not typically explored due to the rigid classification that academia and industry has developed, separating hardware from software, and computer science from physical science. Gershenfeld realized that emergent opportunities and problems are grounded at the interface where information content meets its physical representation (Katz 2002). It is exactly this interface area that is crucial for the discipline of making architecture, which historically involves two fundamental steps—one of designing and one of fabricating. Nowadays, digital tools of design and fabrication allow us to imagine new ways to connect these two dimensions, defining how to realize elements given a certain (algorithmic) description, and how to synthetically describe the physical environment and behaviour using our computers, for example through advanced simulation tools. In brief, connecting atoms and bits (Fig. 2.3).

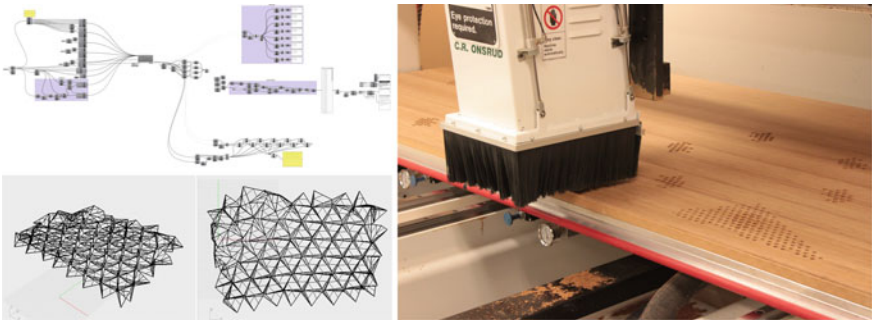

Fig. 2.3 Algorithmic definition and 3D modeling for fabrication (© RVTR)

2.3 How to Make (Almost) Anything in a Fab Lab

Gershenfeld started teaching his class at MIT—"How to Make (Almost) Anything"—in 1998. The course was open to students from different disciplines: artists, architects, designers and various science students, offering lectures on the use of CNC machines employed in industrial production. Despite the lack of profound technical background, the participants soon developed and materialized complete functioning prototypes of various customized devices (Fig. 2.4). Observing this phenomenon Gershenfeld questioned what would be the role of fabrication tools outside the academic field and if they could make any changes when deployed in a different context (Gershenfeld 2005).

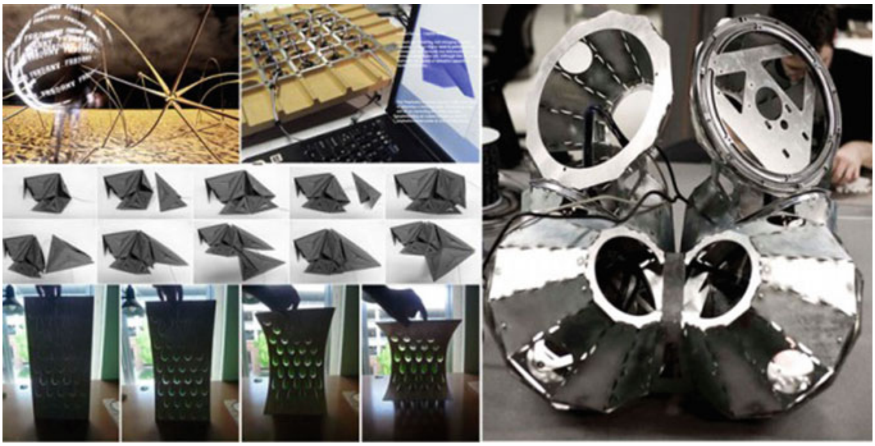

Fig. 2.4 The course "How to Make (Almost) Anything" offered the possibility to the students from different disciplines to develop complete functioning prototypes of various customized devices (ParaPractice)

Fig. 2.5 Fab Lab in Amsterdam. A Fab Lab is a sort of distributed laboratory for research and invention and usually forms a community of learners, educators, technologists, researchers, makers and innovators (Fab Lab Amsterdam)

This question inspired one of the most iconic projects of the Center for Bits and Atoms, the FabLab—an extension of the research into digital fabrication and computation. A Fab Lab is a prototyping platform which provides economical and accessible fabrication tools and processes for rapid prototyping of any object. The original concept was the development of a digital laboratory that would become a flexible model to be replicated in any part of the world, and that would be self-sufficient and available for the use of local communities. Fab Labs are globally conceived as nodes within a laterally distributed network around which a diversified social formation has emerged,

> a community of learners, educators, technologists, researchers, makers and innovators (FabFoundation 2014).

Within a common ground of tools and processes, the Fab Lab program is building a global network emerging in a sort of distributed laboratory for research and invention (Fig. 2.5).

The first Fab Lab digital workshop was set up in 2001 at the Massachusetts Institute of Technology (MIT). The phenomenon quickly spread from inner-city Boston, first to India and Norway, and in just a 10 year period formed a continuously expanding global network (Fig. 2.6). A typical Fab Lab is supplied with an array of flexible computer controlled tools that work with different lengths, scales and materials. The Fab Labs core shared capabilities include CNC laser cutting

Fig. 2.6 Map of the International Network of Fab Labs in 2014. The Fab Lab network is rapidly and constantly evolving (Fab Lab Japan)

machines for press-fit assembly of 3D structures from 2D components; a larger-scale milling machine for furniture and house-sized elements; a signcutter for printing masks, flexible circuits and antennas; a high precision (micron resolution) milling machine for three-dimensional molds and circuit boards; programming tools for low-cost high-speed embedded processors, and design, assembly and test stations. The range of products that might be fabricated varies from integrated circuit boards to complete customized buildings, from bioprinted cells and tissues to solar and wind powered turbines. The platform has set four fundamental qualities for labs willing to join the community: public access, a common shared set of tools and services, participation in the global Fab Lab network and support of the Fab Lab charter (Fig. 2.7).

Fab Labs are vastly adopted within the educational context. In the last few years many architecture schools have developed design/build programs with the objective of providing direct experience in producing architecture, not just in terms of design, but also in terms of gaining deep knowledge about the overall creative process including machines, materials and tools. The concept of Fab Lab as a global network plays a central role in this book: advanced manufacturing is indeed a multi-faceted phenomenon beyond the technical improvements which stimulates a shift in the industrial system, design collaboration, open access to production and social impact on a global level. The concept of an advanced and open productive ecosystem of fabrication is not an utopian provocation but a necessity.

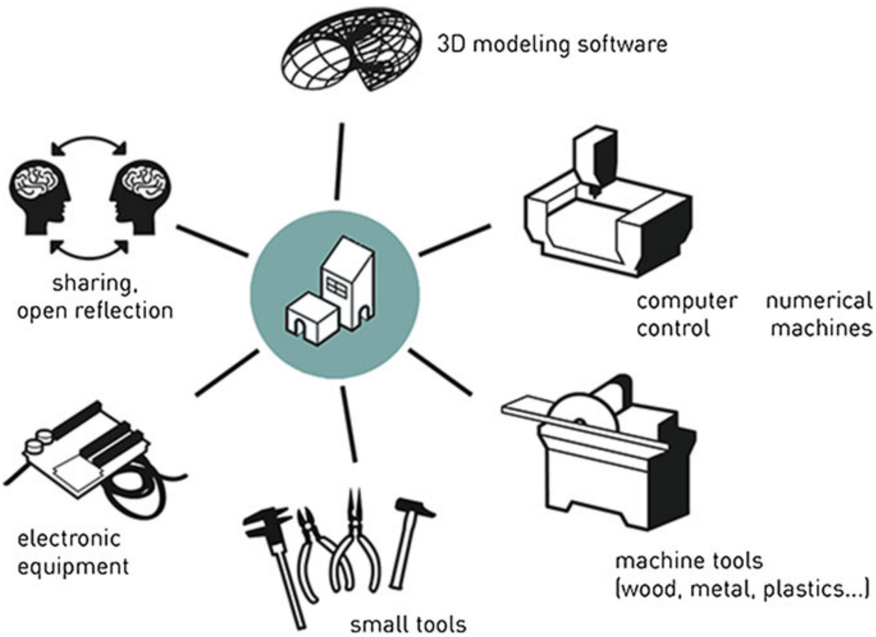

Fig. 2.7 A Fab Lab is both an open source workspace, offering specific machines and tools, and at the same time it is a cultural and social place where people can share ideas (Laboratorio di Progetto e Costruzione per l'Architettura, Faculty of Architecture and Society, Politecnico di Milano, Courtesy of the Students)

2.4 Peer Production and Fabrication Democracy

> We are moving to a future where the factory is everywhere and the design team is everyone (Parvin 2013).

Fab Labs are places of peer production that can potentially challenge the structure of society in the coming years. The sources of knowledge and information are no longer statically located in universities, companies and research centers but they constitute a fluid and adaptive network of servers linked to the Web and its capacity to spread information and innovation. An example of this are online organizations like Kickstarter, which in certain cases is more useful than governmental grants or private funding for the business development of new products. They give the opportunity to novice inventors and designers to use the power of crowd sourcing collaboration in order to support and fund their ideas (Diez 2012). The emergent global peer community requires a lateral, cooperative and decentralized approach, rather than the conventional top-down institutional systems. A common vision between society and institutions is needed in order to make the implementation of the ideas of the Makers' Movement possible on larger scale (Troxler 2013), and also beneficial for the AEC industry.

In spite of this vision, institutions are still playing important roles in providing support and specific competences in the network where individual connections are not yet efficient; with this support, within a decade Fab Labs have developed from isolated initiatives to a global network of labs that spans all the continents. The Fab Lab network is constantly expanding and currently contains about 330 facilities spread over 60 countries among all the continents, increasing accessibility to advanced tools with relatively low economic investments and the diffusing the idea of the "makers" community (a new cultural movement), which is able to cross any type of applied design discipline towards a sort of new "digital craftsmanship" (Anderson 2014).

Nowadays basic desktop 3D printers are accessible to non expert users with a cost of less than $1,000 whereas a couple of years ago they cost several hundred times more. Advanced hardware is getting more flexible, adaptable and customizable. With the advance of 3D modelling software designers have the opportunity to easily conceive or change, and improve the design of any product. Everything, from small everyday objects to building components, can be designed and manufactured, freeing the creative potential towards new forms and embedding new interactive behaviours, thanks to open-source electronic hardware like the pioneering Arduino platform (Fig. 2.8).

The benefits of the first and second industrial revolutions were lower prices and higher quality products, but the consequence was the application of standardization and homogeneity everywhere, which made the market dominated by mass production. Architecture, which is typically a prototypical activity where buildings are designed for a one-client-large market, has been considered in the same way—as a product. The industrial revolutions were indeed a democratization of *products,* while nowadays what is happening is rather the democratization of *production*.

For this reason few companies show interest to invest in rapid prototyping, compared to mass production. Most of the industry considers Fab Labs as toys, in some ways similar to the phenomenon of what has already happened in the transition from mainframes to Personal Computers (Anthes 2006). Conventional companies do not recognize the new means of production as a potential game

Fig. 2.8 Arduino is an open-source physical computing platform based on a simple microcontroller board and on a system of multimedia programming environment that allows to script and control software for the board. Arduino can be used to develop interactive objects, products and prototypes, since it is able to translate inputs from a variety of switches or sensors into a series of physical outputs controlling lights or motors

changer in the next economy of production. In the architecture field the role of the designer has great importance in this phase to directly control the design-to-construction process and engage again in the actual manufacturing of construction systems.

2.5 The Third Industrial Revolution

With the diffusion of Fab Labs and advanced fabrication machines outside the industrial context, several authors theorized the idea of a Third Industrial Revolution (among them Gershenfeld 2005; Anderson 2010; Rifkin 2011; Troxler 2013). The opportunity for a production shift is enabled by a common "computational control" in advanced manufacturing across different fields. Software in any production area, but especially in construction design and engineering, has been strongly developed. Operations that would be difficult to manage just a few years ago are now more and more accessible, reducing the time required to design, simulate, build and test complex manufactured products.

The first industrial revolution began in Britain in the late 18th century with the mechanisation of the textile industry. A single cotton mill could instantly replace hundreds of weaver cottages. In this way a new productive era began based on the concept of mechanization, centralized factories and industrial capitalists. The second industrial revolution occurred later, in the early 20th century. Henry Ford mastered the moving assembly line, opening up the age of mass production. Automation, scientific management and management consultants were introduced and the social effect was the division of society in white-collar and blue-collar workforces (Troxler 2013).

Today we are facing the third industrial revolution, characterized by affordable manufacturing tools connected to the internet. As Troxler notices, this implies two major changes:

> First, affordable tools do not require huge capital investments, they bridge the labour-capital-divide; the owner-maker is re-emerging. Second, digital tools connect designing and manufacturing, they bridge the white-collar-blue-collar-divide; the designer-producer is having a comeback (Troxler 2013).

As for the field of architecture and construction, this determines a new production context where design and construction can be rejoined into a continuous process as it used to be before the Renaissance, when the architect was the "masterbuilder". Nowadays architects can design a building, not only focusing on defining spatial and aesthetic characteristics (important aspects, but not exclusive), but also controlling the whole process "file-to-construction" and actively design building components, fabrication strategies and operative tools.

One of the main concerns and skepticisms is the concrete possibility to produce custom construction components without referring to specialized producers. Workers and owners are historically divided by the possession of the means of industrial production (Gershenfeld 2005). Thanks to several technological advancements those means of production are becoming more and more accessible, in a "democratization of production" that is following what has already taken place in the software and the music industry:

> Music labels and software companies such as Microsoft or IBM were dominating the market. Now anybody can create music, anybody can create software. It is not one versus the others, but an ecology of market that did not exist. There are still labels, there are still mass market softwares, but the most interesting things happening in these sectors are in the intermediate market (Gershenfeld 2013).

In architecture a similar phenomenon is happening, even though dealing with construction requires a much more intensive material engagement than other industries. In this sense, it is improbable to imagine that advanced fabrication means could completely replace the company's means of production, but they are stimulating the concept of customization and have the potential to create a wide variety of new building components that, having the possibility to be uniquely produced, can achieve higher levels of performance and degrees of personalization, overcoming the stagnation of repetitive production in construction (Gramazio et al. 2014).

Finally, as Anderson stated,

> the Third Industrial Revolution is best seen as the combination of digital manufacturing and personal manufacturing (Anderson 2010),

which suggests a possible answer to doubts on the radical diffusion of customized products. With the propagation of digital tools and advanced means of fabrication, collaborations on design and production become easier, overcoming typical limitations such as distance and logistic concerns. Products and components can be tested in a desktop-scale, eventually in a collaborative manner, and can then be transferred to specialized manufacturing resources able to afford large-scale production.

One of the main questions is what can be the impact of such an industrial revolution upon the construction sector, which is typically more resilient to innovation. It is fundamental to highlight how the "digital revolution" has been led by architects in the 1990s, and just 20 years later the topic is becoming globally recognized as an emergent production shift. Nowadays the potential of advanced manufacturing is no longer a matter for a restricted group of interested actors but a priority for the development of a new industrial paradigm. Proof of this can be seen by the decision of the President of United States, Barack Obama, to invest about $2.9 billion for advanced manufacturing Research and Development, including $1 billion to launch a network of up to 15 innovative manufacturing institutes by 2015 (Sargent 2014).

In many design fields, particularly in architecture, drafting and rendering industries have emerged in generating construction documents and images quicker and quicker. Nowadays inventors are fascinated and interested in the availability of computer controlled machines, instead of large factories, and in open-source software and CAD tools instead of sophisticated software and high-powered computers. In the digital age, ideas are conceived as real products traded online (Sass 2010).

When we contextualize this production shift to architecture, typical concerns arise. The first one is from a technical perspective: can we realistically build architecture with Fab Lab facilities? The second concern is in terms of industrial systems: can the Fab Lab network (or others) develop extensively and support mid-scale production in a sustainable way? The last one is related to the concept of open-source: how can intellectual properties and manufacturing production in constructions be managed? In the following paragraphs we attempt at suggesting possible answers to these fundamental topics.

2.6 Building with Fab Lab

In order to prove the technical feasibility of the new industrialization model the main reference is the "Fab Lab House" in Madrid, developed by the Institute for Advanced Architecture of Catalonia (IAAC), the Center for Bit and Atoms of MIT, and winning project of the Solar Decathlon Europe 2010. This prototypical house is indeed conceived to be specifically produced with the use of the international network of Fab Labs as a base of production, and can be produced with local materials anywhere in the world.

The objective of the design team was to produce a solar house prototype that is self-sufficiently generating energy, food and utensils and then to extend this idea into a connected system of similar units. The prototype was produced using state-of-the-art digital manufacturing tools, and constitutes an important demonstration of the potential of the new industrial paradigm. Vicente Guallart, Director of the IAAC, reflects on the implications of this project emphasizing the embedded idea of intertwining medieval principles with modern design techniques. He states that designer and builder should be the same person and that production should take place again in the cities avoiding the high expenses for shipping materials and prefab components (Gallanti 2011).

Technologies of personalized fabrication, together with the versatility of parametric design techniques, allowed the design team from 25 countries to explore the vast possibilities of adaptation between the needs of the users and the answers architecture is able to give (Fig. 2.9).

The dwelling itself represents a curved undulating form which incorporates organic design and a flexible parametric structure responsive to climate changes and adaptable to its surroundings, with an external skin characterized by an array of efficient flexible solar panels. The built prototype consists of 26 cubic meters of timber components digitally cut and assembled to achieve the complex shape, with an elevated floor structure allowing for an open kitchen-garden area at the ground level. The project is conceptually opposed to the typical "box and panel" structure in favor of an innovative system of distributed intelligence: every component of the

Fig. 2.9 The Fab Lab House is entirely fabricated and assembled according to the philosophy of the Fab Lab (Courtesy of IAAC)

Fab Lab House has equal technological, structural and aesthetic value. The design of the cocoon incorporates a new enriched understanding of technological efficiency that is applied to every layer and system of the prototype, from the structure to the finishes.

The project attracted the interest of architects and producers and has been put up for sale with a starting price of €45,000 and initially developed for different configurations: Cottage (12 m^2), Shelter (24 m^2), Studio (36 m^2), House (60 + 60 m^2) and Villa (96 + 96 m^2).

This example proves that the entire design-to-construction philosophy of the Fab Lab is realistic, since a fully-customized residential unit is built in a collaborative and sustainable way. Moreover, it shows that through this production system we can not only replicate existing models of architecture, but literally reinvent new high performance concepts, in this case, of living. This is probably the major factor to impact on architecture: advanced customization let us design and build innovative concepts in a direct way, overcoming the typical resiliency of the overall sector towards innovation.

2.7 A Network of Production—Fab City Barcelona

The diffusion of Fab Labs is also a start towards a new industrial model, integrated within the urban fabric of the city as

> the tool is shaping the city, and vice versa (Diez 2012).

Providing citizens with a new set of advanced tools will definitely change and redefine cities. However, with this new model of production, the raw material supply logistic will need to be rethought, since, environmentally speaking, it is not sustainable for everything to be made by anyone using traditional material resources which are not available everywhere in the same measure. An important challenge will be, consequently, the development of new materials. The production network will share open source international procedures, and make use of local available materials, creating an interesting and sustainable combination of global and local culture and artifacts.

Leading the development of the Fab Lab culture is the city of Barcelona, which already owns one of the most popular and successful manufacturing laboratories in Europe. It is settled in the IAAC—Institute for Advanced Architecture of Catalonia. Since the laboratory's foundation in 2008, its team has been exploring the possibility of a digital production ecosystem spread throughout the city. They called the challenge Barcelona 5.0—transforming the city into a factory of goods, knowledge, collaboration, exchange and invention. The project represents an innovative urban platform to be promoted and funded both by the public and the private sectors.

The general plan is based on an interconnected community of neighborhood Fab Labs, able to produce devices and facilities for the local community and even infrastructures for the future development of other hubs (Fig. 2.10). The project fosters the revival of fundamental principles of architecture and urban planning, a recurrent concept advocated by "Fab-Labbers" around the world, like bringing fabrication back to the cities, back to the hands of the citizens. These cases, supported by both software and hardware platforms and therefore networked with peers with common interests and goals, will change their status of city-users or consumers to become *prosumers* of it, becoming active and conscious agents in the city production (Diez 2012). This social metamorphosis is a shift towards a new industrial era of open-source design and production, a revolution of strong bonds between producers and customers. Cities, led by institutions and governments, should provide commodities and means for people to find solutions to their own needs (Alvarellos 2012).

Tomás Diez, the project manager of the Digital Fabrication Laboratory—Fab Lab Barcelona explains:

> Services are associated with the consumption model, which has the service provider in one side and the consumer in the other, in the new scenarios these both ends are merged, and we need spaces and platforms for this to happen at different levels, from the neighborhood exchange, as happened in the past, to the high tech centers to bring digital fabrication to common people, as happened with web publishing, photography or video making. In the

Fig. 2.10 Fab Lab BCN. Citizens, supported by Fab Labs network with peers with common interests and goals, become active and conscious agents in the city production (Fab Lab Barcelona)

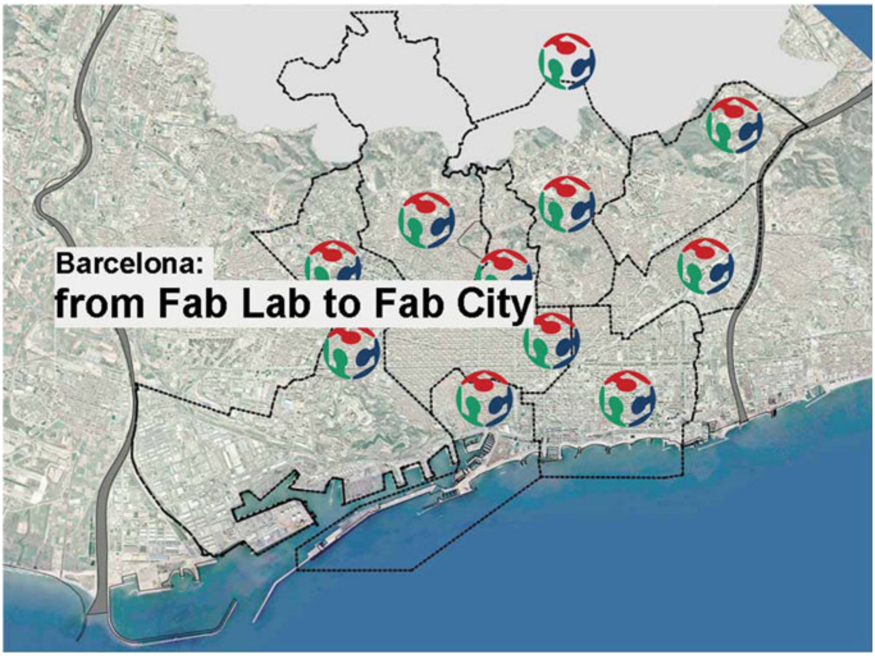

Fig. 2.11 Barcelona 5.0 is based on an interconnected community of neighborhood Fab Labs (Fab Lab Barcelona)

> recent past we became publishers, editors and even journalists, now is the time of the makers (Díez and Guallart 2011).

Fab City is a new model which attempts to give back to the cities the ability to produce through micro factories inserted in the urban fabric and connected to the citizens. The project relies on setting bottom-up processes to engage not only professionals but mostly the citizens. Institutions, companies and individuals are also encouraged to participate and to contribute to the project development and expansion, which offers a realistic perspective of an alternative network of production and construction (Fig. 2.11).

2.8 Open-Source Architecture

The topic of open-source architecture is a powerful emerging paradigm unveiling innovative ways for the formation of both virtual and material designs within a common framework. It represents a platform transforming architecture from a top-down irreversible production chain into a democratic, flexible and bottom-up ecosystem. For the first time, architects have the opportunity to incorporate these two seemingly distinct worlds in order to create an emerging reality, synthesis of data, material, programming, computation and fabrication. Through the implementation of tools and methods for digital fabrication, architects can easily control the data flow and the interaction between hardware and software. Design ideas and concepts permeate the fabrication process in its entirety. This new approach, bridging the gap between digital and material processes, is

> characterized by an unusually large number of precisely arranged elements, a sophisticated level of detail, and the simultaneous presence of different scales of formation (Gramazio and Kohler 2008).

In this transitional era towards open-source hardware and software platforms, personal and mass customization of design and production are blurring the limits between bits and atoms, between designers, producers and the final consumers. The professional scopes of the architect change as well. The collaborative use of open-source software and hardware opens up new horizons for more transparent and liberal development of interventions at different scales and throughout the various stages of the projects realization. The core idea of the open-source architecture is the recognition of the *genius of the mass* involving multiple figures—both amateurs and experienced professionals, clients and communities—working together towards the creation of a powerful networked system solving the issues of our time. This system provides all the actors involved with design tools and methods based on the established and validated principles of open access and collaboration.

Open-source architectural platforms rely widely on digital commons and shared spaces on the internet. The traditional tools, like 2D drawings and sketches, are enriched and sometimes even replaced by the infiltration of interactive 3D software and plugins using relational data and parametric subordination. A fundamental characteristic of the system is the so called *feedback loop* that is established on the basis of the constant interaction between the actors. This approach allows for dynamic and collaborative networking processes that bring design beyond the limits of static geometry. It is described as a complex ecosystem

> distinguished by code over mass, relationships over compositions, networks over structures, adaptation over stasis, life over plans (Bly et al. 2011).

In architecture, interactive sharing tools are still limited within the boundary of a single project, while a more general knowledge diffusion still happens in the classic form of non-interactive media, like printed publications or online documents and forums. A few exceptions, like the Open Architecture Network, aim at collecting and diffusing design knowledge on digital platforms, but without making use of the potential enabled by advanced tools and the predicted next industrial revolution (Stoutjesdijk 2013).

2.9 WikiHouse Project

An experimental implementation of the open-source philosophy in architecture is WikiHouse—an innovative platform that explores the need for democratization of the discipline. It is a nonprofit oriented project lead by Alastair Parvin for the development of an open-source downloadable construction set. The main idea promoted is that everybody might be involved in the design, fabrication and construction of customized houses.

WikiHouse implements a design that is conscious about the needs and the personal preferences of the users, a concept that is in opposition to the construction of whole neighbourhoods of mass-produced units from the type of "one-size-fits-all". This is an important step to promote customized and sustainable design that incorporates the personal values and the identity of the client (Fig. 2.12). Ideally, open-source architecture would give the opportunity to the citizens to participate in planning their cities and building their houses, as well as deciding on the development of their public areas and facilities.

Today we are entering in the Era of the Third Industrial Revolution and a whole new international community of inventors, novice designers and do-it-yourself builders is growing immensely. Using the advantages of open-source software and hardware, this community is ready to plan, materialize and experiment on innovative building design and construction techniques (Parvin 2013).

Fig. 2.12 WikiHouse plywood skeleton (© WikiHouse)

The WikiHouse open-source construction platform is one of the harbingers of this new phase in architecture and construction. It gives architects the opportunity to access an online-shared library and to download 3D models of houses for free. This model can be adapted in a free and easy way to work with 3D software, generating all the files ready to be cut by a CNC machine out of a standard material like plywood sheets. The final result is a fully equipped building kit including all the necessary components for assembling the structure of a house. No additional bolts are needed since it is using a wedge and peg joint typology, and even the mallets might be cut out of the sheets. The construction itself does not require any specific building skills or expertise nor a wide set of building tools. The structure might be erected by a small team of two or three people in just 1 day (Fig. 2.13).

For now, the WikiHouse platform is providing just the main skeleton of the building. Later on, different types of cladding and insulation systems might be incorporated together with the windows, finishings, installations and furnishings. The project introduces a new type of open-house model that could be constantly improved, adapted or extended depending on the needs of the owner. It might be turned into a Fab Lab for the fabrication of other open houses, building up entirely new neighbourhoods of affordable customized housing (Fig. 2.14). This project marks a shift towards non-invasive small scale architecture designed by non-professionals that is

> radically lowering the thresholds of time and cost and skill (Parvin 2013).

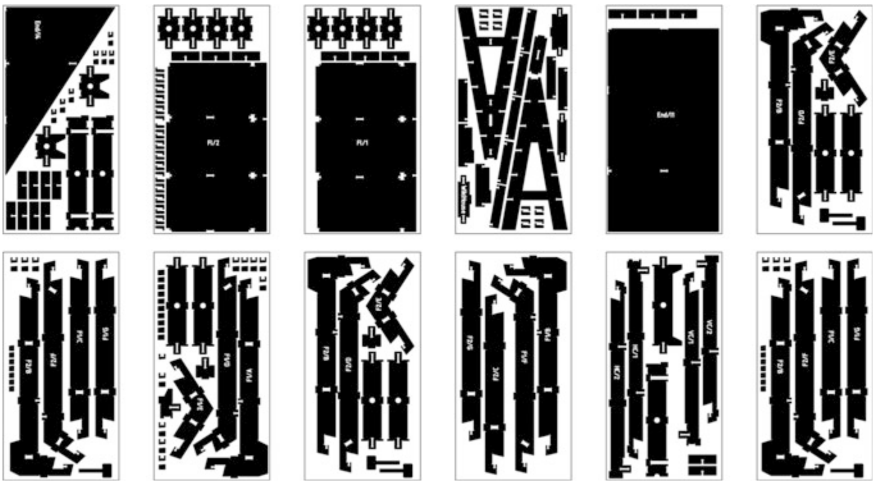

Fig. 2.13 Files ready to be cut by a CNC machine out of standard material like plywood sheets (© WikiHouse)

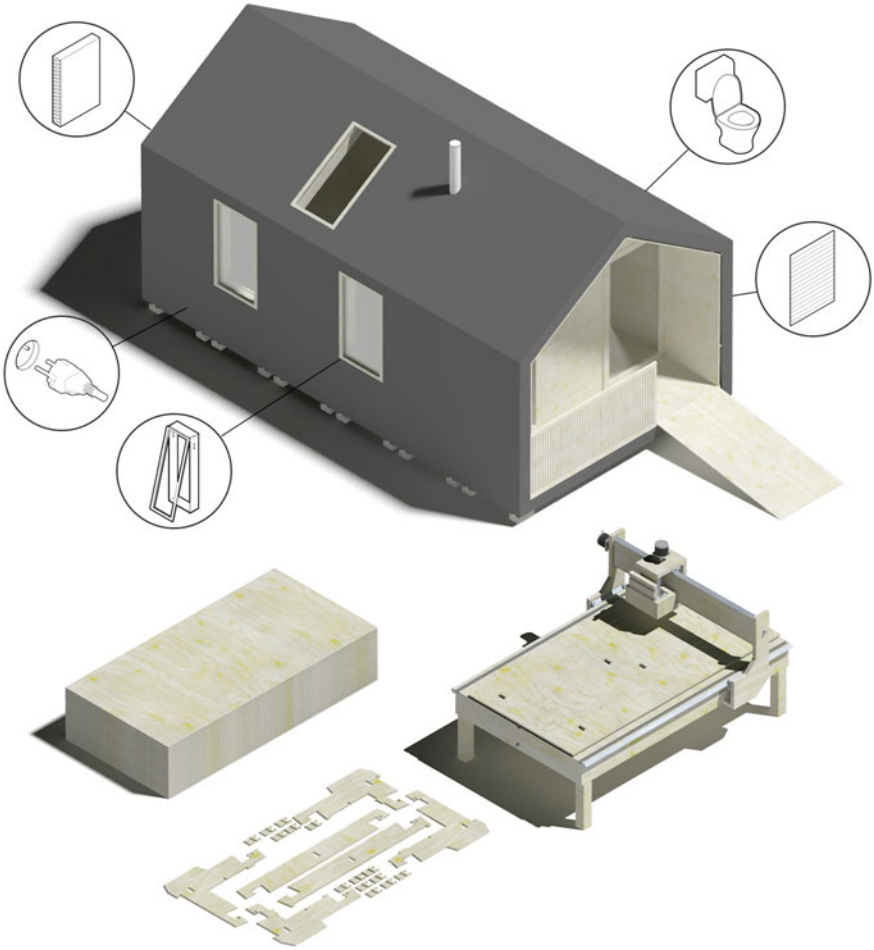

Fig. 2.14 All the components can be quickly digitally designed and produced by a CNC machine (© WikiHouse)

These social and technological advancements are harshly challenging some of the mainstreams of our contemporaneity forerunning a future where open-source factories are everywhere, supporting participative design and construction.

References

Alvarellos S (2012) 4/4 Fabbing & cities: Barcelona fab city. Hugh Dutton Associés. http://complexitys.com/english/44-fabbing-cities-barcelona-fab-city/#.U2ItfPl_vZh. Accessed 05.12.2013

Anderson C (2010) In the next industrial revolution, Atoms are the new bits. In: Wired Magazine. http://www.wired.com/2010/01/ff_newrevolution/all/1. Accessed 5 May 2014

Anderson C (2014) Makers: The new industrial revolution. Crown Publishing Group, New York
Anthes G (2006) Bits to atoms (and atoms to bits). Computerworld Inc. http://www.computerworld.com/s/article/110043/Bits_to_Atoms_and_Atoms_to_Bits_?pageNumber=2. Accessed 23.04.2014
Bly A, Sterling B, Ratti C, Reas C, Somajni C (2011) Open source (OSArhc) A proposition for a different approach to designing space to succeed the single-author model includes tools from disparate sources to create new paradigms for thinking and building. In: Domus Web. Milan. http://www.domusweb.it/en/op-ed/2011/06/15/open-source-architecture-osarc-.html. Accessed 22 March 2014
Davis S (1987) Future perfect. Addison Wesley Reading, Massachusetts
Diez T (2012) Personal fabrication: Fab labs as platforms for citizen-based innovation, from microcontrollers to cities. Nexus Netw J doi:10.1007/s00004-012-0131-7
Díez T, Guallart V (2011) Barcelona 5.0. Production, talent and networks. Regenerating the cities of the future. http://owni.fr/files/2011/09/Tomas.pdf. Accessed 23.01.2014
FabFoundation (2014) What is a fab lab? http://www.fabfoundation.org/fab-labs/what-is-a-fab-lab/. Accessed 5 May 2014
Gallanti F (2011) Fab Lab House. The bending of the solar rays: a prototype of self-sufficient dwelling realized by the students of IAAC and MIT. http://www.abitare.it/en/architecture/fab-lab-house/. Accessed 12 December 2013
Gershenfeld N (2005) Fab: The coming revolution on your desktop – from personal computers to personal fabrication. Basic Books, New York
Gershenfeld N (2012) How to make almost anything. The digital fabrication revolution. In: Foreign affairs Volume 91 No. 6, November/December 2012. http://www.foreignaffairs.com/articles/138154/neil-gershenfeld/how-to-make-almost-anything. Accessed 10.04.2014
Gershenfeld N (2013) Manufacturing's future: effects of technology on industry. http://fora.tv/2013/02/07/Manufacturings_Future_Effects_of_Technology_on_Industry. Accessed 5 May 2014
Gramazio F, Kohler M (2008) Digital materiality in architecture, Lars Muller Publishers, Baden
Gramazio F, Kohler M, Willmann J (2014) The Robotic touch: How robots change architecture. Park Books, Zurich
Katz R (2002) An interview with Neil Gershenfeld. Educause Review. https://net.educause.edu/ir/library/pdf/erm0223.pdf. Accessed 08.05.2014
Kolarevic B (2003) Architecture in the digital age: Design and manufacturing. Spoon Press, New York
Mitchell W J (1977) Computer-aided architectural design. Petrocelli/Charter, New York
Parvin A (2013) The DIY house of the future: Alastair Parvin at TED2013. Ted Conferences. http://blog.ted.com/2013/02/27/the-diy-house-of-the-future-alastair-parvin-at-ted2013/ Accessed 05 March 2014
Rifkin J (2011) The third industrial revolution. How lateral power is transforming energy, the economy, and the world. Palgrave MacMillan, New York
Pine J (1992) Mass customization: The new frontier in business competition. Harvard Business Review Press. Boston, Massachusetts
Sargent JF Jr (2014) The Obama administration's proposal to establish a national network for manufacturing innovation. In: Congressional Research Service report. http://fas.org/sgp/crs/misc/R42625.pdf Accessed 8 March 2014
Sass L (2010) The next industrial revolution: Digital building kits. In: Dave B, Li AI (ed) New frontiers: Proceedings of the 15th international conference on computer-aided architectural design research in Asia CAADRIA (2010), Association for research in computer-aided architectural research in Asia, Hong Kong

Stoutjesdijk P (2013) An open-source building system with digitally fabricated components. In: Stouffs R and Sariyildiz S (2013) Computation and Performance, vol.1 Digital fabrication – Proceedings of the 31st eCAADe Conference. ecaade 260:719–722, Delft, The Netherlands
Streich B, Weisgerber W (1996) Computergestützter architekturmodellbau: CAAD-grundlagen, verfahren, beispiele. Birkhäuser, Basel
Troxler P (2013) Making the 3rd industrial revolution. In: Walter-Herrmann J, Büching C (ed) FabLabs: Of machines, makers and inventors, Transcript Publishers, Bielefeld

Chapter 3
Advanced Machinery

Abstract Advanced Machinery focuses on one fundamental driver of the customization process in the construction sector: the use of advanced digitally controlled fabrication tools. Custom-made architectural systems require tailored fabrication processes, which are described in order to help the designer, with the use of parametric tools to integrate fabrication characteristics in a design. Three main typologies are analyzed: CNC machinery, Robotic Fabrication and Additive Manufacturing. This categorization reflects a different approach that the design team should interpret within a project, while recognizing the different technologies of production. In particular, with the employment of robots, there is a shift from specialized industrial means of production like CNC, to versatile machines. This has the potential to revolutionize the current understanding of mass customization, allowing architects to experiment limitlessly with a wide range of technical and aesthetic solutions. Moreover, Additive Manufacturing has been developing quickly through the last years to accommodate the AEC needs, essentially in two ways: to produce components and sub-components to be assembled and joined to create larger structures, and to "print" large-scale and self-standing architectural elements as a whole. Important research is underway to develop large-scale 3D printers, along with the simultaneous experimentation of different materials and tectonics with suitable properties to operate on the built environment.

Keywords Additive manufacturing · AEC · CNC · CAD/CAM · Large-scale 3D printing · Robotic fabrication

3.1 General

Historically, architects were involved within the construction process, and used to draw what they could actually build, until construction and representation of architecture started diverging, losing a clear connection. CAD software, as better described in the following paragraphs, was first developed in the automotive industry to provide numerically controlled machines with digital information,

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improving control and production speed. In spite of its origins, however, design software has not been integrated within the production process through CNC machines in the architectural field. During the 1980s, architects started using drawing and modelling software, mainly enjoying its potential *per se*. Only a decade later, with the initial studies in digital fabrication, the connection between drawing and producing within a digital environment became clear. The use of modelling software has drastically expanded drawing possibilities, while the digital fabrication technologies have substantially widened the scope of what can be built (Kolarevic 2003). The combination of these two shifts have given the opportunity to imagine and realize highly customized architecture, beyond any limits in terms of complexity and efficiency. This created an interesting playground for growing experimentation on machines, fabrication techniques and materials applied to construction.

An expanding set of fabrication technologies exist today, which are broadly grouped as additive, subtractive, formative and assembly. In additive processes a component is produced by the combination of unfinished materials, or when large architectural assemblages are established by the grouping of single elements. Subtractive processes involve the removal of portions of a material until the final component is formed. Formative processes produce an alteration and modification of unfinished forms, while maintaining initial material cohesion. Lastly, assembly processes increase the material cohesion through the use of durable long-term connections of various components, for example through the use of soldering.

In terms of the design and construction of certain architectural works, it is fundamental to understand, in advance, which techniques can be applied and the specific machine typology to be used for its fabrication, in order to integrate design characteristics and limitations as early as possible. Parametric tools help the designer in considering these as generative parameters in the design process. Three main machine typologies, formulated to organize several techniques in the following paragraphs, can be established: CNC machinery, Robotics and Additive Manufacturing machines. This categorization considers parallel technologies introduced in architecture in different moments, and reflects alternative approaches the design team should interpret within a project, by interfacing with the manufacturing process.

CNC are mainly traditional machines used to work unfinished materials in a specific subtractive or formative process, implemented with Numeric Control. These machines need geometric data, transferred from a CAD model and locally produce a G-CODE with a proprietary software, instructing the machines on the instrumental coordinates and subsequent operations to perform.

Robotic techniques of fabrication are relatively recent in the construction sector and require designers to investigate the fabrication process directly. Given their character as programmable machines with high degrees of freedom, robots often need to employ tailored end-effectors, and to receive precise toolpaths. The fabrication process becomes an integral part of the design, and any technique can be potentially applied according to the characteristics of the robotic arm, such as working volume and payload.

Additive Manufacturing, instead, requires more direct involvement in material logics, considering how actual development is focused on defining proper materials and potential applications in constructions. Moreover, given the almost unlimited capacity in "printing" voxel of material with any form, the actual research and applications reflect the study of novel and efficient material organization in the space, in order to optimize mechanical and physical characteristics.

These different categories would, ideally, contribute to the creation of a new fabrication ecosystem, reinforcing specificities and advantages of each approach, and let designers have more direct control over fabrication, reducing mistakes, imprecisions and limitations which typically arise when construction techniques are developed separately by producers. An increasing interest in controlling tools directly from modelling software is perceivable, showing how architects are working towards a stronger integration with the production of their design.

3.2 CNC Machinery

3.2.1 Origins of CNC

The origin of this technology refers initially to the invention of the Numerical Controlled Machines (NC), made by John T. Parsons during the 1940–1950s, which can be considered a milestone in the process of automatization of industrial machines. Back then, the need for automatization arose to provide a solution for products, such as airplanes and ships, which were (and still are) produced in small quantities, and where the number of identical components is therefore quite limited. After World War II the need for producing new high-performance aircrafts for the aeronautics industry became consistent. The demand for reliable production methods was emergent, since the available machines, conventional and specialized, were unable to respond efficiently to such needs (Bawa 2004). Parsons, as a machining contractor for the U.S. Air Force, conceived a way of using numerical coordinate data to move the worktable of a milling machine for producing complex parts, specifically rotor blades (Groover 2010). Together with Frank L. Stulen, he introduced a method to manufacture curved profiles in a faster and more precise way than merely copying profiles from templates. The novel technological approach used numerical data produced by an IBM punched-card machine to precisely position the milling machine's lead screw in two axes. Based on this success, Parsons conceived the idea of automating a drive mechanism actuated by digital information that would directly operate the lead screws of the milling machine in the three dimensions.

Based on this work, in 1949, the Air Force awarded a contract to the company to study the feasibility of the new control concept for machine tools. The Servomechanisms Laboratory at MIT was then involved in the project and in 1952 produced a working system, capable of producing a cut with high accuracy, adapting a three-axis vertical milling machine using combined analog-digital controls.

Fig. 3.1 Technicians observe the first Numerically Controlled milling machine at MIT (© 2014 Today's Machining World)

At that time, the high cost of $360,000 ($2,641,727.63 in 2005 dollars) and the complexity of the system, did not allow easy diffusion within the industry. In 1953, Lewis Machine Tool Co. together with MIT and General Electric Co. built a digital control system named Numericord which improved the fabrication speed, reducing a normal production duration of 8 h to 15 min. The system was then mature enough to enter the market, and in 1955 the commercially available NC debuted at the Chicago Machine Tool Show. These machines equipped with a generalized language for NC were placed at various industrial plants between 1958 and 1960, providing clear production advantages (Fig. 3.1).

3.2.2 Computer Aided Manufacturing

By the early 1960s, NC machine tools were becoming more commonplace, but a way was still needed to economically generate the digital information to drive these devices with specific drawing tools capable of generating the geometrical data to be then transferred to machines. A fundamental step towards the development of digital drawing was the Sketchpad, a revolutionary computer program written by Ivan Sutherland in 1963 in the course of his PhD thesis, and considered to be the ancestor of modern computer aided drafting (CAD) programs (Fig. 3.2). A major center of research in the field of digital drawing was France, where the automotive sector was very active in the development of digital design tools. As early as 1958, Paul de Casteljau, working at Citroën, developed a mathematical approach for defining surfaces. One year later, General Motors started an experimental project to digitize, store and print design sketches, which later gave rise to the DAC-1 (Design

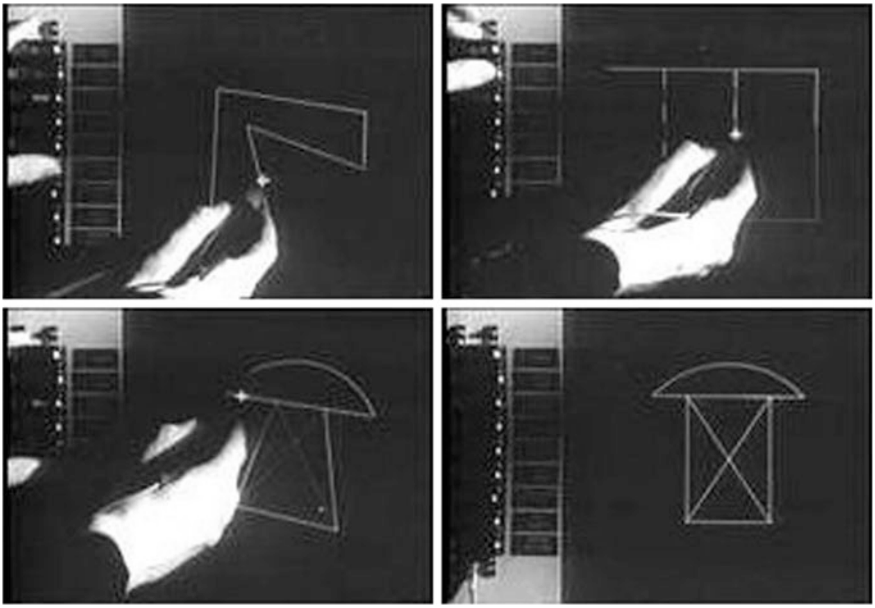

Fig. 3.2 Ivan Sutherland's SketchPad, 1960

Augmented by Computer), a commercial version developed with IBM. Around 1960, Pierre Bézier proposed to Renault's management to develop a method to mathematically define automobile surfaces, and by 1972, with a system named Unisurf, was able to generate digital models that provided data to drive milling machines. The well known Bézier curves and surfaces, nowadays used by many graphic programs, were then used for the first time.

These developments created the foundations for what we nowadays know as CAD/CAM interface, which refers to the integrated use of software systems for computer aided Design (CAD) and computer aided Manufacturing (CAM) to simplify the transfer of information from the initial design phase to the subsequent production phase. This integration is very important for the development of a project and constitutes an important role, in the field of production automation, and nowadays also in the construction field. We can imagine the digital fabrication process as an instrument that is able to transfer the data of entirely digital objects into the physical object itself (Kolarevic 2003).

Actual CNC machines are conceptually similar to these first models, but present day equipment constitutes a vast variety of tools that allow the fabrication of similar elements utilizing completely different processes. For this reason it is important to delineate a brief classification to comprehend the main machine typologies used in the construction sector, which can be classified as subtractive and formative techniques.

3.2.3 Subtractive Processes

Subtractive production processes operate through the removal and separation of virgin material from an original cohesive object, obtaining a reduction in the volumetry. These techniques have large importance within the contemporary digital fabrication panorama, based on their ability to create personalized architectural forms starting from typical construction materials. An understanding of subtractive fabrication techniques is useful to evaluate which procedure, among many, will obtain the necessary level of precision and appropriate economical sustainability. A distinction between these processes can be defined in two groups: one which is based on a direct cutting process and the other which is based on a mechanical subtraction process. The cutting processes work mainly on planar material, allowing variations in thickness. For this reason, it is also defined as “2D fabrication” (Kolarevic 2003). An example of a cutting process machine is the punching tool—the single component is machined by a CAM procedure, which is able to remove as much as 10 mm of planar material thickness. Another process of this type is achieved by laser cutting that requires the energy of a laser, gas (blow torch or plasma flames) or liquid, which presents great flexibility in relation to the material uses and the cut requirements. These systems provide extensive material savings and permit the incision of grooves for various joints to be added afterwards.

CNC Milling—Multi-axis milling is one of the most noted fabrication technologies, in development since the 1970s in the United Kingdom, and in use for fabricating construction elements since the 1980s (Kolarevic 2003). In the architecture field this technique offers the possibility to work very hard materials by using multiple axes and directions directly from information generated by CAD designs. CNC milling is managed by internal programs that oversee and automatically regulate the speed and depth of the process, even though it is useful to test it before the final fabrication to avoid any unforeseen issues. Although this technique may be extremely flexible, it does present some issues related to longer production times, extensive material waste and some geometrical constraints related to certain angles and curves limited by the machines construction (Fig. 3.3).

Like the majority of digital fabrication processes, these machines use STL files, which means that the geometrical data is imported to the machines software to define the parameters and regulations for the various tools, speeds and tolerances. Different cutting heads can be chosen depending on the desired precision, speed and final surface finish. The production of complex forms is created by the progressive fabrication of parallel sections, and thanks to the extensive maneuverability of multi axis milling machines, it is possible to produce components with a wide variety of angles, simplifying the creation of complex forms. The fabrication process is therefore based on the continual rotation of the cutting bit, making incisions. In architecture, the five-axis cutting mills are mainly used for the creation of complex forms in wood and foam molds for glass and plastic. 2D sheets are cut with milling when other laser production processes or water jet cutting are not able to manage complex materials. CNC milling is generally considered the most flexible

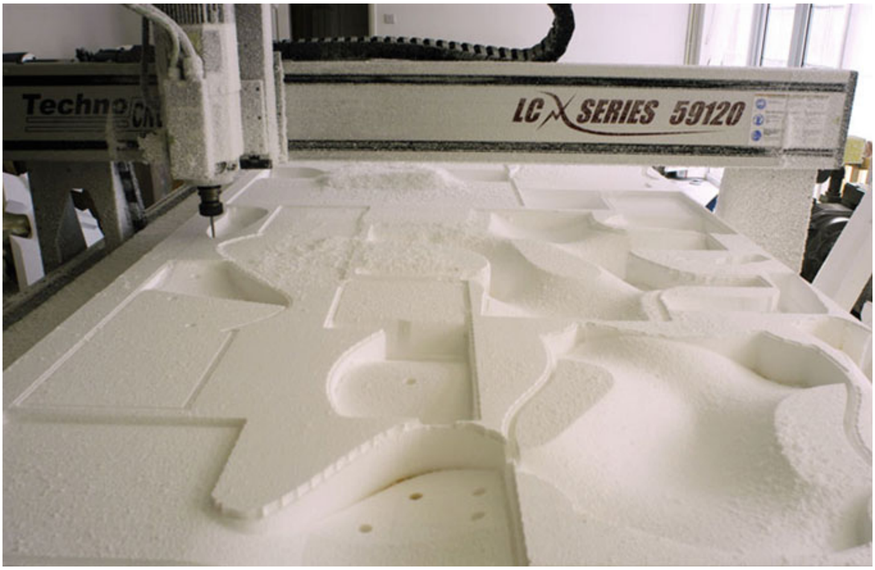

Fig. 3.3 CNC milling with a 3-axis milling machine (© 2010 MESA Studio)

instrument for subtractive production, but it is still important to evaluate which is the most appropriate fabrication method for each individual case.

CNC Laser Cutter—One of the main strategies for thermal cuts is based on the use of a high intensity energy ray of light (laser). The ray occurs by the light amplification stimulated by the elevated emissions of electromagnetic radiation. Once the material is excited, a mirror reflects the ray internally until it reaches enough energy to produce a monochromatic beam that is emitted in a controlled process. The virgin material that is used, usually in the form of sheets or tubes, is cut by absorbing the laser energy, and as a result, is intensely heated in a short amount of time, which causes the material to melt, burn, vaporize or break down by a stream of gas, leaving behind a clean surface finish. This technique was first used as a cutting method in the beginning of the 1970s, and later during the 1980s it became diffused through machines that were able to offer greater cutting capacity and speed. Laser cutting machines are useful in constructions when there is a need for cutting complex forms or the serial production of slightly different components. Thanks to the integration with numerically controlled machines, the designed forms that are simulated and calculated by the computer can be produced quickly. This procedure does not have any particular dimensional limitations, given that laser cutters of 10 by 50 m exist and are already in use for ship manufacturing projects. In industrial manufacturing, the use of carbon and neodymium lasers are able to cut materials as thick as 15–25 mm in steel, aluminum, zinc, copper, etc. The laser beam is controlled within the X and Y axis, and is able to level out imperfections thanks to automatic adjustments in the Z axis. Presently, the speed achieved by this process allows the cut of several meters per minute, a very quick production time for the construction sector. In the past few years, these machines have been used diffusely to create installations and architecture prototypes through the dry assemble of non-identical components. The laser is able to not only cut through the materials, but also to mark it (useful to tag components and assembly directions).

CNC Water Jet Cutting—The water jet cutter is a machine that in architecture is mainly used for cutting metals, stone and plastics using a high pressure water jet mixed with abrasive materials. The process recalls the erosive quality of water seen in nature, which is sped up and concentrated. This system is often utilized when the material to be cut is not able to withstand elevated temperatures associated with other cutting processes. The numerical controlled machine is based on vectorial data from a CAD file and is able to produce complex planar geometries with very high cutting precision. This technique utilizes a cutting water jet which is expelled at speeds of 1,000 m/s to cut steel sheets up to 400 mm, titanium, glass, stone and concrete (as thick as 180 mm) and ceramic, as the time of the cut is proportional to the thickness of the component. Only water is used if less resistant materials need to be cut, like insulation boards, foam or plastic. Otherwise an abrasive material, usually sand, is added to the water to cut thicker or more resistant material sheets. More recently, five-axis water jet machines have been introduced, while the traditional ones work on three main axes, allowing inclined cuts, that must be defined in a separate file. This technology, compared to the laser cutting machine, allows even irregular surface cuts and produces surface finishes that do not require additional processing.

Hot Wire Cutter—This technique allows the production of a large quantities of varying geometries in an extremely efficient process, from the construction of final components to the production of partial elements that are assembled into a multi-layer composition. In this process a numerically controlled 4-axis machine cuts foam materials with absolute precision using a heated wire. Materials that can be cut must have a density between 15–50 kg/m^3. This technique is commonly utilized for large forms, like boat hulls. The machine is commonly made up of two large openings, composed of aluminum profiles and guidance control systems mounted upon a frame. The distance between the two openings can easily be adapted based on the cutting needs and material sheets that are placed on the wire frame bed. A motor manages the movement and speed along both axes to guide the component during the production process, while an electronic mechanism controls the cut axis in case of varying inclinations. A software remotely controls the movements, speed and temperature of the system, automatically self-regulating depending on the geometrical characteristics and materials used. Once the cutting phase is complete, even through multiple cutting processes for more complex geometries, the component is initially very delicate and requires a layer of glass resin, applied directly or by spray, to protect the constructed parts from environmental exposure (Fig. 3.4).

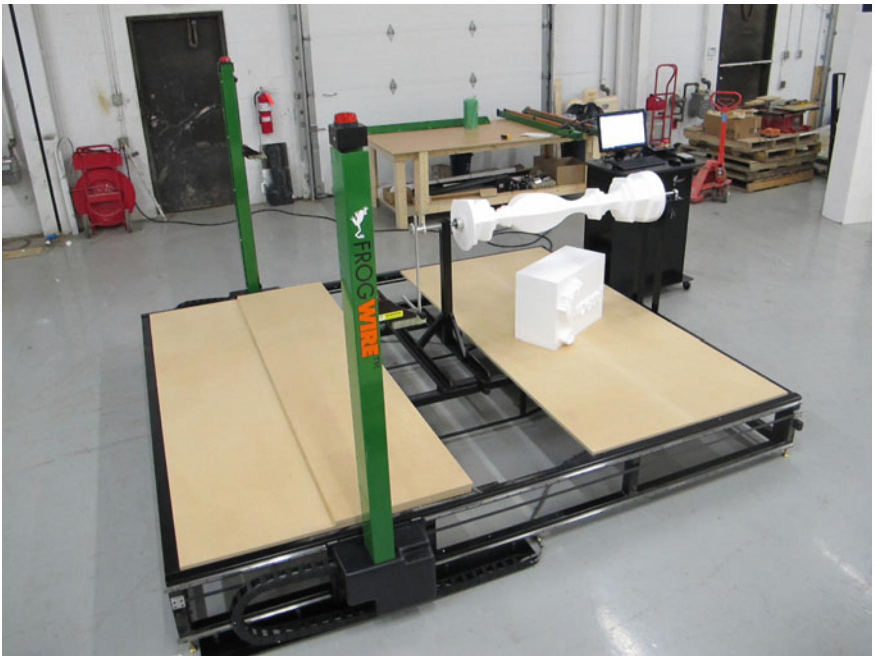

Fig. 3.4 4-axis CNC foam carving router (© FROG3D Streamline Automation)

3.2.4 Formative Processes

The formative processes are secondary procedures that are applied to semi-finished products in order to deform or remodel the geometrical characteristics through the use of mechanical forces, heat or steam (Kolarevic 2003). These processes are mainly utilized on metals and plastics, but can also be applied to wood and mineral materials. They are achieved by mechanical compression and tension, applied to the processed component to produce different performance characteristics. Formative processes can be divided into hot methods, in which the compression and heat melt the material crystalline structure and lead to deformation, and cold methods, in which the form of the final object is produced exclusively by stressing the material, without modifying its mineral structure.

CNC Bending—In general, the bending process refers to folding a material, which undergoes a plastic deformation (Fig. 3.5). In order to ensure the effectiveness of this bending process, the applied pressure must be greater than the elastic limitations of the material. In the case of bending, through the use of numerically controlled machines, the semi-finished forms, like metal sheets, bars, ducks and tubes, are formed mainly based on digital processes. The initial development of this technology in the 1970s has been further optimized and simplified in the subsequent years. CNC bending centers allow the range of folds and surface

Fig. 3.5 CNC bending machine (© 2011 Jiangmen Dongji Metal Products Co.)

patterns to be programed, leading to a variety of forms that encounter geometrical limitations only in the case that the machines collide with each other in large-scale applications. This manufacturing procedure is subject to continual development, expanding the possibilities to produce even more complex forms.

CNC bending processes in architecture are mainly used for the production of complex load bearing structures, in order to reduce the number of soldering joints in respect to the assemble of linear components. The reduction of construction phases leads to greater precision and speed in creating the final product. Given the direct relationship between the digital file and the possibility to assign free-form curves, this process proves to be optimal even for the production of few elements. The bending processes can generally be subdivided into two different levels of complexity. In the case of 2-axis bending, practically any type of metal profile can be utilized. With the 3-axis bending, the component is transformed based on two planes that are predisposed to bend in various directions. In the latter case, tubular profiles are generally used.

Bending Typologies—The bending of metal sheets takes place on a flat surface and is completely automated in order to allow bending profiles, angles and curves to be repeated. The contraction of the curve during the bending of the sheets must be calculated in advance. The various bending procedures are listed below. The first process uses a CNC Bending Press—a machine tool operated electro-hydraulically, composed of an upper and lower table. The bending press folds sheets of various thicknesses as small as a few millimeters. It assigns a particular bending angle for the sheet, applying a vertically oriented pressure, employed by the upper panel that moves towards the lower one. The punch, mounted at the lower edge of the upper panel, compresses the sheets towards the matrix, determining angle and forms that will be imprinted on the sheet. Thanks to the numerically controlled process, the bending angle tolerance is respected within a thousandth of a millimeter. Programming the desired processing typologies gives the opportunity to regulate the bending press in order to automatically calculate the optimal bending cycle to guarantee the precision of the angle and the final product.

Another methodology utilizes sliding folds in which a sheet is rolled out until it reaches a metal profile imprinting a fold on the surface, which is maintained in position by a large clasp. This method has the advantage of being more flexible than the bending press because variable angles can be used, even at the same price, without changing the machine components and therefore producing complex curvatures.

A third typology is composed of rollers or cylinders. This technique can incorporate three or four parallel rollers positioned in a way that the sheet, passing between them, follows a circular trajectory, in which the curve is regulated by acting on the reciprocal position of the roller. The position of the folding bars, in respect to each other, determines the curvature, obtaining conical and cylindrical forms. This process is therefore able to create a wide variety of forms.

CNC Hole Punching—This process is based on a single hole punching machine, which moves vertically and, through a powerful hydraulic force on the sheet, changes its form. From the 1980s the hole punching machine has been integrated with computers that control the position of the material in respect to the processing tool. The form of the hole depends on the shape of the bit head of the tool used, as new machines are even able to automatically change during the procedure. The possible results are variable and can also be carried out in sequence, consisting of: surface hole punching, in which the surface of a component is altered above its point of elastic strength to be bent or cut; cutting that is repeated in order to cut sheets; and rotational hole punching.

Hydroforming—A third productive process, different from bending and curving, is based on processing techniques under pressure, able to plastically treat deformable material sheets, like steel or other metals. This process takes its name from a formative procedure developed in the 1940s based on a high-pressured hydraulic liquid (between 3,000 and 50,000 kN) to deform panels. The processing method takes place in room temperature in a single pass, and allows the formation of concave shapes that would otherwise be difficult, or even impossible, to produce without the use of printing solids. Hydroformed components can often be made with weight-rigidity ratios and cost far less than traditionally printed and soldered pieces. It is possible to employ various material typologies, different thicknesses, and even sandwich components that contain steel and various plastic materials, without the modification of the print; it is actually the water that must adapt to the thickness of the panel used. Hydroforming, regarding processed sheets, is the most economical method to create printed components. The surface quality of the sheets in contact with the water is absolutely superior compared to other printing systems. The hydroformed sheet actually deforms uniformly, and after the hydraulic pressure stops, the elastic condition of the surface returns to a stable state without distorting the component's geometry. In the case of tubular components, the process is revolutionary because it can obtain geometries that were otherwise possible only through processes like plastic and fusion injection. The materials utilized for the hydroform process are aluminum, brass, copper, steel, magnesium, titanium and nickel. The principle uses within the architecture field are related to the production of soldered plates and joints, as well as for the production of curved façade modules, which are produced quickly without material discontinuity.

3.3 Robotic Fabrication

3.3.1 Evolution of Robotic Arms

An industrial robot is defined as an automatically controlled, multipurpose manipulator programmable in three or more axes (ISO 8373:1994). The industrial robots are generally designed to move material, parts, tools or specialized gear through multiple programmed motions to perform a variety of tasks. The most common manufacturing type, the robotic arm, is adapted also for the purposes of architecture. It is a type of mechanical programmable device with functions similar to the human arm, and typically constituted by seven metal segments, joined by six joints allowing either rotational movement (articulated robot) or translational (linear) displacement. A computer moves the arm very precisely, repeating the same movement while motion sensors make sure it moves just the right amount (OSHA Technical Manual 1996).

What differentiates the robots from regular machinery is their functional autonomy and their ability to adapt and respond to variations in the environment. The end effector of a robotic arm, can be designed to perform as a transporting device—for material handling, machine tool load and unload functions, gripping; in some kind of additive manufacturing processes—e.g. assembly, welding, gluing, painting and spraying; or in subtractive processes—e.g. milling, cutting, grinding, deburring, polishing etc. (Singh et al. 2013). The first modern robots were used in factories, specifically in automated mass production lines as fixed machines performing simple tasks which allowed production without the need for human assistance.

The concept of devices capable of performing human-like operations dates back to ancient times. In the early 1950s, scientists at the University of California scrutinized detailed drawings from Leonardo da Vinci's *Codex Atlanticus* where they found the drawings of what can be considered today the first robotic design (Fig. 3.6). Da Vinci's "robot" was designed in 1478 and represents a mechanism that features a front wheel drive, rack-and-pinion automobile. It was, surprisingly fully programmable, with the ability to control its own motion and direction (Moran 2007).

Fig. 3.6 Model of Leonardo's robot (considered the very first robot) as displayed in Berlin (Erik Möller)

All the major developments in the field, however, took place much later, in the 1960s and precisely in 1956 when George Devol and Joe Engelberger conceptualized the design of the first industrial robotic arm called the *Unimate* (Fig. 3.7).

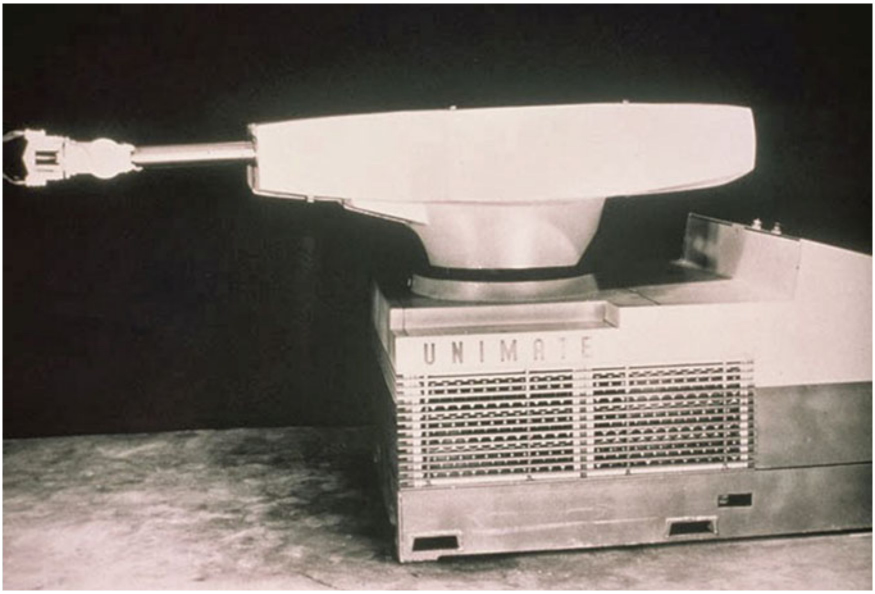

Fig. 3.7 The first industrial robotic arm, called the Unimate

The prototype, heavily inspired by the works of Isaac Asimov, weighed two tons and was controlled by a program on a magnetic drum, mainly to perform object transfers at short distances. The robot was driven by hydraulic technology, which was the dominant technology used in the industrial robot business during the first decade of its development (IFR 2012).

In the academic field an important advancement was made in 1969 by Victor Scheinman at Stanford University who invented the *Stanford arm*, a six-axis articulated robot. This was the first electronic computer-controlled robot to follow accurately, arbitrary paths in space, and thus widening the potential use of the robot to more sophisticated applications such as assembly and welding.

The end of the era of hydraulic-driven robots was marked in the beginning of the 1970s when the first robotic arm with six electromechanically-driven axes, *Famulus* by KUKA, was introduced. The next advancement was marked by the development of the all-electric micro-processor controlled IRB 6, by ABB (ASEA). Electric driven robots made new applications possible that were not achievable with the use of hydraulic technologies, in particular arc welding (Bayegan et al. 2005).

The first Z-shaped robot (the most common typology nowadays, employed both in industry and in the field of architecture) was developed in 1985 by KUKA and was a novelty in robotics since it replaced the traditional parallelogram scheme and saved floor space in the manufacturing environment. It was completely flexible with its three translational and three rotational movements summing to 6° of freedom (Singh et al. 2013).

3.3.2 Robotic Fabrication in Architecture

During the 1980s in Japan large contractors started trials for the application of robots at the building scale. They were customized to perform different actions, like fire-proof material spraying, concrete pouring, steel structure erection, external wall painting and inspection of high-rise building facades (Hisatomi 1990). These first attempts in introducing robots to the field of architecture and construction were developed to improve working conditions and increase productivity, and were not yet applied to the design and production of customized components.

Nowadays, 30 years later, researchers and designers re-examined the topic of robotics in construction, and this time followed new strategies and set different goals. Unlike the utopian proposals of Archigram, or the highly specialized robots in Japan, the current focus is in the implementation of industrial robotic arms in fabricating architecture (Brell-Cokcan and Braumann 2012). The recent explorations aim at reusing already available robots through developing custom software interfaces and end-effectors.

Pioneers in introducing industrial robots in the construction industry are Gramazio and Kohler. Their research, initiated in 2006, demonstrated that robots are not simply replicating human labor but they could be actually programmed to execute fabricating strategies beyond human capabilities (Fig. 3.8). During the last

Fig. 3.8 Pike Loop, A Robot-built installation in NYC—Gramazio & Kohler, pioneers in the use of industrial robots in the construction field (Courtesy of ETH)

few years more than fifty architectural facilities around the world have acquired industrial robots and now are currently testing innovative uses and techniques (Rob|Arch 2014).

3.3.3 From Component Customization to Tailored Fabrication

Typically, a high-level of customization of building components is reached through design post-adaptation in order to fit industrial and market requirements. This process is inherently limiting the potential configurations of a single construction component and generally reducing the overall level of customization. Robotic fabrication in the construction field has, in opposition to its commonly-accepted role to execute repetitive commands, the advantage to perform a multitude of tasks controlled from a common programming platform. With its employment, production logics can change radically for the construction field, shifting from specialized industrial means of production like CNC, to versatile machines. This has the potential to revolutionize the current understanding of mass customization, moving the focus from geometrical post-optimization, to integration of robotic performance within the design process (Paoletti and Naboni 2013). The use of algorithms to control fabrication tools is just a natural extension of parametric modeling, helping the understanding of specific fabrication processes and simulating the kinematics of the machine tool.

The use of industrial robots would normally demand architects to migrate geometries from a CAD software to machines with a linear workflow, essentially converting geometries into working paths. This procedure is essentially transferring construction trajectories, and can be intended as limited in terms of interactions between design and production phases. This deficiency has been overcome by the

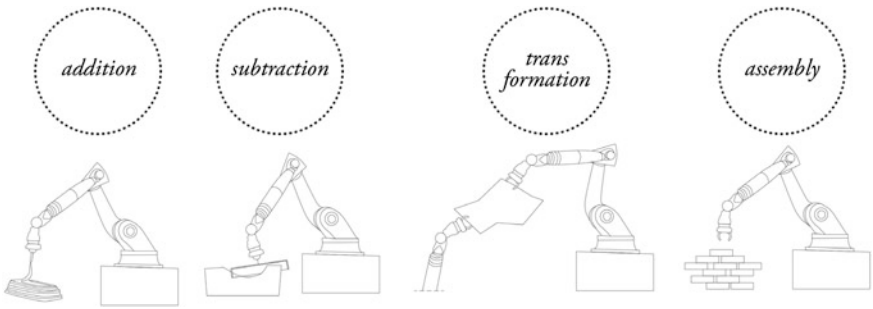

Fig. 3.9 Robot manufacturing is characterized by a high degree of flexibility (Laboratorio di Progetto e Costruzione per l'Architettura, Politecnico di Milano, Courtesy of the Students)

development of specific software tools, providing architects with an easier way to control both the design environment and the physical production. The use of plug-ins such as KUKA prc, Super KUKA, HAL 5 and Scorpion for Grasshopper favors the integration of the dynamic machines into the modeling environment, simulating movements within the CAD space. High-level programming languages like RAPID, Python and C++ are also used by architects and designers for controlling the movements of industrial robots. The increasing capacity to control robots by architects is strengthening the interaction between design software and machines, in a full integration of the two systems. This has the potential to challenge a typical linear process from design to construction, and gives the possibility for multiple directions of development for an architectural work. The following paragraphs propose a concise overview on different robotic fabrication procedures nowadays, proving how the flexibility of these machines enables architects to experiment in a wide range of technical and aesthetic solutions (Fig. 3.9).

3.3.4 Robotic Assembly

The robotic-assisted assembly is a process where a robotic arm selectively places different materials variating their spatial distribution and thus fabricating highly informed building components. Commonly employed in this method are relatively small building elements, such as bricks, which allow bigger variations in their assembly in building interfaces, such as walls or other structures, but also other materials, like fibers which applied layer by layer could be organized in a complex way to form building components or full-scale structures. This approach offers precise and efficient production of geometrically versatile structures with reduced waste of material. Besides exploring and upgrading traditional construction methods, the robot-assisted assembly stimulates the development of novel techniques for fabrication, hardly achievable manually.

Pick-and-Placing—The Swiss researchers Fabio Gramazio and Matthias Kohler from ETH University of Zurich worked, together with their collaborators and students, on robotic selective placement of different materials and components. The research investigated the potential of a typical robotic feature, the "pick-and-place" that is the capacity of automatic positioning and assembling of components. A six-axis industrial KUKA robot, with a movement range of 3 by 3 by 8 m, was equipped with a specially designed gripper tool able to pick up a brick and lay it down in a defined position (Bonwetsch et al. 2006). The first result of this research is the so called "Programmed Wall", a seven-hundred-brick wall materialized with the logic of the masonry structure, including its assembly and static properties, but at the same time taking advantage of the flexibility offered by the robotic fabrication (Fig. 3.10). A major aspect of the research was dedicated to the development of customized software and hardware (Bonwetsch et al. 2006). A computer script was specifically developed to transfer the CAD data into robot data. The design parameters were translated into algorithmic definitions, starting from the simple assembly logic of a traditional masonry bond and gradually increasing the complexity of the script. The 3D modeling and animation software *Maya* was also employed coupled with its embedded scripting language MEL (Fig. 3.11).

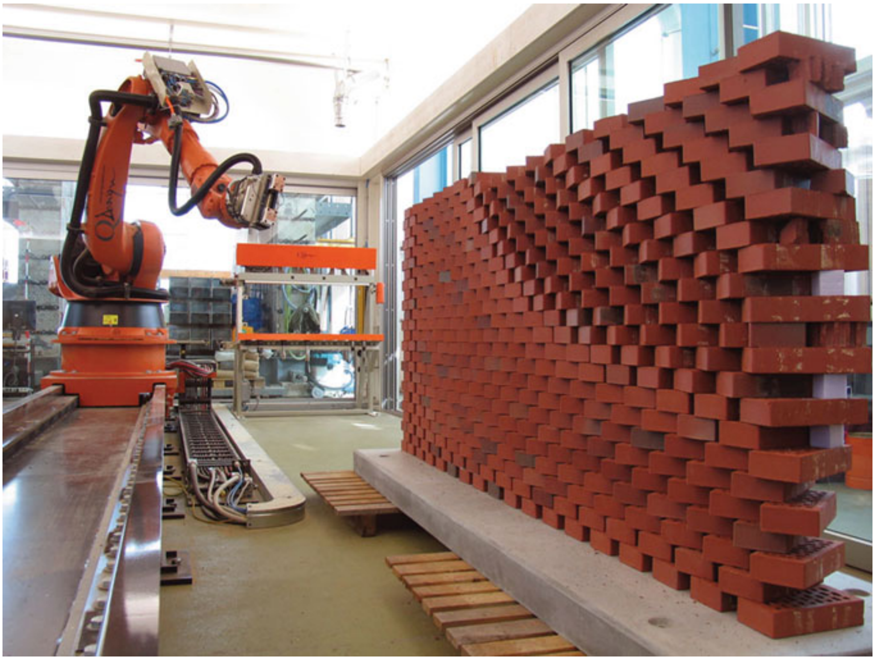

Fig. 3.10 The Programmed Wall, ETH Zurich, 2006—research on the potentialities of robotic manufacturing for pick-and-place, employing a robotic arm equipped with a specially designed gripper tool able to pick up a brick and lay it down in a defined position (Courtesy of ETH)

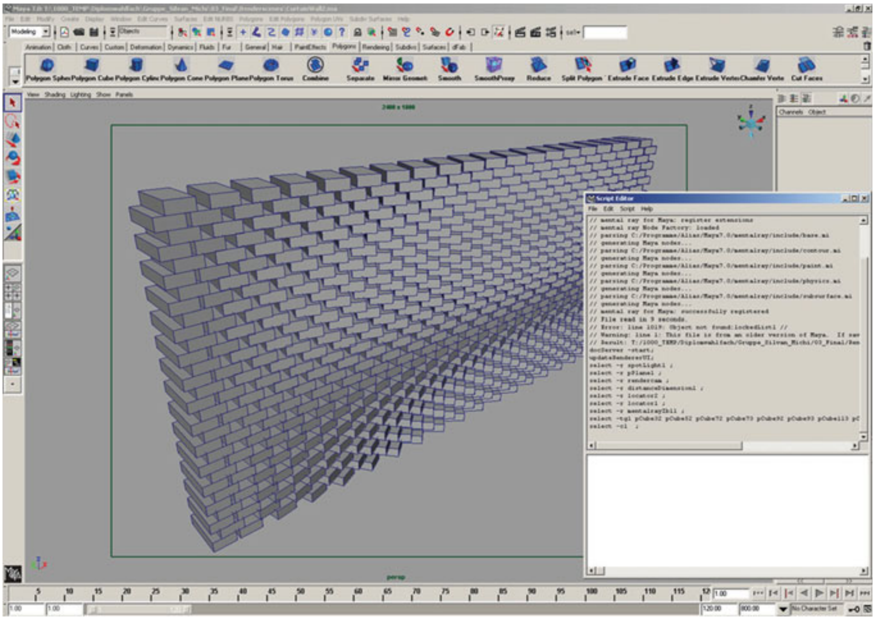

Fig. 3.11 The Programmed Wall, ETH Zurich, 2006—The software *Maya* was employed coupled with its embedded scripting language to transfer the digital information to the robot (Courtesy of ETH)

This robotic assembling method has been later improved, as it has been applied to real buildings, exploring various deposition resolutions, as well as different materials and combinations. As it will be discussed in the Chap. 4, Gramazio and Kohler designed a new free-standing and self-supporting front facade made of bricks for the headquarter of the brick manufacturer Keller in Pfungen (2012), and previously the Gantenbein Vineyard Facade, in Fläsch (2006).

Winding—The Institute for Computational Design (ICD) and the Institute of Building Structural Design (ITKE) of the University of Stuttgart have developed the ICD Research Pavillion 2013–2014, involving a robotic fabrication method applied to a winding technique for manufacturing modular, double-layer fiber composite structures. The research analyzes the functional principles of natural lightweight structures and applies them to a new robotic fabrication method. Architects and engineers studied on the elytron, a protective shell for beetles' wings and abdomen, which consists of natural fiber composites and provides mechanical properties. Looking at the natural structure of the material and through comparative studies of different beetle species, a structural principle has been identified and transferred into the structural morphologies design. The Elytra morphology is based on a double layered structure connected by column-like doubly curved support elements, the trabeculae, whose articulation is highly differentiated throughout the beetle shell. Thanks to the potentials of computational design and simulation tools, both the robotic fabrication characteristics and the biomimetic principles have been simultaneously

Fig. 3.12 ICD/ITKE Research Pavilion 2013–2014. Each component of the pavilion is customized and with an individual winding pattern of the carbon fibers (Courtesy of © ICD/ITKE University of Stuttgart)

integrated in the design process. Considering their structural performances, glass and fiber reinforced polymers were selected as building materials, to be winded on a double layered modular system to obtain the final complex configuration.

Two collaborating 6-axis industrial robots were employed to wind the fibers between two custom made steel frame effectors (Fig. 3.12). The fibers are initially tensioned linearly between the effector frames and subsequently wound—fibers lie on and tension each other, determining a reciprocal deformation. The interaction among the fibers defines the doubly curved surfaces that compose the bespoke components of the structure. The robotic production method has been fundamental for the construction of this complex fiber structure, since the conventional fabrication methods usually involve unique elements that would require extensive formwork and prohibitively complex molds. Six layers of glass and carbon fibers were involved: the first glass-fiber layer provided a formwork system for the following carbon fiber layers and defined the geometrical elements, while the subsequent carbon fiber layers provided structural resistance and were individually varied through the fibers anisotropic arrangement (Fig. 3.13). The experiments on robotic winding were previously initiated by ICD and ITKE Institutes through the 2012 research pavilion—the world's first architecture entirely realized by robotic fibre winding. In this case a 6-axis robot worked with an external seventh axis, placing the fiber on a temporal steel frame connected to a robotically controlled turntable that rotated in a circular motion. About 30 km of fiber were used for the

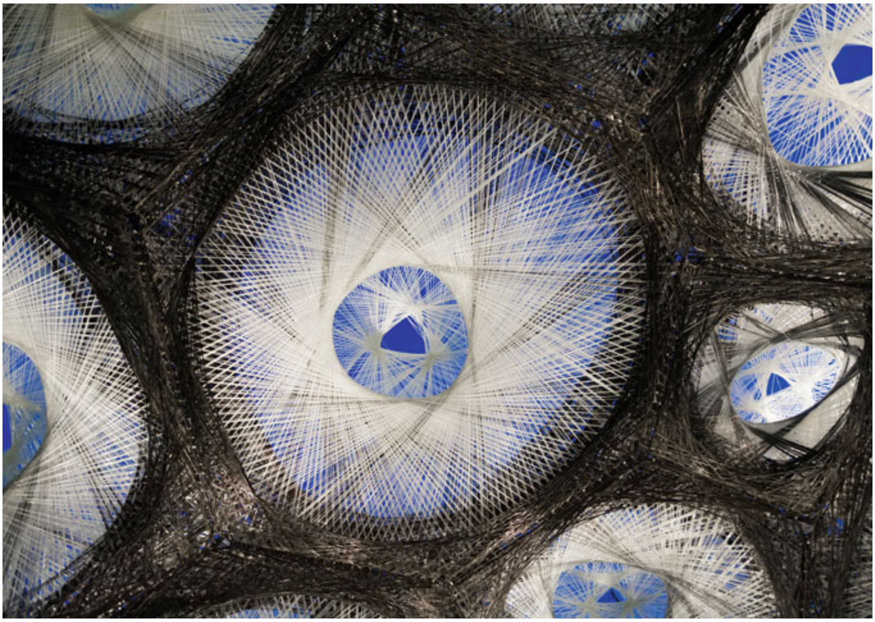

Fig. 3.13 ICD/ITKE Research Pavilion 2013–2014. Robotic fabrication for winding glass- and carbon-fiber components (Courtesy of © ICD/ITKE University of Stuttgart)

fabrication of the pavilion (Fig. 3.14). Both of the projects represent significant progress in terms of fabrication technology: form-finding, material and structural design have been integrated in the design process and developed through the employment of robots enabling a fabrication technique impossible to replicate with other means of production.

3.3.5 Robotic Formative Processes

Robotic formative techniques generate components through an alteration in the form of unfinished components. This group of robotic procedures include bending, forging and forming which, alternatively to the performances offered by traditional CNC procedures, permit turning flat two-dimensional elements into fully formed three-dimensional objects. Commonly, these reshaping processes involve the application of mechanical forces, heat or steam. The utilization of sheet material to represent a surface through processes like folding, incremental forming or bending is a powerful approach which offers a high degree of customization and numerous applications in architecture as in cladding panels, building skin or furniture.

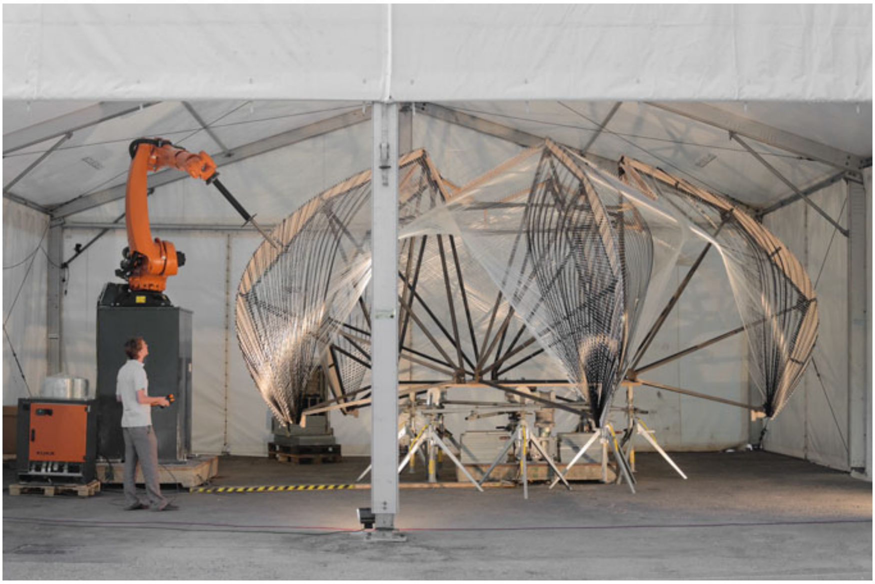

Fig. 3.14 ICD/ITKE Research Pavilion 2012—the world's first architecture entirely realized by robotic fibre winding (Courtesy of © ICD/ITKE University of Stuttgart)

Robotic Incremental Sheet Metal Forming—Amar Kalo, Michael Jake Newsum and Wes McGee developed the Robotic Incremental Sheet Metal Forming technology based on the employment of the Single Point Incremental Forming (SPIF), a process that allows the formation of customized double curved volumetrical forms from metal sheets. The SPIF process deforms the metal sheets incrementally at local points in order to assume a specific geometrical configuration. This method employs a robotic arm equipped with a round tool that moves in space according to a programmed toolpath for the direct translation of the digital model into the customized product (Kalo et al. 2014). In order to achieve the desired geometry, multiple toolpaths are incorporated within the robotic process, defining a multi-pass forming technique that improves the resultant precision and accuracy. Since the forming process requires a parametric toolpath generator, a series of digital tools were developed in order to translate the desired geometry into spatial movements, practicable, by a robotic arm (Kalo et al. 2014).

A wide variety of materials, including stainless steel, copper, brass and different kinds of aluminum can be processed. Each of them was tested with different thickness ranges and demonstrated different performance criteria or limitations, according to its own elastic properties. In order to understand the material breaking point the researchers analyzed the redistribution of the material after being formed. Indeed, as the metal sheet was stretched by the round tool moving on it, its thickness diverged and test pieces were cut in half. In this way the distribution of

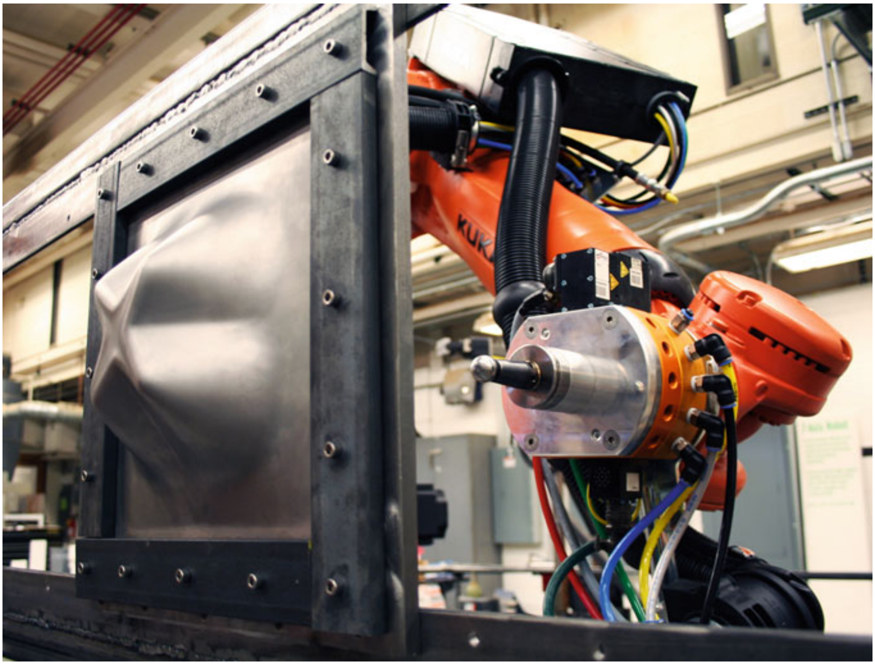

Fig. 3.15 Incremental Sheet Metal Forming, Robot fabrication (Courtesy of Amar Kalo)

the material and the variable thickness of the section could be analyzed (Kalo et al. 2014). Once the research defined steel sheets of a certain thickness as the optimal selection for further experiments, they were later used to be formed into prototypes with specific geometries (Fig. 3.15). The curved components were further formed with additional ribs that serve to corrugate the metal sheets and thus reinforce the most shallow geometries to avoid deformation or collapsing (Kalo et al. 2014). Future planned research will focus on the study of the distribution and orientation of ribs to better stabilize the metal panels.

Robotic Rod-Bending—The most common digital fabrication practices usually break down virtual surfaces discretizing them into components through strategies like sectioning and paneling. WavePavilion provides an alternative to this, introducing lines as a tool for describing the space, creating surfaces and volumes. WavePavilion is an architectural installation generated by computer algorithms and built using custom digital fabrication technology which employed a multi-use 7-axis robot paired with a bespoke CNC rod-bending device, overcoming the limitations of the conventional CNC machine. WavePavilion has a footprint of 6 by 9 m and stands 4.2 m tall, containing over a kilometer of 6.5 mm diameter steel rods (MacDowell and Tomova 2011). The materialization of this highly specific structure has been possible thanks to the development of the precision toolset controlled by communication codes. The behaviour of the robot was guided by a *kukaCode*

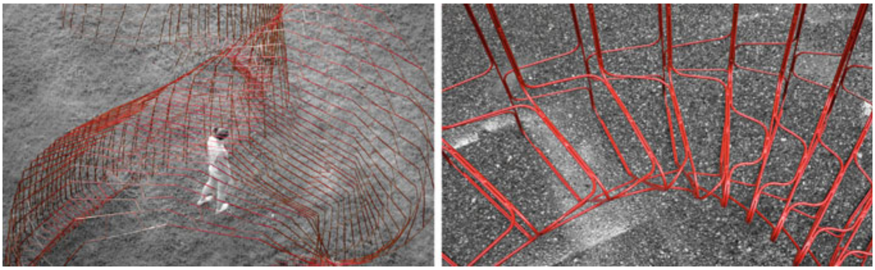

Fig. 3.16 WavePavilion is realized employing a multi-use 7-axis robot paired with a bespoke CNC rod-bending device (Courtesy of Parke MacDowell)

series of commands, whereas the rod-bender was controlled through hex base machine code. The code was obtained through the translation of a customized script written for the digital analysis of the pavilion's geometry (Fig. 3.16). The system could be upgraded for architectural uses through the addition of a secondary membrane that would serve as a building envelope. The welded knots used for the pavilion assembly might be replaced with mechanical connections in order to increase the building assembly speed (MacDowell and Tomova 2012).

3.3.6 Robotic Subtractive Processes

Another great advantage offered by robotic fabrication is related to the production of architectural volumes not achievable with traditional CNC machines. Even though the idea of using robotic applications to subtract material seems to be equivalent to the performances offered by CNC milling or cutting machines, robotic manufacturing provides three-dimensional movements, and therefore a wider level of freedom while still maintaining the mass materiality of volumes. Regarding the subtractive procedure, a limiting aspect of CNC milling and cutting is the time factor—at the architectural scale the process of removing material requires considerable machining time and often becomes unsustainable. A robotic arm can significantly reduce the time of production and minimize the waste material as well.

Hot Wire Cutting Fabrication—The Robotic Hotwire Cutting (RHWC) consists of a robotic arm equipped with a thin wire heated by an electric current to approximately 200 °C to cut polystyrene or similar types of thermoplastic foam. The foam vaporizes just ahead of the wire and minimal energy is required to cut through the stock. This method has a series of specific constraints that must be embedded within the control software. The kerf width is directly proportional to the speed, so control over motion is extremely important. The input geometry is most often described by an upper and lower curve, generating a loft between them and thus generating ruled surfaces. By utilizing the seven axes of the robot simultaneously, large parts can be machined in one step.

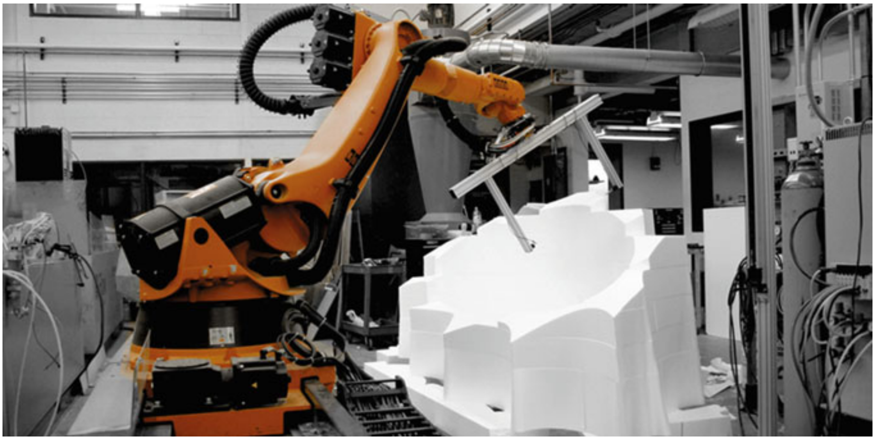

Fig. 3.17 A multi-axis CNC hotwire-cutter capable of processing four meters long EPS blocks was employed for the Periscope Tower (Courtesy of matter design)

A real example of this technology is the Periscope Tower by Brandon Clifford and Wes Mcgee of Matter Design, a temporary installation designed for the Young Architects Forum of Atlanta. For the production, a hotwire cutter was mounted onto a robot, creating a multi-axis CNC hotwire cutter capable of processing 4 m long EPS blocks (Fig. 3.17). This method produces no kerf waste at all but only minimal waste which is 100 % recyclable. A 14-m high tower composed of non-repeating cut blocks, was assembled in only six hours.

More recently Hyperbody and ROK-Rippmann Oesterle Knauss from ETH Institute of Zurich collaborated on the RDM Vault project, which is based on robotic cutting processes. The project was developed in Rotterdam during one of a series of workshops co-taught by Jelle Feringa, in collaboration with Matthias Rippmann and Silvan Oesterle from Hyperbody and the Faculty of Architecture TU Delft. The research project focused on the design and fabrication of funicular shape vaulting structures, employing RhinoVault software as an intuitive design tool and PyRAPID software to translate the geometrical information into robotic motions.

The research team excluded the employment of CNC milling, because it was prohibitively expensive, while RHWC permitted the reduction of costs and fabrication time. However, one of the main challenges of the project was the design of a custom-built hot wire cutting machine to be employed in the manufacturing of the customized components of the vault (Fig. 3.18). RHWC provided the possibility to treat and elaborate the components according to a three-dimensional manufacturing technology, maintaining the mass volume of the material (Brell-Cokcan and Braumann 2012). In this sense, the fabrication constraints became design parameters defining a novel robotically supported design-to-operation process that takes into consideration all the project phases. During the initial phase of experimentation, RHWC was exploited to cut the vault components from EPS foam.

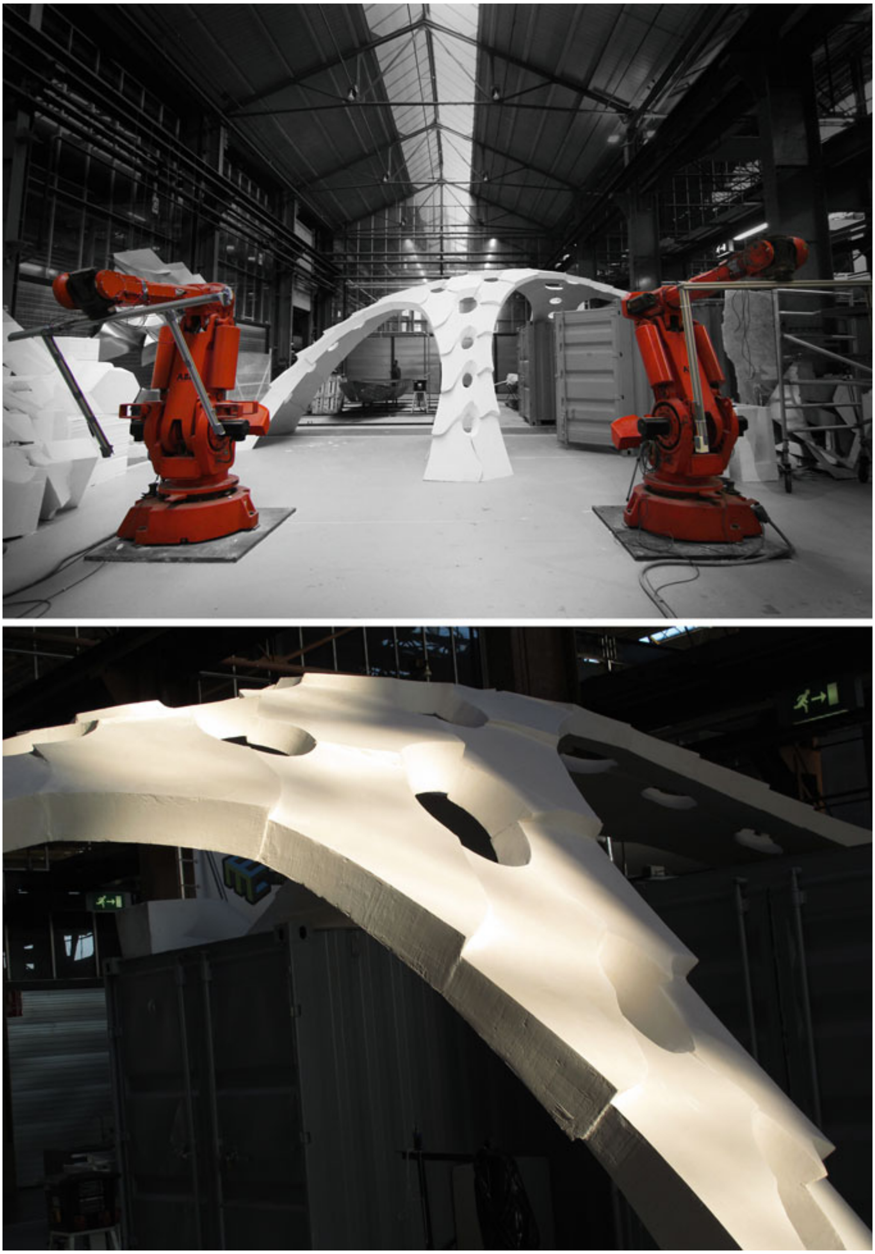

Fig. 3.18 RDM Vault. Robot Hot Wire Cutting process applied to EPS vault components (Courtesy of Jelle Feringa)

The fifty-three unique components were nested entirely within a volumetric block of material. The EPS elements were later covered and treated with a gypsum and acrylic composite material and glass-fiber, providing a structural reinforcement and a fireproofing layer, increasing longevity (Feringa and Søndergaard 2014). In this way the additional layering made the fragile foam components merge into a continuous shell structure, evident in the final product that looks like a compact and solid glass-fiber reinforced shell. The structural concerns on EPS Hicon A/A components led the research team to employ more permanent materials like stone, exploiting the robotic flexibility and replacing the hotwire with another tool. The technology has been improved with the employment of Robotic Diamond Wire Cutting (RDWC) that uses diamond wires as a much more resistant tool capable to work harder materials, which is driven by a hydromotor in order to perform the abrasive process and cut the stone at a very high speed (Fig. 3.19). The initial tests were made on engineered limestone—an inexpensive material, while further experiments have been conducted using marble (Feringa and Søndergaard 2014).

Another research project named Opticut, carried out by Jelle Feringa and Asbjørn Søndergaard, seeks to synthesize two diverse approaches—that of topological optimization and robotic hotwire cutting. This strategy is an extension of the approach they adopted for the previous Unikabeton project, where CNC-milled casts were used to manufacture a topologically optimized concrete structure, which proved to be inefficient and expensive for large-scale implementation (Søndergaard et al. 2013) (Fig. 3.20). The Opticut project, conducted as a collaboration between the Aarhus School of Architecture and industry partners Hicon A/A, Hyperbody Robotic Laboratory, TU Delft, Odico Formwork Robotics, Confac A/S and Soren Jensen Consulting Engineers A/S, has adopted the hotwire cutting of EPS moulds for the production of concrete panels with unique surface geometries (Feringa and Søndergaard 2012a, b). The method proved to be time-efficient in producing single ruled surfaces, in addition to its economical quality and ability to provide a level of precision unachievable manually. A bespoke software for transferring the ruled paths to robot code was developed and utilized, as well, in controlling the tool orientation and the accessible range of the robot. The software also nests the elements efficiently within the standard EPS block. A great advantage to this method is the high precision which, compared to the previously tested CNC milling, produces far smoother casts, and thus translates into cleaner surfaces for the finished concrete structure.

Multiaxial Milling—The ICD/ITKE 2011 Research pavilion is an example of robotic-assisted fabrication, giving a different insight into the use of milling techniques. This work integrates fabrication and biomimetic principles with structural and architectural demands, resulting in a full-scale prototype, characterized by a complex morphology made of components coming from 6.5 mm thin finger-joint plywood sheets (Menges and Knippers 2011) (Fig. 3.21). Given the history of finger joints as an ancient and widely applied technique in the architecture field, their high structural capacity, eliminating the need of additional fasteners, has been proven over time but is mainly achieved through time-consuming manual work. Moreover, in the case of the Research Pavilion, the finger joints complex geometry

Fig. 3.19 Robotic Diamond Wire Sawing (RDWS) uses a diamond wire in order to fabricate marble pieces (Courtesy of Jelle Feringa)

Fig. 3.20 CNC-milled casts were used for the manufacturing of the topologically optimized concrete structure of Unikabeton (Courtesy of Asbjørn Søndergaard)

and various angles proved to be impossible to fabricate even with a standard CNC machine. As seen already in other case studies, the most practical method would involve using a custom made cutting and milling tool, paired and installed on a seven-axis industrial robot, which could produce the 850 individual plates with the 100,000 differentiated finger joints in total (Fig. 3.22). An additional turntable on which an unprocessed piece can be machined from any direction was also installed. Each plate of cross-laminated plywood was mounted on the turntable, robotically trimmed, cut and mitered according to the varying angles of the neighboring plate (Schwinn et al. 2012). The researchers used an open and neutral CNC code which made the interoperability and collaboration between contractors much easier with

Fig. 3.21 ICD/ITKE Research pavilion 2011 was realized with just 6.5 mm thin plywood sheets connected through differentiated finger joints (Courtesy of © ICD/ITKE University of Stuttgart)

Fig. 3.22 Custom-made cutting and milling tools were installed on a seven-axis industrial robot (Courtesy of © ICD/ITKE University of Stuttgart)

Fig. 3.23 Gaudi's Sagrada Familia. Mark Burry and his team turned to the robotically assisted methods for milling the granite blocks (© 2014 Royal Melbourne Institute of Technology)

different machines. Using such open standards, the fabrication process becomes independent of a robot brand and can be performed in any laboratory or industrial environment.

Another interesting case of robotic-assisted milling is the realization of the highly complex geometric narthex columns of Gaudi's Sagrada Familia, by Mark Burry, where granite blocks were shaped in a faster and more efficient solution compared to the recent manual work of highly experienced craftsmen. Full-sized version of the columns were produced in painted glass-fibre-covered polystyrene, machine cut by a CNC robot. The columns, erected and placed, on-site stayed untouched for 5 years. The model has become a prototype for a whole series of subsequent processes leading to its "file-to-factory" production in granite. Today, the 18 unique (no mirror copies) columns are cut with a bespoke seven-axis cutting and routing robot. The robot can work with blocks of granite up to 6 m long, with high precision, reducing drastically the amount of labor hours. The 18 narthex columns range in height from 7 to 10 m and each was reduced to only three elements, from the five that were originally designed (Burry 2012) (Fig. 3.23). Due to the adoption of these techniques, the construction of the Sagrada Familia has been simplified. The installation of the stone columns, which previously took up to four times as long for recutting and fitting, has been reduced substantially. The communication from the digital model to built form has been streamlined and made faster than ever.

3.3.7 Outlook on Robotics in Constructions

Despite the potentials offered by digital fabrication with CNC machines, the construction industry has rarely integrated innovative processes on a large-scale, usually due to high cost products, low flexibility of the machines and time-related concerns. As a consequence, non-standard shapes and components are often re-designed after the initial proposal to fit the construction standard of particular machines. This text shows an alternative to this typical workflow focusing on, how in the last years, the development of robotic fabrication is consistently changing the production perspective towards a new professional paradigm where design software can be integrated directly with fabrication tools in the project.

Robots, as universal and programmable machines, offer a chance of high flexibility, and the analysis of the reported techniques highlights how the use of industrial robots move the attention from shape-oriented design towards material production system. The use of robotic fabrication presents several advantages: flexible functionality, changing from a milling machine to a 3D-scanner just by switching its end-effectors; enlarged and geometrically customizable working space; affordable prices if compared with multi-axis CNC machines. These systems have yet to compete with mass production and the associated economies of scale in fabricating widely distributed products, but they have already shown the potential to empower highly customized solutions. These devices can be tailored to local or personal needs in ways that are not practical or economical using mass production lines. The actual use of robotics under the experiments of several pioneers highlights promising potential and results, but still with an uncertain vision on how this new tools can be implemented on an industrial scale.

In this sense the use of robotics needs to go beyond the limited idea of advanced crafting to achieve a level of integration on a wider scale, that is currently hard to imagine. Within this scenario it appears that the implementation of more accessible software is fundamental, in order to be used by less specialized operators, and able to suggest alternative configurations for the production of construction components.

3.4 Additive Manufacturing

3.4.1 Principles of AM

Additive Manufacturing (AM) is a process of incremental formation executed by the addition of subsequent layers of materials without using supplementary instruments or molds, in a process that is fundamentally opposite to the milling subtractive procedure (Kolarevic 2003). Among the various terms used to define this process, commonly known as 3D printing, additive manufacturing is preferred over layer manufacturing because it applies to various conditions, including future technologies which may differ from contemporary practices, such as multi axis applications (Hopkinson et al. 2006). The main additive fabrication techniques share the same basic principle, in that a solid digital model is sliced into sectional layers then transferred to the manufacturing machine. Physical and chemical processes lead to the creation of solid homogenous forms composed of amorphous materials like liquids, powders, gas and fibers. This process offers a wide degree of flexibility and economic potential because the components are made directly from natural materials. The main advantage comes from the possibility to produce unique components, which would not be economically sustainable to produce with traditional manufacturing techniques (Hauschild and Karzel 2011). This feature, together with the high freedom enabled in realizing complex forms, make the additive manufacturing process particularly relevant within the perspective of advanced customization, and explains the increasing involvement of architects in the development of techniques and applications in this field.

3.4.2 Evolution of 3D Printing

Additive manufacturing is a relatively young manufacturing field. The first additive manufacturing process was indeed introduced in 1986 by Chuck Hull, co-founder of the American company 3D Systems Corp, who invented the process known as stereolithography (SL) in which thin layers of ultraviolet light-sensitive liquid polymers are solidified using a computer-controlled laser beam (Wohlers 2012). Hull also developed the STL file, a format widely accepted by rapid prototyping software, as well as the digital slicing and infill strategies, common to many 3D printing processes today. From that moment on, the field of AM experienced an exponential growth with many production methods quickly evolving.

Starting from year 1991, alternative prototyping technologies to stereolithography have been introduced. Firstly, the technology of extruding thermoplastic materials in filament to be laid in layers, most widely associated with the term “3D printing”, was commercialized by Stratasys under the name fused deposition modeling (FDM). The next year, another two AM technologies were commercialized: the Solid Ground Curing (SGC) from Cubital and the Laminated Object Manufacturing (LOM) from Helisys. SGC used a UV-sensitive liquid polymer solidifying full layers in one pass by flooding UV light through masks created with electrostatic toner on a glass plate, while LOM bonded and cut sheet material using a digitally guided laser (Wohlers 2012). Another technology using lasers to fuse powder materials, the Selective Laser Sintering (SLS), became available in 1992. In the following years several other additive manufacturing processes have been developed, among them, the 3D Printing (3DP) by Massachusetts Institute of Technology (MIT), using an inkjet mechanism depositing liquid binder onto powder.

In the last decades, low-cost 3D printers have been introduced to the market. 3D Systems sold its first 3D printer, Actua 2100, in 1996, using a technology that deposits wax material layer by layer using an inkjet printing mechanism. The same year, Z Corporation launched its 3D printer based again on the MIT’s inkjet technology. The Z402 3D printer used starch- and plaster-based powder materials and a water-based liquid binder to produce primarily concept models (Wohlers 2012).

AM has also been developed for metalworking. Starting in the 2010s, machine tool builders have developed devices incorporating both subtractive and additive manufacturing in one work envelope (Zelinski 2014). However, previously developed techniques like laminated object manufacturing (LOM) and some drop-on-drop processes also incorporate "subtractive" cutting or milling operations. Yehoram Uziel from Soligen Technologies licensed, in 1991, the MIT's inkjet printing technique for exclusive use in the metal-casting industry (Wohlers 2012).

The additive manufacturing technology continues to improve in various ways, from the fineness of detail a machine can print, to the amount of time required to clean and finish the object when the print is complete. The speed of the processes is always increasing as the materials and equipment are getting cheaper and more accessible. The size of the printing machines is also developing in a wide range.

Today there are around fifty different additive manufacturing procedures that are based on different chemical and functional principles, which can be utilized in every phase of the design and production of a component with low limitations related to geometry, complexity or material composition. The demand for additive processes in architecture is growing, especially for the development of technologies that speed up the construction process, based mainly on the study of new natural materials physically and chemically compatible with the needs of the construction sector.

3.4.3 3D Printing in Architecture and Construction

The construction activity in general can be considered as an additive procedure, that consists mainly of the deposition of different sub-components and the overlapping of successive layers of materials. Additive manufacturing can be applied in the AEC sector essentially in two ways: to produce components and sub-components to be assembled and joined in order to create larger structures, or to "print" large-scale and self-standing architectural elements as a whole. Large-scale 3D printing can be particularly useful to build complex geometries without the elevated cost of manual labor or the addition of temporary structures, significantly reducing the time of construction and allowing unseen levels of freedom in the design and realization of forms. Since the mid-1990s, several research groups and companies have attempted to apply additive manufacturing at the building scale, but this currently remains one of the biggest challenges. The main limitations of 3D printing in architecture are related to the size of the machines available in respect to the scale of the buildings. In response to these constraints, during the last several years, significant research has been conducted to develop large-scale 3D printers together with the simultaneous experimentation on different materials with suitable properties for the application in the built environment.

3.4.4 Large-Scale 3D Printing

Contour Crafting—The first attempts to face the challenge of building a 3D printed architecture have been addressed by the American based Contour Crafting and the Italian based D-Shape. Contour crafting, an experimental project being developed since 1998 by Professor Behrokh Khoshnevis, director of the Center for Rapid Automated Fabrication Technologies (CRAFT) at the University of Southern California (USC) in Los Angeles, has gained significant importance. This system is recognized as a milestone in the attempt to transfer rapid production technology to the construction scale and offers a solution to the manufacturing of an entire structure in a single day by utilizing direct layer production that avoids extended installation times and reduces production costs by 75 % (Khoshnevis 2014). This technology is defined as a hybrid automated fabrication technique that is combining an extrusion process that is forming the object surfaces and an injection filling process to build the object core. The extrusion nozzle is equipped with a top and side trowel which collaborate to create a smooth outer and top surface of each layer. Additionally, the side trowel could be deflected in order to shape a non-orthogonal surfaces, or at the same time, allow for thicker material deposition while maintaining a smooth surface finish. (Khoshnevis 2014). A great advantage of this process is the possibility for a thick layer deposition, which in most processes is physically impossible, like in the cases of using a laser or adhesive liquids which cannot penetrate deep enough into the powder in order to solidify it. The thicker material deposition cuts the production time significantly, which is an essential issue for large-scale additive manufacturing.

A wide choice of semi-fluid materials could be used, such as polymers, ceramics, composite wood materials, mortar, cement, concrete and other materials, that once deposited by a nozzle are able to quickly solidify and resist pressure from the weight of the structure itself (Fig. 3.24). The forms created through this technique are self-supporting during the fabrication process, and therefore additional structure is not necessary thanks to the quick curing times, which can be controlled by chemical additives. Currently, the Contour Crafting technology can build a 185 m^2 house with all utilities for electrical and plumbing systems in less than 24 h. Based on these characteristics, the system presents a notable advantage in respect to other construction methods, especially in terms of production costs (reduction of manual labor and materials), environmental advantages (given the absence of waste materials) and quicker manufacturing times considering the lack of temporary supports (Khoshnevis 2014).

D-Shape—A more recent alternative for large-scale 3D printing is marketed by D-Shape, developed in 2004 by the Italian engineer Enrico Dini. This production process is similar to others in the design of 3D geometries as the printing itself resembles that of an inkjet printer. The system works with the injection of a sand and epoxy resin bond that combine together in layers of 5–10 mm and do not require the use of additional structures to support the printed object. The machine has an aluminum structure of 6 by 7.5 by 7.5 m that creates a gantry crane construction system.

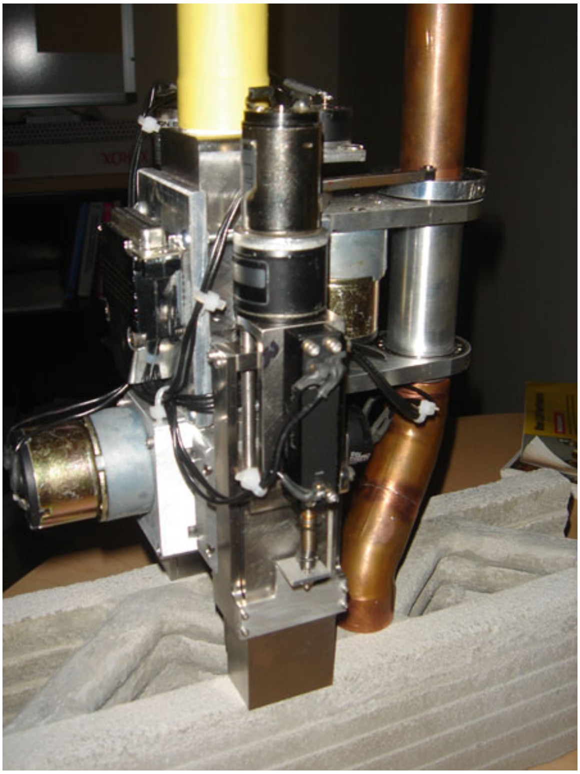

Fig. 3.24 Contour Crafting printing process, showing the employment of a large-scale 3D printer (Courtesy of Berok Khoshnevis, Contour Crafting)

The possibilities of fabrication are therefore reduced to an area of 6 by 6 m with a height that theoretically is limitless, though determined by the self-supporting characteristics of the structure. The geometrical data from the design project is verified by finite element software, and if necessary, optimized for production. As in desktop 3D printers, a STL file is transferred to a computer that manages the machine and can begin the layer printing process. The significant innovation by the D-Shape system is, however, in formulating specific materials that are suitable for the needs of large-scale printing and the application in the construction sector. A particular material has been developed—a chemically refined sand with low viscosity and high surface tension resembling a type of structural ink. The high curing periods are achieved through spraying the material using three hundred nozzles. The sand is deposited in layers, while a second spray adds a fluid component that infiltrates within the granular material, and through a catalytic reaction, forms a homogeneous mass (Fig. 3.25). Thanks to the microcrystalline structure of the mineral, this material has very high durability and surface strength. The catalytic reaction occurs quickly, achieving very high strength in little time. Other components, such as fiberglass and carbon fiber can be added to further increase the strength of the system (Dini 2010a, b). The process converts the granular components to their original rocky structure obtaining a final product with a finishing similar to marble.

Fig. 3.25 D-Shape by Enrico Dini allows printing large-scale objects with the employment of a chemically refined sand as a binder (Courtesy of Enrico Dini)

Emergency 3D printing of houses—Although contour crafting and D-Shape constituted the first important experiments of large-scale 3D printing, the ambition of producing buildings through additive manufacturing has spread to other interesting applications. In 2014 the Chinese company WinSun Decoration Design Engineering Co. employed a huge 3D printer to build ten houses in twenty-four hours. The massive 150 by 10 by 6 m machine sprayed a special mixture derived from cement and construction waste to build the basic components of the house, layer by layer (Balinski 2014). Unlike other attempts related to research experiments, the Chinese company is probably the first one in reaching the goal of 3D printing a whole building, effectively demonstrating the benefits of such an innovative technique in construction (Fig. 3.26). Since the ten houses are built with recycled materials, each building with a size of approximately 195 m^2 could be realized with a minimal budget of less than $5,000. This example demonstrates how the technological equipment and technical competences can become affordable within only a few years, providing cheaper and quicker alternatives to the building fabrication process. The benefits of such an important transformation are remarkable, providing possibilities to supply housing for emergencies or the lower class.

Fig. 3.26 Chinese Company WinSun Decoration Design Engineering Co. built ten completely 3D printed houses in 24 hours (© Winsun New Materials)

3.4.5 Manufacturing Building Components

Materials—One of the most important recent applications of 3D printing in architecture is related to environmental sustainability. Additive manufacturing technology commonly employs granulated materials, which makes waste materials particularly convenient for their use. Emerging Objects, a research project initiated by Rael San Fratello Architects, is focused on experimenting on a wide range of atypical materials and their implications in additive manufacturing techniques, including selective laser sintering, fused deposition modeling, 3D printing and laminated object manufacturing (Rael San Fratello Architects 2014). Among the tested solutions are: polymers, wood, nylon, paper, acrylic and even edible materials such as chocolate and salt (Rael San Fratello Architects 2014). Recycled agricultural waste is also adopted, creating a grain similar to natural wood (Fig. 3.27). The idea of Emerging Objects is to use natural resources applied through 3D printing techniques in architectural and building components. Wood, local salt and sand are reused with the aim to print blocks or panels which can be assembled as sunscreens, interior partitions, building skin elements or even furniture. The results of this research led to the development of the 3D Printed House 1.0, based on the integration between traditional construction methods and 3D printing technology, designed for the Jin Hai Lake Resort Beijing. This project deploys a series of small scale printing machines to fabricate an array of components, that are than assembled together. The design concept of the house is based on the idea of differentiation, and offers the possibility to use 3D printed organic vessels made of salt polymers to enclose bedrooms, bathrooms and family-dining rooms, while the exterior cladding is composed of reinforced cement polymer printed blocks (Fig. 3.28). The inner volumes create a series of translucent spaces, in this sense, the vessels define the interior volume, containing intimate spaces and capturing light from a skylight above. The 3D printable salt polymer employed in the fabrication of these elements is derived from a combination of salt and glue that

Fig. 3.27 Wood block designed by Anthony Giannini of Emerging Objects—an example of 3D printed wood as a possible building material obtained by waste (© Emerging Objects Corp.)

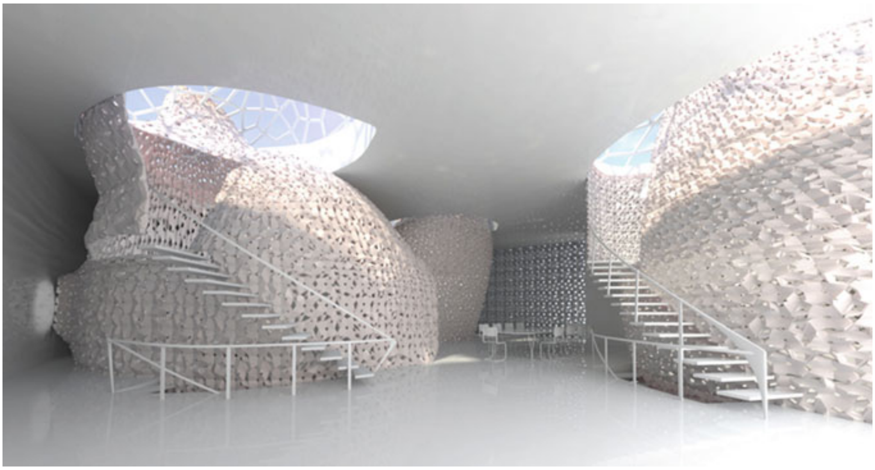

Fig. 3.28 3D printed house 1.0 shows an interior space made of 3d printed mixture obtained by salt and glue constituting an efficient, translucent and inexpensive material (© Emerging Objects Corp.)

Fig. 3.29 Emerging Objects experiments with several material applications in additive manufacturing, focusing on the idea of reusing waste. Pictured above, recycled paper employed for 3D printing a house (© Emerging Objects Corp.)

provides an ideal 3D printing material, since it is waterproof, strong, lightweight, translucent and inexpensive (Rael San Fratello Architects 2014). The same composite material was used for the fabrication of the Saltygloo pavillion (Fig. 3.29).

3D Printed Steel Joints—A team lead by Arup has developed a technique for 3D printing structural steel joints in a project revealed in 2014 in collaboration with WithinLab (engineering design software and consulting company), CRDM/3D Systems (expert in additive manufacturing) and EOS, which was involved mainly in the early stages of development. The pioneering proposal by Arup represents a solution for steel nodes in lightweight tensile structures characterized by complex shapes and customized design. The newly developed process is based on the principle of additive laser sintering, employing steel derivatives as the printing material. The structural nodes have been originally conceived in stainless steel and later produced with maraging steel, compatible with the technology of the machine owned by the partner CRDM. This material is about four times stronger than normal construction steel, which made Arup eager to experiment with it and further explore its potentials. EOS, the additive manufacturing expert involved in the project, reported that this technological solution guarantees a 40 % reduction of CO_2 emissions over the whole lifecycle in respect to traditional casting processes (Fig. 3.30). Furthermore, the process of direct metal laser sintering (DMSL) satisfies many design requirements, reducing weight and preserving geometrical freedom. Due to the nature of additive manufacturing techniques, the production of waste materials is minimized and the weight of the final product reduced by 30 %. A current redesign project claims to reach levels of weight optimization higher than 50 %. In order to verify and improve this method, testing prototypes were scaled down to 40 % of the original size, thus being 14 cm high, without compromising the structural properties of the joints. In order to verify and improve this method, testing prototypes were scaled down to 40 % of the original size, thus being 14 cm high, without compromising the structural properties of the joints.

Arup imagined to develop the technology in the application of large sculptures, as an intermediate test before using it in buildings (Arup 2014). An important consideration is that larger machines are currently being engineered and special hybrid materials being developed, thus the building industry should soon be able to answer to almost any specific demand of the designers and clients within the construction field.

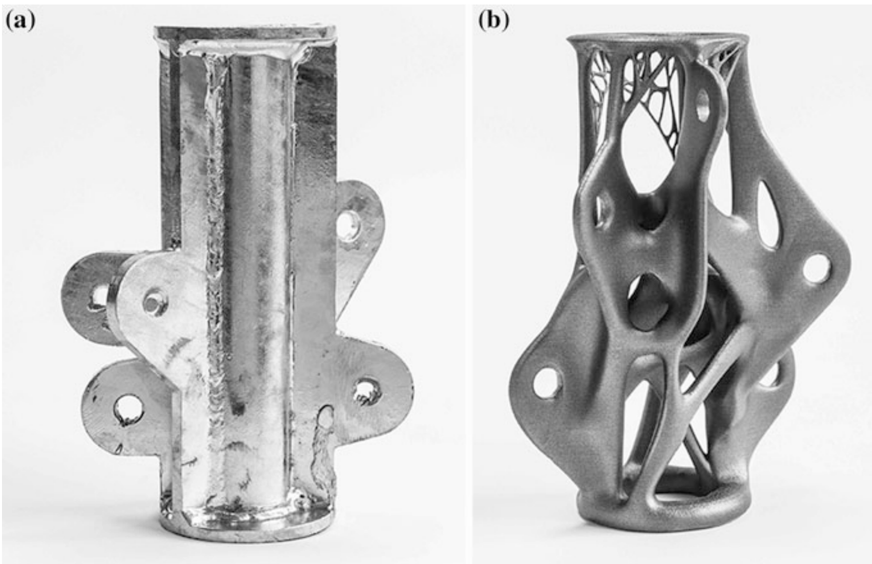

Fig. 3.30 From the *left*: **a** Steel joint produced with traditional method; **b** 3D Printed Steel joint produced with Direct Metal Laser Sintering (DMLS) technology (Courtesy of Arup, © Davidfotografie/David de Jong)

Minibuilders—One of the main issues related to additive manufacturing at the building scale is the dimensional constraints of typical gantry fabrication systems, in which the manufactured object size is strictly limited to machine working volumes and capacity. Seeking to overcome this limitation, a team of researchers at the Institute for Advanced Architecture of Catalonia (IAAC), led by Sasa Jokic, and Petr Novikov, and including Stuart Maggs, Dori Sadan, Jin Shihui and Cristina Nan, have worked on a fabrication method that employs mobile 3D printing robots, called Minibuilders. The innovative system is composed of three different robotic devices with complementary functions (Fig. 3.31).

Foundation robots are initially employed to fabricate the first twenty layers of the structure, following a track sensor to move around and recognize the layering path of the object to be printed. The robots are connected through pipes to the supplier robot, feeding then with the printing material. Since they host the printing heads, the foundation robots gradually move and lay material, thus constructing the building layers. Once the construction is higher than the foundation robots' arms, grip robots intervene, clamping themselves on a specific area of the already printed structure to depose additional layers. These second robots have nozzles mounted to them that connect to rotational and steering actuators, which allow the creation of curved walls (Fig. 3.32). As the grip robots fix themselves to the previously printed layers, they dry the material that supports the next layers of the printed object with heaters that are installed on them. Since the robot grip is very strong, and the curing time of the material is fast, these robots can potentially print ceilings and horizontal partitions. A third printing device, a vacuum robot, is used to reinforce the printed structure, moving up and down the construction, depositing an additional layer nearly perpendicular to the existing ones. This multi-device technique certainly needs to be improved, but represents an interesting contribution in the evolution of the printing technology for full-scale buildings, since it provides a promising solution to face the conventional printing machines dimensional limits (IAAC 2014a, b).

3D Concrete Printing—The Innovative Manufacturing and Construction Research Centre (IMCRC) at the Loughborough University initiated the Freeform Construction project, in collaboration with the UK Engineering and Physical Sciences Research Council (EPSRC) and other partners such as Foster+Partners and Buro Happold. The research team developed a large-scale printing machine capable

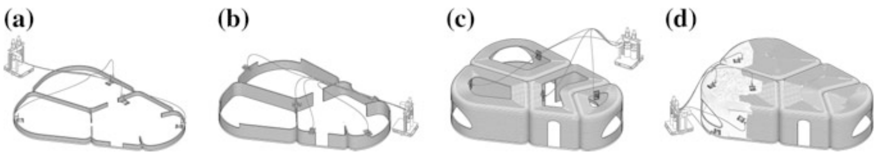

Fig. 3.31 The diagrams show the sequence of work with Minibuilders From the *left* **a** Foundation Robots working on the footprint, producing the first twenty layers of the building; **b** Grip Robots extending the existing structure with additional layers of printed material; **c** Grip Robots printing horizontal partitions; **d** Vacuum Robots reinforcing the printed structure with an additional layer perpendicular to the existing ones (Courtesy of Institute for Advanced Architecture of Catalonia)

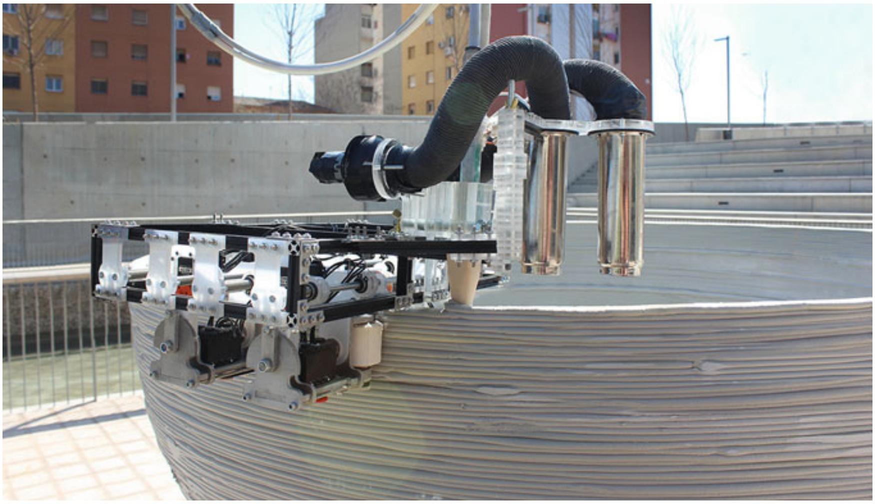

Fig. 3.32 The Grip Robots cramp themselves to the existing structure, and thanks to their four rollers, they create curved walls while sedimenting further material (Courtesy of Institute for Advanced Architecture of Catalonia)

of fabricating concrete parts with dimensions up to 2 by 2 by 2 m (Loughborough University 2014). This technique is similar to the Fused Deposition Modelling (FDM) process that extrudes a bed of hot thermoplastic that subsequently cools and solidifies, with the difference that in this case a concrete layer is deposited through a nozzle that works at a constant speed (De Kestelier and Foster 2012). What differentiates this technique from the aforementioned Contour Crafting and D-Shape is the possibility of printing large-scale volumetric components on-site. The concrete is positioned with high precision, without the employment of supporting material or formwork (Fig. 3.33). Free-form construction methods could deliver non-repeating components at an effective cost, which makes the application of this technology

Fig. 3.33 Free-form construction in its geometrical complexity (© 2014 Loughborough University)

very likely in the manufacture of components to be assembled on-site (De Kestelier and Foster 2012). Amongst the numerous benefits over traditional approaches the most notable ones are: the possibility to achieve structurally optimized constructions, functional integration, and the reduction in the assembly complexity.

Anti-gravity 3D Printing—Conventional methods of additive manufacturing have been typically restricted, both by gravity and printing techniques based on 2D layers that neglect the structure of the object. Material is an alternative technique that, by using innovative extrusion technology, can neutralize the effect of gravity during the course of the printing process, allowing the creation of 3D curves. The patent-pending method has been developed by Petr Novikov, Saša Jokić from IAAC and Joris Laarman Studio. It offers the flexibility to produce objects characterized by three-dimensional curves instead of two-dimensional geometries and thus permits the printing of irregular height buildings, inclined curves or vertical surfaces. A wide number of material experimentation with different polymers had been carried out until, finally, a rapidly-hardening double component polymer was selected as the most appropriate mixture (Laarman et al. 2014). Simultaneously, the design team worked on the production of the first prototypes of the extruder. The source material was mixed through a static mixer-nozzle and a two-barrel constant-rate plunger extruder. During the initial phase of the research, acrylic tubes were used as extruder cask attached to the robotic arm, but the test failed because of the high viscosity of the material; the acrylic elements have been later substituted with aluminum tubes. After several tests on material properties, different heating and deposition speeds, a 50 cm long spiral line connected to a vertical surface was printed (Laarman et al. 2014). Since the combination and the synchronization of the robotic movements and material extrusion have been fundamental for this project, a custom made plug-in for the Rhinoceros 3D modeling software was employed to control these two factors. The plug-in could control both the robot printing the structures and the thickness of the printed curves, adjusting the extrusion speed (Laarman et al. 2014). In Mataerial, the hardening thermo-resin combined with an innovative extrusion technology provides a concrete solution to overcome the need of sustaining elements during the printing process (Fig. 3.34).

Following the same principal technique, Joris Laarman Lab in collaboration with Acotech Automation BV and HAL robot programming and control and supported by Autodesk, has upgraded the technology, adapting it to print free from metal structures and in turn developing the MX3D-metal printer. In this case an industrial robot is coupled with an advanced welding machine which can print metals such as stainless steel, aluminium, bronze or copper (Fig. 3.35). Through the addition of small amounts of molten metal, this technique operates regardless of orientation and inclination and without additional supporting structures. The printing specifications, such as pulse time, pause-time, layer height and orientation, are modified according to the different types of lines to be produced. Autodesk is helping the development team provide a user-friendly software which would allow printing directly from CAD software. The Dragon bench is the first prototyped design object using this technology and it demonstrates the potentials of the machine. The three and half meter long and two and a half meter wide airy, undulating piece, wrought from

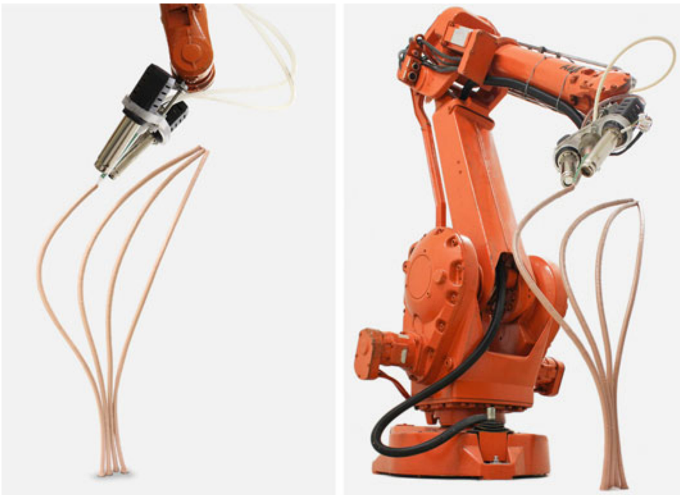

Fig. 3.34 Using an innovative extrusion technology, the form is not affected by the gravity force thus no supporting material or structure are required. The process allows to print any geometries or surfaces as it combines 3D curves instead of 2D horizontal layers (Courtesy of Institute for Advanced Architecture of Catalonia)

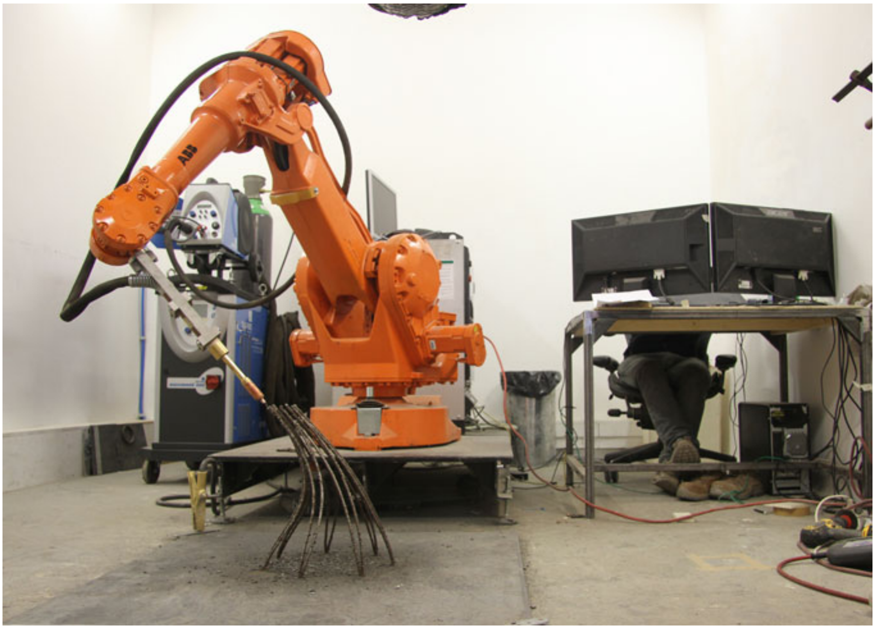

Fig. 3.35 The industrial robot is coupled with an advanced welding machine which can print with metals like stainless steel, aluminium, bronze or copper (Courtesy of Joris Laarman Lab)

Fig. 3.36 DRAGONBENCH by Joris Laarman Lab, Acotech Automation BV. The three-and-half-meter long and two-and-a-half-meter wide airy, undulating piece wrought from stainless steel has been manufactured by an algorithm of Laarman's design (Courtesy of Joris Laarman Lab)

stainless steel, has been manufactured through the use of an algorithm (Fig. 3.36). The ability of this system to print quite fast at an optimized cost, compared to the traditional selective laser melting (SLM) or electron beam printing, together with the fact that the printed metal lines can intersect and intertwine without additional support, suggests that the MX3D printer might be applied in the production of metal reinforcements for complex shaped concrete structures (Halterman 2014).

3.4.6 Perspectives in AEC

The AEC industry is a latecomer regarding the actualization of the potential offered by advanced computational design. Traditional materials and construction techniques are not flexible enough to build complex and highly articulated architecture in a sustainable way, and usually require excessive manual labor costs. Within the field of construction, the shift from prototyping to direct manufacturing is mainly connected to material improvements, which in comparison with product design is more complicated to achieve. Material characteristics, mechanical properties and dimensional requirements are key elements in additive manufacturing. In the last several years numerous research studies focused on testing new materials, and on conceiving new strategies for an "unlimited" printing area. Within this rapidly evolving framework, where manufacturing capabilities are in constant evolution, it is currently difficult to preview the effective impact of additive manufacturing in the AEC sector on a short term, but the state-of-the-art methods suggest promising results on a longer perspective.

References

Arup (2014) Construction steelwork makes its 3D printing premiere. http://www.arup.com/News/2014_06_June/05_June_Construction_steelwork_makes_3D_printing_premiere.aspx, Accessed 14 June 2014

Balinski B (2014) Chinese company 3D prints 10 houses in a day from recycled material. In: Architecture & Design, Cirrus Media. http://www.architectureanddesign.com.au/news/chinese-company-3d-prints-10-houses-in-a-day-from Accessed on 25 May 2014

Bawa HS (2004) Manufacturing Processes I. Mechanical engineering series. Tata McGraw-Hill Education, New Delhi

Bayegan M, Niklas, Erenmalm S, Leffler N (2005) Special report: Robotics. ABB Review, ABB LTD, Zurich

Bonwetsch T, Kobel D, Gramazio F, Kohler M (2006) The informed wall: Applying additive digital fabrication techniques on architecture. Synthetic landscapes proceedings. ACADIA 06:489–495, ETH Zurich

Brell-Cokcan S, Braumann J (2012) Rob|Arch 2012: Robotic fabrication in architecture, art and design. Springer, New York

Burry M (2012) Models, prototypes and archetypes. Fresh dilemmas emerging from the ‘file to factory’ era. In: Sheil B (2012) Manufacturing the bespoke. John Wiley & Sons Ltd., Chichester

De Kestelier X, Foster N (2012) Design potential for large-scale additive fabrication, Free form construction. In: Glynn R, Sheil B (2012) Fabricate. Making digital architecture. Riverside Architectural Press. Toronto, pp. 244–249

Dini E (2010a) The technology. http://www.d-shape.com/tecnologia.htm, Accessed 6 June 2014

Dini E (2010b) What is D-shape. http://www.d-shape.com/cose.htm, Accessed 6 June 2014

Feringa J, Søndergaard A (2014) Fabricating architectural volume: Stereotomic investigations in robotic craft. In: Gramazio F, Kohler M, Langenberg S (2014) Fabricate: Negotiating, design & making. gta Verlag, ETH Zurich, pp. 76–83

Feringa J, Søndergaard A (2012a) An integral approach to structural optimization and fabrication. Synthetic digital ecologies proceedings, ACADIA 12_15:491–497. San Francisco

Feringa J, Søndergaard A (2012b) Design and fabrication of topologically optimized structures. An integral approach - a close coupling form generation and fabrication. eCAADe 30:495–500, vol. 2. Czech Technical University, Prague

Groover M P (2010) Fundamentals of modern manufacturing: Materials, processes, and systems. John Wiley & Sons Ltd., Chichester

Halterman T (2014) Grace and robotic metal 3D printing – Joris Laarman’s MX3D-METAL, http://www.3dprinterworld.com/article/grace-and-robotic-metal-3d-printing-joris-laarmans-mx3d-metal, Accessed 15 June 2014

Hauschild M, Karzel R (2011) Digital Processes (Detail Practice). Birkhäuser GmbH, Basel

Hisatomi Y (1990) Introduction of construction robotics in Japan. IABSE Journal 4:26–30. ETH, Zurich. http://dx.doi.org/10.5169/seals-31666, Accessed 20 July 2014

Hopkinson N, Hague R, Dickens P (2006) Rapid manufacturing: An industrial revolution for the digital age. John Wiley & Sons Ltd., Chichester

IAAC (2014a) A radically new 3D printing method, http://www.mataerial.com/, Accessed 15 June 2014

IAAC (2014b) Minibuilders. http://iaac.net/printingrobots/ Accessed 15 June 2014

International Federation of Robotics (2012) History of industrial robots. From the first installation until today. http://www.ifr.org/uploads/media/History_of_Industrial_Robots_online_brochure_by_IFR_2012.pdf Accessed 20 June 2014

ISO (1994) Manipulating industrial robots vocabulary. Robots manipulateurs industriels: vocabulaire. ISO 8373:1994, Geneva

Kalo A, Newsum M J, McGee W (2014) Performing: Exploring incremental sheet metal forming methods for generating low-cost, highly customised components. In: Gramazio F, Kohler M, Langenberg S (2014) Fabricate: Negotiating, design & making. gta Verlag, ETH Zurich, pp. 166–173

Khoshnevis B (2014) Contour crafting. Robotic construction system. University of Southern California. http://www.contourcrafting.org/, Accessed 13 June 2014

Kolarevic B (2003) Architecture in the digital age: Design and manufacturing. Spoon Press, New York

Laarman J, Jokić S, Novikov P, Fraguada L E, Markopoulou A (2014) Anti-gravity additive manufacturing. In: Gramazio F, Kohler M, Langenberg S (2014) Fabricate: Negotiating, design & making. gta Verlag, ETH Zurich, pp. 192–197

Loughborough University (2014) 3D concrete printing: An innovative construction process, http://www.buildfreeform.com/, Accessed 15 June 2014

MacDowell P, Tomova D (2011) Robotic Rod-bending digital drawing in physical space. Integration through computation proceedings. ACADIA 11:132–137. Calgary

MacDowell P, Tomova D (2012) Wave pavilion. In: Glynn R, Sheil B (2012) Fabricate. Making digital architecture. Riverside Architectural Press. Toronto, pp. 80–83

Menges A, Knippers J (2011) ICD/ITKE Research Pavilion 2011. ICD Institute for Computational Design, Faculty of Architecture and Urban Planning. http://icd.uni-stuttgart.de/?p=6553, Accessed 15 June 2014

Menges A, Schwinn T (2012) Manufacturing reciprocities. Special Issue: Material Computation: Higher Integration in Morphogenetic Design. AD 82:118–125. doi:10.1002/ad.1388

Moran M E (2007) Evolution of robotic arms. J Robotic Surg 1:103–111. doi: 10.1007/s11701-006-0002-x

Osha (1996) Osha technical manual. Government Institutes Publishing, USA

Paoletti I, Naboni R (2013) Robotics in the construction industry: Mass customization or digital crafting? In: Emmanouilidis C, Taisch M, Kiritsis D (2013) Advances in production management systems. Competitive manufacturing for innovative products and services. IFIP WG 5.7 International Conference 397: 94–300. doi: 10.1007/978-3-642-40352-1_37

Rael San Fratello Architects (2014) Emerging objects, http://www.emergingobjects.com/, Accessed 8 June 2014

Rob|Arch (2014) Robots in architecture. Robotic fabrication in architecture, art and, design. http://www.robarch2014.org/ Accessed 20 April 2014

Singh B, Sellappan N, Kumaradhas P (2013) Evolution of industrial robots and their applications. In: International Journal of emerging technology and advanced engineering. 3:763–768. doi: 10.1.1.413.8024

Schwinn T, Krieg O, Menges A, Mihaylov B, Reichert S (2012) Machinic morphospaces. Biomimetic design strategies for the computational exploration of robot constraint spaces for wood fabrication. Synthetic digital ecologies proceedings, ACADIA 12:156–169, San Francisco

Søndergaard A, Amir O, Knauss M (2013) Topology optimization and digital assembly of advanced space-frame structures. Adaptive architecture proceedings. ACADIA 13:367–368. Cambridge

Wohlers T (2012) Wohlers report 2012: Additive manufacturing and 3D printing state of the industry. Annual worldwide progress report. Wohlers Associates, Fort Collins, Colorado

Zelinski P (2014) Add-on additive manufacturing. The capacity to build 3D metal forms is a retrofittable option for subtractive CNC machine tools. In: Modern Machine Shop, Additive Manufacturing supplement. http://www.mmsonline.com/articles/add-on-additive-manufacturing Accessed 20 June 2014

Chapter 4
How to Build (Almost) Anything Customized

Abstract *How to build* (*almost*) *anything customized* analyzes, through a selection of case studies, the state-of-the-art workflows in the creation of highly customized architecture: unique prototypes for individual customers in specific contexts. Employing computational design tools and high-precision digital machinery, it is currently achievable to build with personalized construction systems, in a relatively limited budget and timeframe. Referential projects in the field of computational design are organized, technologically-wise, by their fundamental focus of customization—skin system, structural application, or interior interface—presenting a wide range of design research, digital techniques, and fabrication strategies. With an overview of the full workflow, that involves different professional actors, production technologies and software interoperability, the case studies are described from design to realization, with particular focus on the advanced fabrication strategies adopted to achieve highly complex architectural systems. Emergent design approaches, some truly experimental and others more consolidated in the practice, are intertwining spatial design with research on new tectonics and material systems to deliver high performance architecture.

Keywords Advanced customization · Digital fabrication · Interior interface · Parametric design · Skin system · Structural application

4.1 How to Build (Almost) Anything Customized

In 1998, Neil Gershenfeld started teaching a class at MIT called "How to Make (Almost) Anything" and introduced the idea of personal fabrication through the use of digital tools in the school curriculum. The chapter titled "How to build (almost) anything customized" is not only a tribute to a milestone of the history of personal fabrication, but an idea to apply the same vision to the sector of architectural design and construction.

Thanks to many technological advancements, (almost) every technical system in a building can be tailored nowadays. Architects are used to conceptualizing unique buildings, but the traditional building industry does not have the flexibility in

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delivering personalized construction systems and sub-components. Product standardization has become the principal way in controlling the economic feasibility of the construction process. From the 2000s architects started experimenting with CNC machines and their impact in construction. Nowadays, we can finally imagine to build architecture that is almost completely customized using high-precision machinery, in a relatively controlled budget and timeframe. We can build (almost) anything customized, even unique prototypes for individual customers in specific contexts.

This chapter represents a collection of recent works of customization in architecture. The selected case studies show different scales and approaches, some truly experimental, others more consolidated in the practice. They all contribute complementary to the idea of full customization in construction.

In contrast to other texts on this topic, a classification by machining process is not proposed, since this book states the idea of a synergic "digital fabrication ecosystem", in opposition to rigidly framed fabrication methods. In this chapter the projects are organized by paradigmatic architectural systems in order to underline the potential applications within construction. The three main categories are skin, structure and interior, conceived as a potential context for application and not as a rigorous technological subdivision. In this way we attempt to shift the focus from process to product, from machines to custom architectural components, going beyond the limits of a mere technical term. Some of the projects respond literally to this classification, while others are apparently more resistant to an explicit framework, blending among technological categories. We believe this apparent classification limit is an actual confirmation of the idea of advanced customization: architectural creations can no longer be classified only on the base of functional construction layers.

4.2 Skin Systems

In this section several case studies are collected that address innovative and highly customized skin systems. In the last few years, mainly influenced by computational design, building envelopes have been the object of extensive studies among contemporary designers. The influence of parametric design has promoted a dominant idea of continuous architecture, in which façade and roof blend together in one or more surfaces, populated by computationally informed patterns. Given this specific importance, it is not surprising to realize skin systems that present mature samples of customizations.

Casting aggregate structures explains the design and production process for the Italy Pavillion for Milano Expo 2015 by Nemesi & Partners, an interesting implementation of concrete and steel cast panels.

Robotically fabricated brick façade is a description of the Brickfaçade of Keller AG Headquarter by Gramazio & Kohler, which represents a successful case of robotically controlled additive manufacturing processes installed on a real building. It shows how the programmability of a robotic arm can lead to the reinvention of the traditional building technique of masonry, taking advantage of the high speed and precision of the robotic “pick-and-place” feature.

Digital design with local manufacturer shows how the non-periodic façade pattern of the Tori Tori Restaurant in Mexico city, by Rojkind Arquitectos + ESR-AWE Studio can be built conveniently when architects are able to provide fabrication data directly to the CNC machines of local metal manufacturers.

A web-based platform for a complex façade from Crawford Architects’s Zahner Factory Expansion in Kansas City, is an interesting case of skin customization achieved through a web-based platform which allows the designer to tune project features interactively, while also keeping track of costs.

From BIM to tailored skin production describes how the New York by Gehry tower (NYbG) employed the tight collaboration between the architect and the contractor, supported with a full BIM implementation, in managing the project complexity, and allowed the possibility of a tailor made façade system to be built efficiently with zero change orders from the contractor on the curtain wall, which is not always granted in highly complex buildings like this one.

Material customization analyzes the Arboskin Pavillion in Stuttgart by ITKE, University of Stuttgart. The experimental pavilion pushes the boundary of customization to respond to the increasing demand for sustainable and resource-efficient building materials, which are combined to deliver a complex shaped cladding system.

4.2.1 Casting Aggregate Structures

Nemesi & Partners—Italy Pavillion, Milano Expo 2015

The project of the Italy Pavilion is the result of an international design competition held by Expo 2015 SpA and won by Nemesis & Partners among 68 other participants in April 2013. The Italian Pavilion involves the construction of Palazzo Italia (about 13,000 m^2 on 6 levels above ground) and the temporary buildings along the Cardo (about 10,700 m^2 on 3 levels above ground). The main focus of this case study concerns the innovative skin and structure of Palazzo Italia, which is the only building from Expo 2015 that will be permanent. This is a very important condition to understand the philosophy of the project and the technologies employed.

Palazzo Italia has been designed by Nemesi & Partners, a young Italian firm, with the aim of creating an iconic building representing the idea of inclusion, through an internal piazza, and a branched structure for the outer casing that recalls a forest. Thus, the design of the “skin” evokes a primitive and technological image and simultaneously creates a light and shade effect. From the outside, the volume is rigorous and compact in order to give a unitary vision for communication purposes and to be strongly recognizable in the Expo area (Fig. 4.1). Once the visitor comes inside the building, he passes through a covered square where it is possible to experience an “organic landscape”. The structural elements, rising from the ground like roots, support the four blocks where exposition spaces, an auditorium, offices

Fig. 4.1 Palazzo Italia, view from *outside*: the volume is compact and well connected to the ground by big root-like foundations (Reproduced with permission of © Nemesi & Partners srl)

and conference halls are located, thus creating an "urban forest" (Fig. 4.2). Gradually the heaviness of the structure is replaced by the perception of lightness, just like a tree, inspiring fluidity and dynamism according to the most contemporary design requirements. Even the roofing system has been designed to complete the tree-metaphor: it will be realized by photovoltaic glasses and flat or bent geometric panels that will contribute to the buildings gold classification following the LEED rating system. A conic glass skylight will be suspended upon the inner square and the main stairway, flooding the inner spaces with natural light.

Palazzo Italia will have a mixed steel-concrete structure, with a white concrete external skin and internal glass facades, while the 3,300 m^2 technological roof will be made of steel, glass and photovoltaic panels. The main interest of this case study is focused on the white 9,000 m^2 façade customization made up by 900 elements with a typical dimension of 4 × 4 m and 20 cm thickness. The components are made of a special mixture of concrete poured in molds, which have been designed in order to address structural and aesthetic issues in the same element. The first layer is the structural one—similar for each floor, while the external pattern, in order to recall the idea of a tree, is different for every panel.

All the molds are made of polystyrene and different one from the other: 600 molds are plane and 300 are angular. The molds have been studied by the designer in Rhinoceros and then imported by the manufacturer in CATIA, a software which enables a direct script from CAD to CAM (Fig. 4.3). Every panel has been analyzed with a Finite Element Analysis (FEM) tool in order to verify the structural issues. Even the material composition of the elements has been specially customized by Italcementi for this project: the "i.active bio-dynamic" concrete is more fluid than

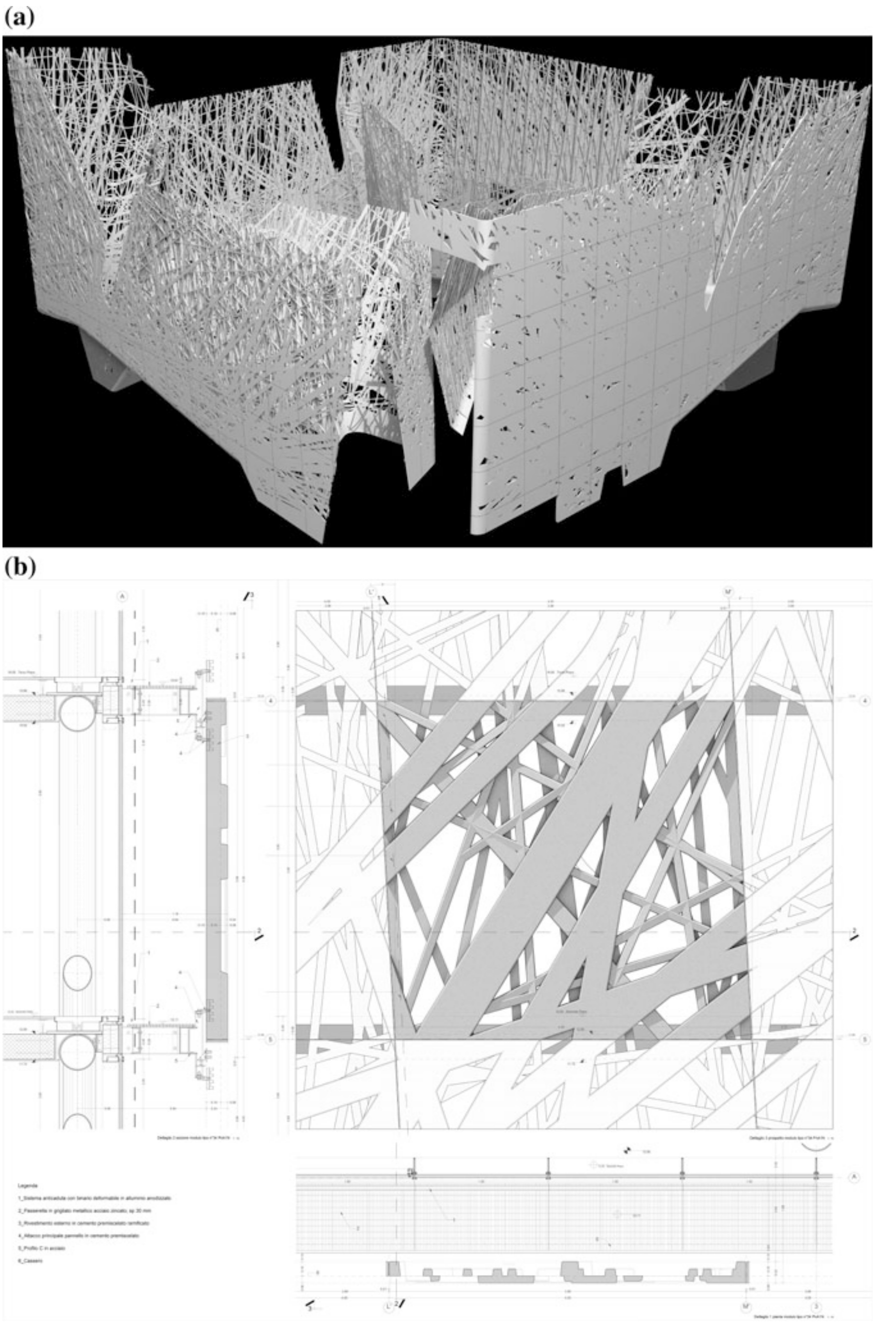


Fig. 4.2 **a** Skin system design (Reproduced with permission of © Nemesi & Partners srl). **b** Skin system: working drawing (Reproduced with permission of © Nemesi & Partners srl)

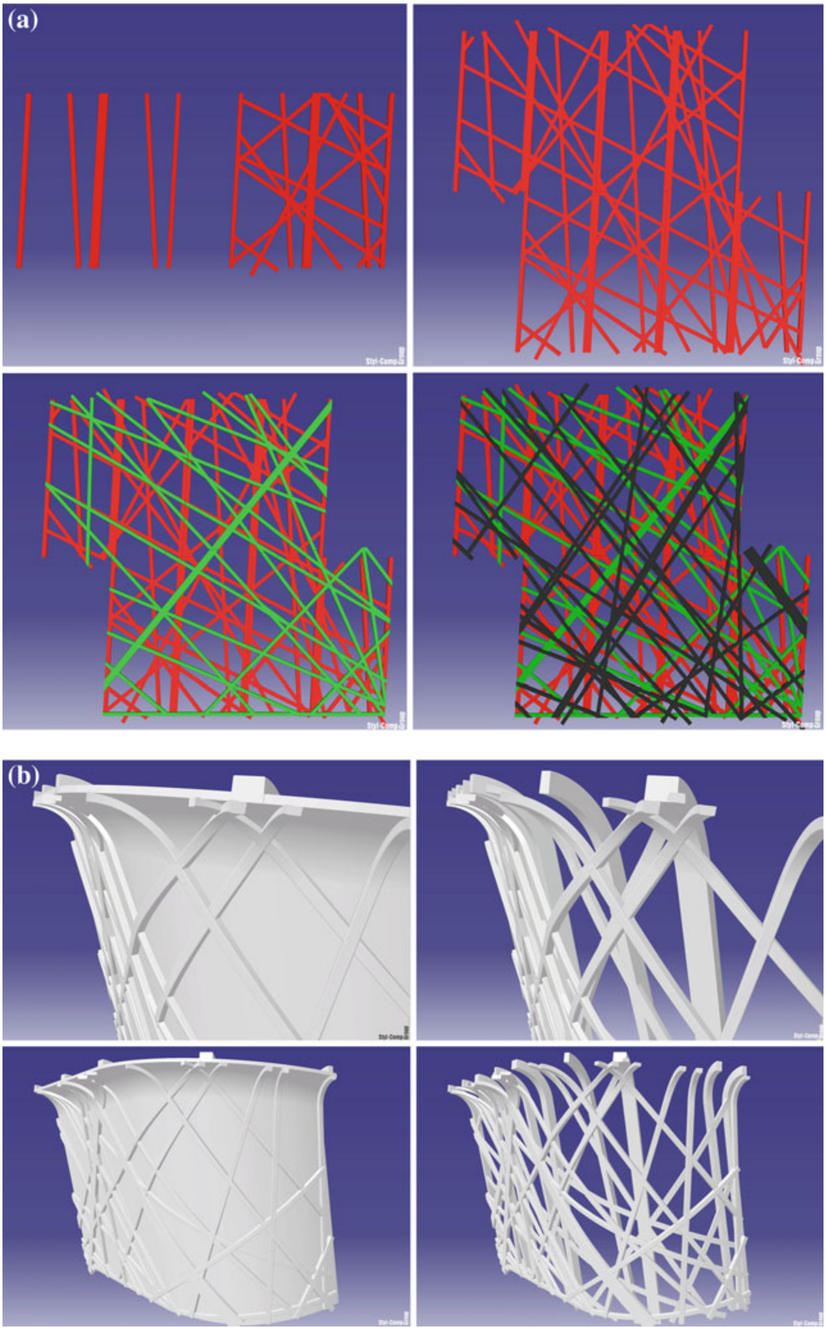


Fig. 4.3 **a** Geometric generation of the façade (Reproduced with permission of © Styl Comp). **b** Base and intrados system (Reproduced with permission of © Styl Comp)

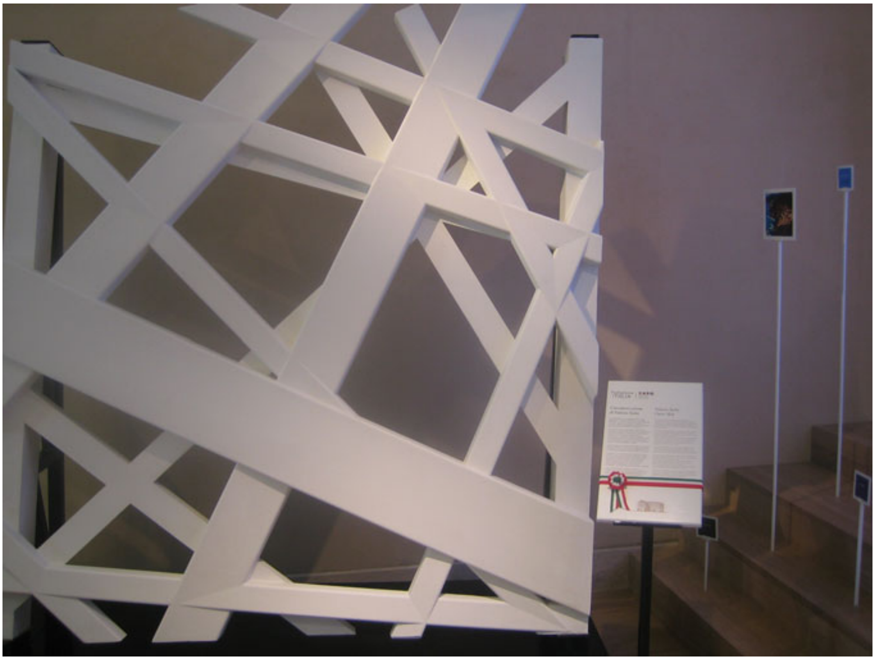


Fig. 4.4 Mockup of the façade system (Reproduced with permission of © Styl Comp)

the one traditionally used in order to avoid any imperfections and, thanks to its active properties, is able to capture some pollutants from the atmosphere, transforming them into inert salts and contributing to the oxygenation of the air. The color of this concrete is very bright and white due to the addition of Carrara Marble powder, obtained from recycled leftover material (Fig. 4.4). The production process involves low-speed pouring of the concrete and adding holes in the molds in order to avoid air imprisonment that decreases the performance. The operations on-site are done with an internal and external crane and every panel has two fixing systems that allow up to 8–10 units to be assembled in a day. The fixtures are done with a patented Styl Comp solution called BS fixing that allows easy positioning of each component. The cost of the constructive system is around €800/m^2 while maintenance is suggested once a year.

Big-scale components, studied with parametric technologies in order to be effective on a construction site, is the privileged way to innovate in the building sector. The concrete components of Palazzo Italia are at the very forefront of technological advancements in the traditional precast concrete industry which nowadays can benefit from new tools to develop custom molds or even directly personalized components. The weight of these components is still very high, but the simple process of assembly and the complete package solution can overcome some of the installation challenges. The use of parametric tools to customize molds can give the designer the possibility to interact with the manufacturing process.

4.2.2 Robotically Fabricated Brick Façade

Gramazio & Kohler—Brickfaçade of Keller AG Headquarter, Ofenhalle

The Swiss-based duo Gramazio & Kohler have been working since 2005 to explore the potential of robotic fabrication for architecture at ETH in Zurich. Particularly, they investigate robotic additive fabrication processes and their implications on architectural design and construction. In order to do this, Gramazio & Kohler have started their research from a simple and coarse construction element, like the brick, trying to explore the potential of robots in building, apart from the repetitive tasks they are usually employed for. The two Swiss designers implemented their research in various academic experimental projects, attempting to design innovative masonry systems which could only be realized by a machine able to manage highly complex patterns, almost impossible to be achieved by the traditional craftsmen. The implicit goal is to find a specific aesthetic expression for the robotic fabrication that does not emulate the man in the built-up process. Thanks to digital fabrication methods new configurations for walls and façades become possible through 3D manipulations like rotation and twist, opening joints, vertical offsets and complex curvatures. In the case of Keller AG façade the two Swiss architects created a diagrid brick structure that stands paradigmatically in front of the glass façade of the new headquarters where the production site and a furnace was once located. Bricks are rotated on their vertical axis while gradually offset to create a diagrid composition, inducing a vibrant alternation of light and shadow (Fig. 4.5). Working with very simple elements, like bricks, allowed the designers to concentrate more on the combination of digital design and fabrication without the necessity to develop complex building components. The new Keller AG façade is made of 5,400 clinker bricks, assembled in panels off-site by a robot according to a parametrically generated model, developed with the commercially available 3D modelling software Rhinoceros and its extension, Rhinoscript. A custom computer script was developed to translate the CAD data into control data for the robot, allowing for direct fabrication from the design model. In 6 days a crew of craftsmen assembled the structure on-site from the prefabricated brick panels, assembling about 40 elements a day (Fig. 4.6). The weight of each element was between 50 and 70 kg, and was optimized as much as their dimensions allowed to ensure handling on the building site. The brick grid was fixed by steel anchor bolts to the glass façade at regular intervals (Gramazio and Kohler 2014).

Gramazio & Kohler favor additive principles for the production process, which means that material is build up from smaller units into the intended shape. According to the designers, the advantages are multiple: compared to the subtractive and formative fabrication the additive manufacturing allows a differentiated design of the cross section of a component while avoiding waste of material. For the fabrication, the designers worked with a six-axis industrial robot. Robots, as

Fig. 4.5 The design of the façade would have been almost impossible to realize by a human (Reproduced with permission of © Gramazio & Kohler)

opposed to specialized CNC fabrication machines are generic, i.e. they have not been designed to perform a singular fabrication process but represent the possibility to reach a point in space in order to perform a physical action (Fig. 4.7). The tool can be customized and uniquely programmed for the specific fabrication process. According to the Swiss architects, establishing a new relationship between humans and machines can lead to a future in which automation will not be exclusively driven by rationalization and cost optimization anymore, but will concentrate on the architectural added value emerging from the synergy of human and machine strengths.

The bricks employed in this fabrication process must have highly precise geometrical requirements like parallelism, planarity, orthogonality and height. This enables only the horizontal layer to be glued, and not the vertical one, assuring compelling strength for structural reasons. The glue deposition is performed by the robot. Bricks are assembled in the desired pattern to form a prefabricated panel that may measure from 2.8 to 4 m, depending on the robotic arm dimensions: in the case of the Ofenhalle project façade, the elements were simpler and smaller (Fig. 4.8).

Digitally controlled additive manufacturing in architecture is a promising research line and the Ofenhalle experimental project represents one of the first

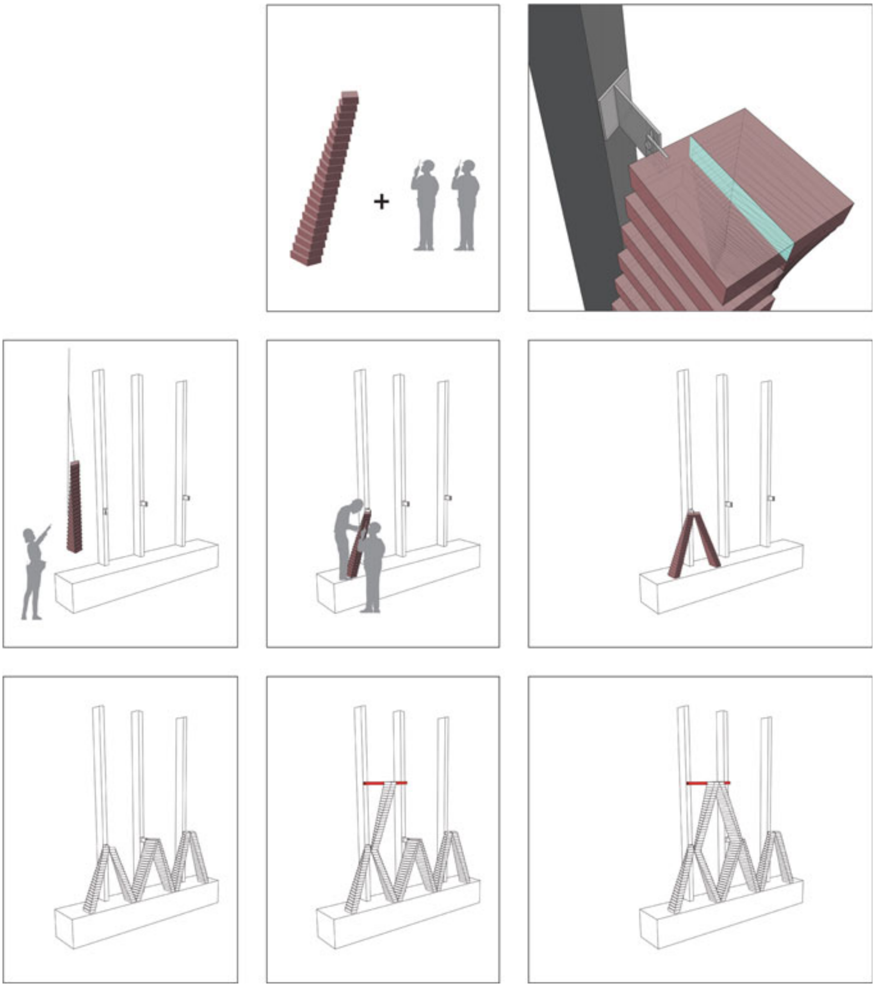


Fig. 4.6 Construction scheme: the diagonal element has been robotically fabricated off-site and assembled on-site by craftsmen (Reproduced with permission of © Gramazio & Kohler)

successful cases in this field. It shows that non-standard solutions can be easily accomplished when the design data is directly used to control the fabrication process. As a result, an innovative architectural product has been achieved, which could not have otherwise been conceived or fabricated manually.

Fig. 4.7 Mockup construction: the robot is building the structures for supporting the diagonal elements (Reproduced with permission of © Gramazio & Kohler)

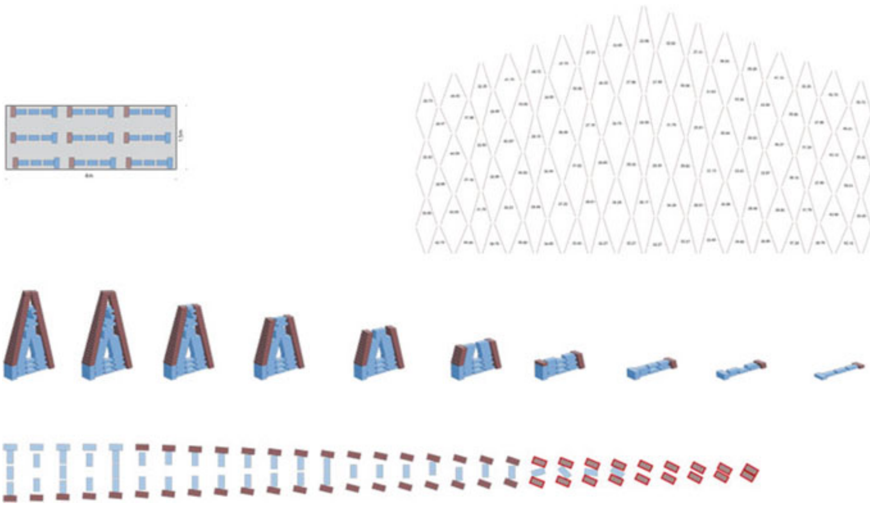


Fig. 4.8 Construction scheme of the *triangle*: the diagonal elements are obtained with a supporting structure (Reproduced with permission of © Gramazio & Kohler)

4.2.3 *Digital Design with Local Manufacturer*

Rojkind Arquitectos + ESRAWE Studio—Tori Tori Restaurant, Mexico City

This case deals with the new location of a Japanese eatery in Mexico city, called Tori Tori. Some years ago, the owner decided to move to Polanco, an exclusive aging residential neighborhood characterized by low-rise mansions, foreign embassies and museums, where architecture is rapidly changing its original functional vocation towards a commercial one. The client, traditionally linked to his native country Japan, bought an old 1920s house where he imagined to build a Japanese garden with a koi pond. Michel Rojkind, the architect in charge, freely interpreted the client's request and suggested something different to show the cosmopolitan and contemporary character of his client. Thus, he completely transformed the old house, wrapping it with an eye-catching façade skin with a wavy steel pattern and, together with Hector Esrawe who designed the interior, created different ambiences with a strong relationship between the interior and exterior spaces (Fig. 4.9).

Externally, the 850 m^2 lot is surrounded by an ivy covered wall. The entrance is discreet and only marked by a small sign engraved with a Japanese rooster, the Tori Tori logo. Once inside the property, the eye is immediately caught by the grid structure that wraps the south and the west elevations from the ground to the roof of the building. Two 7.3 m high lattices cover the old house that has been spoiled from all its features and has now wide floor-to-ceiling glass opened towards the garden. The project shows a particular attention to explore a new, digitally influenced, materiality.

> We are always experimenting on patterning that is more inhabitable and design driven,

says Michel Rojkind (Virginia Tech Interior Design 2012). Indeed he and his firm partner Gerardo Salinas modeled more than 20 different lattice designs with their laser cutter before obtaining the shape they wanted, i.e. a pattern suggesting the calmness of a Japanese koi pond. The digital mesh evokes a water texture and gives a dynamic sensation to the building: the spectator, looking at it, cannot stop adjusting his own eyes to the pattern in the same way it happens with flowing water.

The restaurant skin is particularly interesting in terms of advanced customization (Fig. 4.10). If computer-aided design allowed the architect to conceive a complex pattern and geometry, its realization did not demand titanic investment. Michael Rojkind had previously worked with large, well known architectural metal fabricators, thus he developed knowledge on utilizing local resources to achieve his vision on a tight budget.

> Digital design is important to us he says, but I love using local fabricators (Virginia Tech Interior Design 2012).

The economic feasibility is a fundamental key to accomplish mass customization in buildings. The façade is made up of two metal planar surfaces, each around 8 cm (3 in.) thick and standing about 20 cm (8 in.) apart. Each element is a flat CNC laser cut steel sheet, whose perforation and mutual positioning (slightly varying from one plane to the other) have been meticulously studied with the software Maya in order to create a three-dimensional effect and allow views of the outdoor patios to the diners.

Fig. 4.9 **a** External view: a 1920s house has been wrapped by a digitally handcrafted cladding (Reproduced with permission of Rojkind Arquitectos, photo by Paul Rivera). **b** Detail of the metal cladding: slightly offsetting the layers and painting them two tones of *gray*, give the illusion of movement enhanced by the *blue* LEDs lights during the night (Reproduced with permission of Rojkind Arquitectos, *photo* by Paul Rivera)

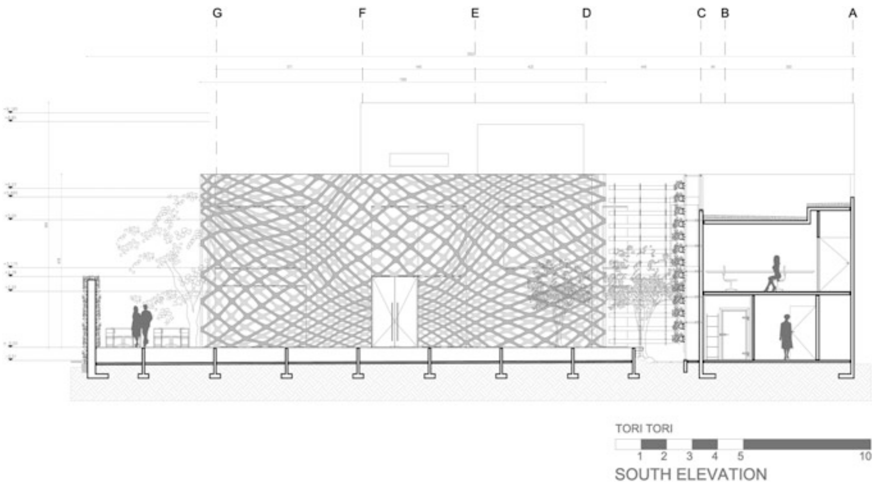


Fig. 4.10 Exterior facade (Reproduced with permission of Rojkind Arquitectos)

To limit the costs, Rojkind and his team divided the digital design into 1.2 × 2.4 m^2 (4 × 8 ft) sections, which is the standard size of a light-gauge steel plate, and built the meshes as a hollow structure using 1.2 cm (½ in.) thick plates. Using standard materials and the architect's digital files, the local manufacturer, Zinbel, spent 3 months milling more than 150 steel plates on a water jet laser cutter, hand-welding the cut panels into hollow assemblies and filling them with expanding foam insulation. Once the panels were ready, a crew of up to 45 metal craftsmen, coming from the Oaxacan region, erected the cladding on-site in 4 months: they fixed the panels by stainless steel tie rods at the roof and at around 3 m (10 ft) above the ground, so that the meshes were self-supporting and met the local structural and seismic requirements. Finally they welded the foam-filled sections and precisely adjusted all joints, which were coated afterwards with a grey automotive paint—light gray for the inner side and a darker one for the outer one (Fig. 4.11).

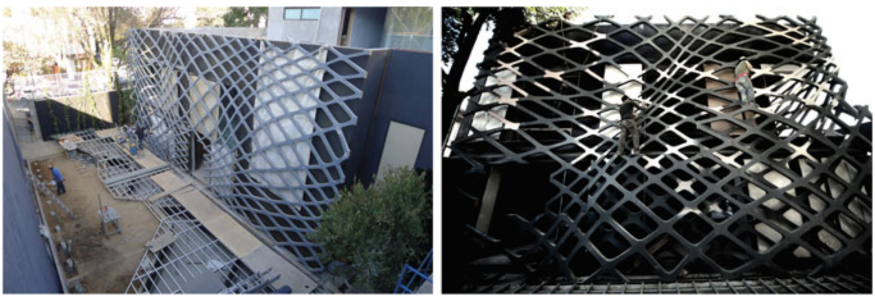


Fig. 4.11 Façade installation: thin-gauge steel plates were welded in place and hand-finished by a team of about 40 local metalworkers (Reproduced with permission of Rojkind Arquitectos)

This project shows that digital design is available not only to wealthy clients, but also to ordinary ones. Indeed the most compelling aspect of this work is the way the architects translated complex geometries into simple and understandable drawings and later managed to synergically employ traditional local expertise in metal manufacturing.

4.2.4 Web-Based Platform for a Complex Façade

Crawford Architects—Zahner Factory Expansion, Kansas City

In July 2009 Crawford Architects were hired directly by Zahner, a Kansas City-based internationally acclaimed engineering and metal fabricator, to design their factory expansion. The new building was required to represent the engineering and metal fabrication services provided by Zahner Factory, making it a showcase of their metalworking capabilities (Loria 2012).

The project focused on creating an additional space for the existing Zahner Factory and renovating the underutilized plot area. The new expansion building is characterized by a steel façade system that demonstrates high-level technological innovations developed by Zahner and becomes the physical manifesto of the company's capabilities and qualities (Fig. 4.12). The building façade is realized through custom-made aluminum panels designed with the latest developed software and wrought with Computer Numerically Controlled machines. The intervention was designed to host an additional assembling workspace for the factory, and therefore required adequate height so that the workers could move material without obstructions and employ, when needed, two large bridge cranes. The design of the

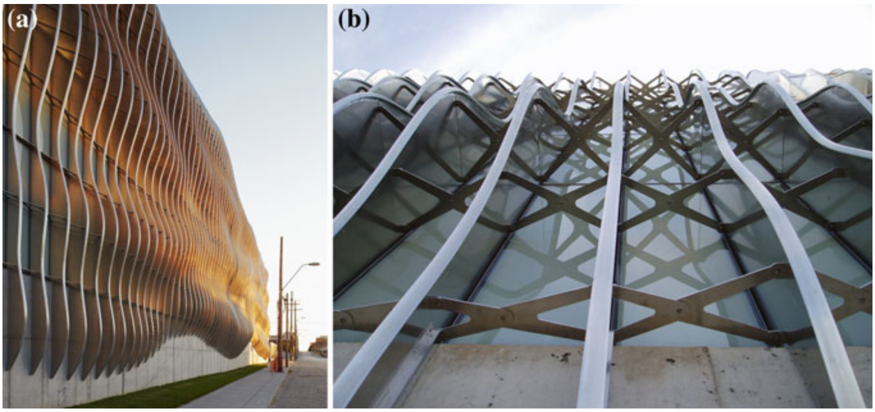


Fig. 4.12 **a** Zahner Factory facade, exposing the metal engineering capabilities of the client (Reproduced with permission of Crawford Architects, Courtesy of © Mike Sinclair). **b** Facade detail, showing the undulating steel components and the glass elements (Reproduced with permission of Crawford Architects, Courtesy of © Mike Sinclair)

façade is based on the idea of using a set of Zahner metal sheets for the exterior skin of the building. In particular, the design team focused on employing "DT" fins directly on the new building which are commonly used as a structural backup system behind many of Zahner's organic façades (Zahner 2012).

Crawford Architects took nature as inspiration by studying the geometrical shapes of ripples in the sand in shallow water. The final shape of the exterior is characterized by a growing form obtained through a sweeping motion that enhances the aesthetic complexity. This dynamic element assumes even a metaphoric meaning as a link between art and science in the surrounding urban environment,

> paying also the tribute to both Zahner's past and future (Crawford Architects 2014).

As its materiality represents the company's innovations and products, the façade's dynamic aspect refers to Zahner's ability to continually improve its technological and engineering system. The new façade is characterized by a sophisticated construction system. For this reason Crawford Architects used a computer-based algorithm to realize a three-dimensional digital model. 3D modelling software was essential to develop the façade system as it allowed the extraction of technical information and shop drawings for the construction phase. Furthermore, specific information such as structural loads and technical details were also obtained from the 3D model. In parallel, the design team worked with several iterations of physical models and mock-ups to find the optimal and appropriate form for the façade system. Within this project Zahner started to develop and experiment with new software called ShopFloor—a web-based platform providing an intuitive tool for the designers to manage complex buildings (Fig. 4.13). The system also gives information about production and pricing, and the software output can be pre-engineered and fabricated by Zahner. ShopFloor was released to the public as a beta product in January 2014 and constitutes the first application developed by the metal factory, available to the public.

Fig. 4.13 The new software ShopFloor™ developed by Zahner within this project is a web-based platform providing an intuitive tool for the designers to manage complex buildings (© 2014 Zahner)

> We have built a tool that uses our factory floor like a massive rapid prototype machine,

says CEO/President Bill Zahner.

> You see the price, you manipulate your design, and we build it. This model has never been applied to architecture (Zahner 2013).

In this sense, designers can exploit the potentialities of 3D modelling software, with the advantage to see the price changing according to the modifications of their three-dimensional model. A factory engineer, Craig Long, affirms

> With our tool, everything you design is quantifiably buildable (…) So we thought, what happens when a designer can see the cost of a façade? It is that missing piece of the puzzle. For the designer, it is knowledge, and it is power (Zahner 2013).

Sophisticated software such as CATIA was employed throughout the fabrication phase, to produce each of the individual vertical fins of the façade system. Considering its articulated and curvy shape, a varying amplitude of the waves that constitutes the whole form was needed to be coordinated with the structural capabilities of the "DT" members. Zahner's "DT" shape comprises a cut flat aluminum plate fixed to an extruded aluminum, which is "D" shaped. The "D" shape is ribbed to allow metal panels to be fastened at any angle to the structural member. The façade of the building was realized in duly wrought aluminum panels and glass elements between the metal fins (Fig. 4.14). The glass addition modifies the principle of a solid metal surface into transparent elements, able to control the natural light.

Considering the project through all of its phases, several aspects could have relevant potential in the future, particularly, the ShopFloor software developed within the design phase. The idea of a 3D modelling software that allows the designer to modify his project according to the price is undoubtedly a revolution, especially regarding the role of the architect, which with new technological frontiers

Fig. 4.14 **a** Façade aluminum components, installation (Reproduced with permission of Crawford Architects). **b** Façade glass components, installation (Reproduced with permission of Crawford Architects)

is more often assuming the competences of both builder and producer. The Zahner Factory Expansion is proving how a balanced combination of advanced technologies, qualified competences and dedicated digital software leads to economically efficient customized components for architecture (Zahner 2013).

4.2.5 BIM Platform to Tailored Skin Production

Gehry Partners, LLP—New York by Gehry (NYbG), New York

Measuring more than 265 m in height, the NYbG Tower at 8th Spring Street is the tallest residential building in North America. Designed by Gehry Partners, LLP, the building's sculptural façade gives a sense of continuous movement resembling the surrounding ocean rippled by the wind and, thanks to this, always offers different views to the occupant (Fig. 4.15). The skyscraper was designed and constructed using Building Information Modeling (BIM) which supported all the critical construction information that enabled an automated design-to-fabrication process. The project is an excellent example of how BIM is revolutionizing the building industry and streamlining quality and resources.

The NYbG Tower stands on an area of about 4,000 m^2 and, compared to the former site design, minimizes the building footprint with 30 % of the site dedicated to urban plazas with pedestrian spaces on both the east and west sides of the building. The various outdoor amenities are also located here, including the landscaping, water features and public seating areas. Hosting about 900 high-end units, the T-shaped tower is predominantly residential despite the lower stories which host a public city school and office spaces for the New York Downtown Hospital. This

Fig. 4.15 NYbG tower is a new landmark on Lower Manhattan's skyline (© Lester Ali)

simple five-story brick basement links the upper exceeding tower to the minor scale of the surrounding buildings. The development of the form began by using the classical proportions of the New York City towers and the traditional setback rules which are the origins of the typical “wedding cake” designs in the city. These guidelines created the initial volume of the tower, but since the owner’s request was to have bay windows in each residential unit, Gehry inserted them in his own way. Instead of aligning the bay windows vertically, the architect moved them slightly from floor to floor and varied them from unit to unit. In this way ripples were created and then emphasized on the seven sides of the building, leaving only the south side (the top of the T) as a flat plane. Due to this design decision, each floor plate is different from the other and the slab edges are in a different plane on every floor.

The main design, construction and economic efforts were focused on the undulating façade which is made up of 7,700 unique curtain wall units comprising a total of 39,737 m^2. Gehry Partners developed the external surfaces and the wire-frame for the curtain wall units in collaboration with the contractor, Permasteelisa Group. Apartments’ sizes vary from 41 m^2 studios to 158 m^2 three-bedroom flats at the top of the tower where a swimming pool and other amenities at the occupants’ disposal are located. All residential units are provided with natural light and natural ventilation to minimize the demands on artificial ventilation and lighting, which is naturally provided in 75 % of the building’s residential corridors. Work was completed in 2010.

The tower was designed using “Digital Project”, a software developed by Gehry Technologies after many years of experience on huge data management in complex building planning. This software is a web-based file management and BIM collaboration platform that helps in sharing and synchronizing project information virtually, regardless of the location or the local time of the user. “Digital Project” enables cost and fabrication information to be automatically produced for every design iteration, which allowed the team to optimize the design quality while continually meeting the client’s budget. Since the platform supports a wide range of model types, the different software used by the various design experts and subcontractors did not present a problem. Throughout the design process, the building programme changed (from the initial plan of a condominium to the final solution of rental units) producing more than 100 different variations of the building model, a dozen of which arrived to shop drawings. In addition, the tower’s exterior façade was completely documented in a 3D computer model, elaborated by Gehry Technologies, providing a platform for close collaboration between the owner, the architect and the curtain wall fabricator. As the project progressed, the 3D modeling software was instrumental in the fabrication of the façade panels. The undulating curtain wall was rationalized into three types of geometries—standard flat panels, moderately shaped panels, and highly shaped panels.

The contractor, Permasteelisa Group, used the model’s dimensions and geometries to price the curtain wall units while the design was being finalized. Once the shop drawings were produced automatically from the digital model, Permasteelisa connected them directly to the production machinery, downloading the geometry of each panel to produce CNC data and drive the manufacturing process (Carr 2011).

Fig. 4.16 Exact placement of 14,000 brackets of the curtain wall on the slab edges was required (Reproduced with permission of Permasteelisa Group)

Specifically, they used CATIA for designing and SolidWorks to send the drawings directly to the CNC machines (Minutillo 2010). The accuracy of the model also enabled the project team to precisely model and coordinate all the concrete slab edges and the fixtures required for installation, including approximately 14,000 aluminum brackets, embedded in the slabs, from which the curtain wall panels would hang. Therefore, the slabs' shape depended on the development of the façade and each floor was completed in about five working days (Fig. 4.16).

NYbG Tower is a reinforced concrete building: the structure is composed of cast-in-place concrete floors supported by reinforced concrete columns and shear walls. The lateral wind and seismic resisting system is composed of reinforced concrete shear walls that are all arranged around the central core, thus offering the architect freedom in the interior design. In order to simplify the formwork, columns were designed and constructed to stay in the same plane for about every 8–12 floors. The curtain wall was chosen to be a cell system, which is something rare in residential buildings, as traditional panels are opaque and the frames are included within. In this case, the cell system allowed the assemblage of the cladding without external scaffolding and with greater precision since the panels are fixed to the structural slabs through brackets embedded in the concrete. The cells are made up

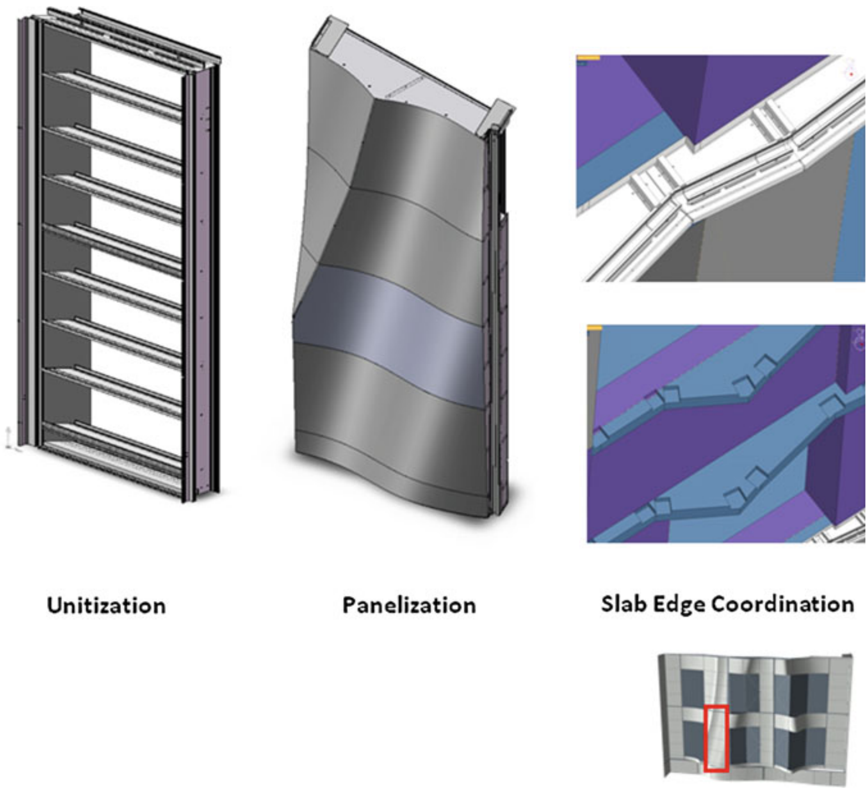


Fig. 4.17 Gehry Partners (GP) developed a concept for a flat, unitized curtain wall with a back-ventilated rain-screen cladding attached to its front (Reproduced with permission of Permasteelisa Group)

of a steel structure to which the external cold-formed panels are fixed (Fig. 4.17). A conventional curtain wall requires the units to be aligned in order to achieve an air and water tight barrier, but in NYbG Tower this was not possible due to the slight offset of each unit from the one below. By sharing knowledge and experience on similar non-ordinary projects, the contractor designed a two-piece gutter system that satisfied unit offsets up to 38 cm (15 in.).

The tight collaboration between the architect and the contractor, supported with a full BIM implementation, made managing the project complexity possible, and the realization of a tailor made façade system built with cost-savings in mind in a controlled time frame (Fig. 4.18). Thanks to the coordination from the design process until the final fabrication, there were zero change orders from the contractor on the curtain wall, which is not always granted in highly complex buildings like this (Shelden and Kashyap 2012).

Fig. 4.18 Mockup of the cladding system (Reproduced with permission of Gehry Partners, LPP) Gehry Partners, LLP

4.2.6 Material Customization

ITKE University of Stuttgart—Arboskin, Stuttgart

The Arboskin research project has been developed by the University of Stuttgart ITKE (Institute of Building Structures and Structural Design) in 2011 and received the German 2013/2014 award in "Landmarks in the Land of Ideas" as one of the most innovative projects in the science category.

Employing thermoformed sheets of bioplastics, researchers at the University of Stuttgart ITKE developed the Arboskin project and built the first fully recyclable, fire-retardant, high-strength pavilion. The pavilion was designed with the aim to explore the application of bioplastic materials in the architecture and construction fields. Coherently with the German University's experience in studying computational design, Arboskin is a significant sample of computationally-based research projects that experiments with the use of new materials in architectural façades (Fig. 4.19). The doubly curved skin of the pavilion is realized with bioplastic pyramidal components that are mechanically assembled to create the free-form structure, demonstrating how the combination of sustainable materials and complex geometries are achievable through the application of new technologies. With its experiments on the

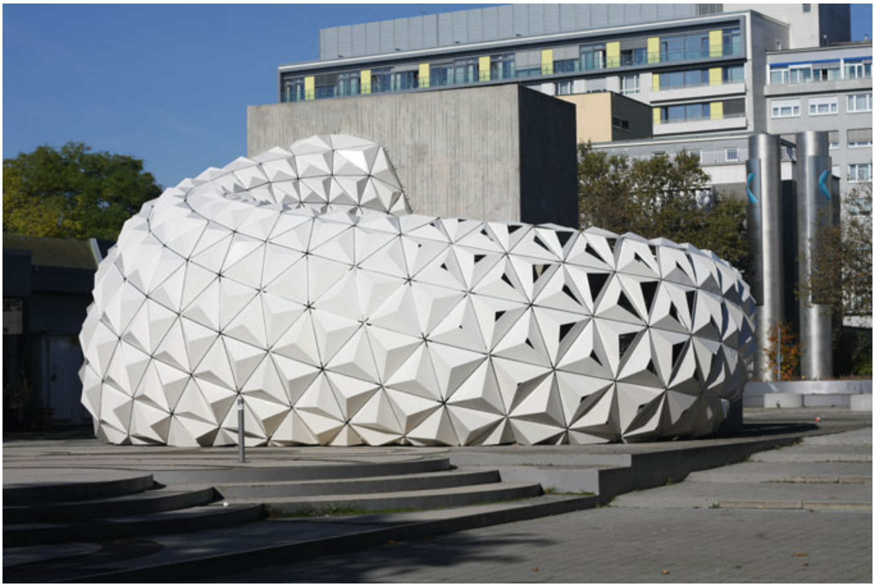


Fig. 4.19 Arboskin Pavilion built with bioblastic components (Reproduced with permission of ITKE, Courtesy of Manfred Richard Hammer)

potential of natural resource materials for architectural application, it is pertinent to interpret this kind of research as a test on “material customization”.

The pavilion was developed within the framework of a Research Project Bioplastic façade—a project supported by EFRE (Europäischer Fonds für Regionale Entwicklung/European Fund for Regional Development). As the material composition is the central interest of the research, the ecological aspect clearly plays a fundamental role in the aim of reducing petroleum-based and additive components. In order to obtain this result, different experts have been involved in exploring a new thermoformable bioplastic material that would characterize the project and could be applied in the future to any architectural cladding surface. The pavilion structure is characterized by a complex geometry and a shell structure based on a system of 388 bioplastic pyramids of different dimensions (Fig. 4.20). The project exploits the structural properties of the material, testing its potential for future applications (Griffiths 2013).

With the aim to define the desired shape, its geometrical characteristics and opening pattern, parametric software has played a fundamental role. The computational tools were further exploited to extract shop drawings and geometrical information for both the fabrication and assembling processes (Fig. 4.21). The bioplastic material used in the pavilion can be defined as a customized material, as it has been produced by the German company, Tecnaro, according to the specific requirements needed for the pavilion mainly focusing on the concept of recycling. The material is called Arboblend and it has been studied also by the Institute for Water Engineering, Water Quality and Waste Management ISWA, a project partner.

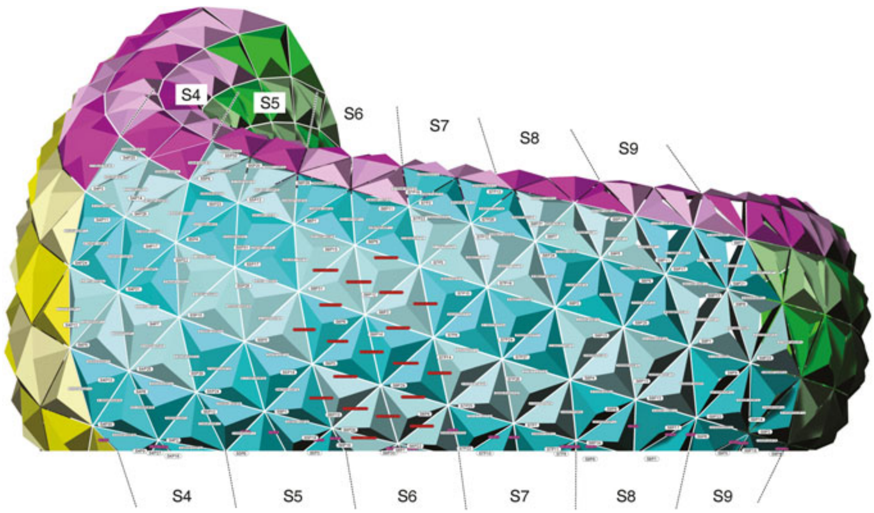


Fig. 4.20 Arboskin Pavilion was developed through the use of 3D software that allows to extract specific information about the bioplastic components (Reproduced with permission of ITKE, Courtesy of Manfred Richard Hammer)

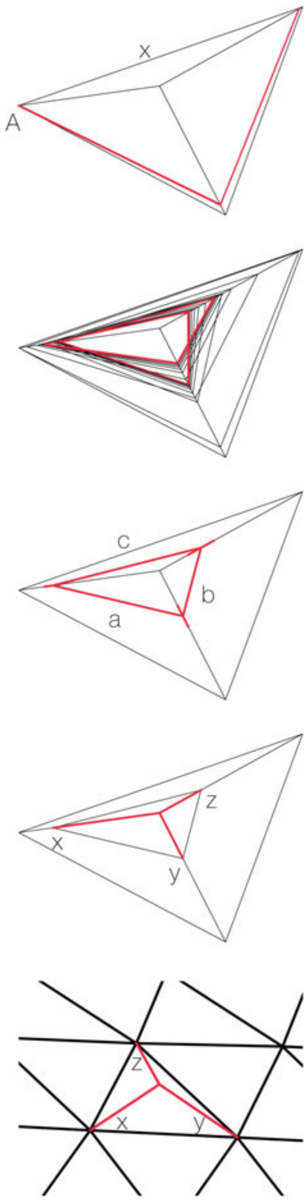
The pavilion has a structure made of a metal welded mesh that supports the pyramidal elements obtained through thermoformed bioplastic sheets. Most of the materials employed in Arboskin are renewable and produced by natural resources, thus promoting the petroleum derivative reduction. Usually bioplastics are obtained from renewable biomass resources and they are often defined as biodegradable. Considering several applications, biopolymers are valid alternatives to plastics derived from fossil fuels. In this specific case, the design team tested the material in order to confirm its resistance to microbial degradation. The new material provides an optimal and environment-friendly solution to obtain semi-finished products that could be employed in any cladding for flat or free-formed surfaces, for both interior and exterior applications, providing good structural performance as well.

The pavilion skin could be defined as a non-load-bearing façade, but, as the Arboskin design team states,

> contrary to common non-load-bearing façade constructions, this construction involves the load-bearing properties of the double curved skin […]. On the one hand, this innovative measure shows the potential of modified bioplastics as a bracing material (up to $E \approx 4{,}000\ N/mm^2$) suitable for exterior applications as it adds only a minor load due to its own weight ($13\ kN/m^3$); on the other hand, it allows for the construction of a façade that utilizes a minimized number of points of support and/or mounting brackets on the structural work behind it (Knippers 2013).

Arboblend is therefore an innovative recyclable material that satisfies the requirements for durability, stability and inflammability standards for buildings. The doubly curved skin is realized with 3.5 mm thick bioplastic elements that are mechanically assembled through bracing rings and joints. The components

Fig. 4.21 Development of the pyramidal skin components (Reproduced with permission of ITKE, Courtesy of Manfred Richard Hammer)



employed in Arboskin were produced from bioplastic granules extruded into sheets that can be later wrought through laser cutting, CNC milling, drilling, printing, laminating or thermoforming processes (Fig. 4.22). The extrusion process of the Arboblend sheets was deployed in collaboration with Bauer Thermoforming. Once extruded the bioplastic elements were formed under high temperatures.

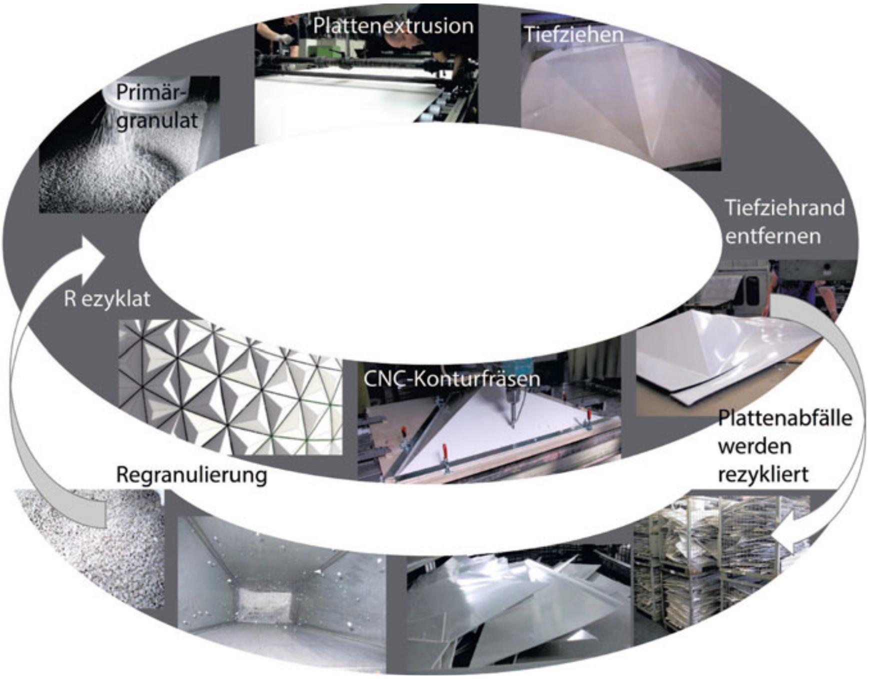


Fig. 4.22 The cycle of production and recycling of the bioplastic components (Reproduced with permission of ITKE, Courtesy of Manfred Richard Hammer)

This process allows any desired shape and geometry to be obtained for the components, providing an innovative solution for contemporary architecture tendencies that go through complex forms. The waste material from the thermoforming process was re-used in the production process. After forming the bioplastic elements into molded components, a CNC milling machine is used to remove sections from the pyramidal components and to create a pattern of openings on the pavilion surface. The pyramidal components of the pavilion were then fixed to the supporting metallic mesh and assembled together. At the very end of their life-cycle the sheets of the façade components can be disposed into nearly carbon-neutral substances.

Considering that the experimented bioplastic components can be shaped to be applied to any building exterior or interior, the pavilion constitutes a driving example for a sustainable cladding system. Thermoformable bioplastic is a considerable alternative for the future as it maintains the ductility and recyclability of the plastic polymers, offering the additional advantages of being a material derived from renewable resources.

4.3 Structural Applications

In this section several experimental projects that address the structural system are illustrated. Tailoring structural systems is one of the biggest challenges in the construction sector since regulations and safety impose standardization either in materials and construction techniques or in calculus procedures. However, in the last few years, several research studies are attempting to study innovative structural systems, assisted by the evolution of computational software that is allowing complex mechanical analysis, and consequently opening unveiled research directions. In this section several different approaches are described that address the customization of structures from software optimization to custom-made components.

Shape optimization with bespoke in-house software tools defines the Shenzhen Bao'an International Airport by Fuksas, and in particular, highlights how large-scale, free-form architecture can nowadays be optimized significantly with custom software tools, and consequently be assembled in a relatively short time, despite construction complexity.

3D Printed Nodes Shroud illustrates an interesting potential for 3D printing in structural applications. In the 6, Bevis Mark project by Fletcher Priest Architects, joint sheaths are realized in order to create smooth transitions among structural profiles. This is claimed to be the first actual application of 3D printing for a real building component, and reveals several interesting aspects of additive manufacturing: tailored joints can enlarge the aesthetic catalogue of solutions of typical steel profiles, which can nowadays be organically connected.

Non-standard 3D printed bricks describes an experimental project that deals with ceramic 3D printed bricks, as well as a range of block solutions tuned according to several performative parameters which tell us how construction components can be specifically designed and realized according to different needs, overcoming the "design-by-catalogue" approach to technological systems. The project is Building Bytes by Brian Peters.

3D Printing research-by-doing shows the first experimental attempt to realize a fully 3D printed house. The 3D Print Canal House by DUS Architects is not only a demonstration of printing experiments on different techniques and materials but also a research center showcasing new-generation open source technologies.

4.3.1 3D Printed Nodes Shroud

Fletcher Priest Architects—6, Bevis Marks, London

6, Bevis Marks has been designed by Fletcher Priest Architects of London and began in August 2008. The mixed-use building is located at 6, Bevis Marks in the City of London, and was commissioned by AXA, Wells Fargo, BlackRock and CORE with main contractor the construction firm Skanska. The project is an integration of the 1980s structure present on the site, providing nine additional floors and three private terraces, including a sky court on the roof. Significantly interesting in this intervention is the application of additive manufacturing for the structural system. As the roof is characterized by a steel canopy framework supported by branched columns, one of the challenges of the project was to design and produce a technological solution characterized by geometrical continuity.

Within the city of London where historical traces and modern presences coexist the design is based on the idea of celebrating the "old" and the "new". As a matter of fact the project deals with contemporary technologies, form and materials without rejecting the link with the existing context. One of the driving ideas of the project is the connectivity in both metaphorical and physical sense. Streets and outdoors spaces of the existing context are reconnected through the new intervention, which provides an additional pedestrian bridge and that creates new shortcuts and sidewalks, referring to the tradition of London. The façade creates a connection between the adjacent buildings relating the project to the existing context. The intervention focuses on the role of open space and doubles the previous public space: the roof terrace is undoubtedly the most recognizable element of the building, providing the visitors with spectacular views of London. The rooftop assumes both a symbolic and functional role with its covered garden, creating a link with the open terrace garden and the levels below. At the same time it defines the south façade of the building architecturally as well as, providing a proper solar shading to the South–West elevation. From a programmatic point of view, the roof canopy covers an enclosed pavilion, connecting it to the external terrace and allowing different uses for the building inhabitants.

The roof terrace is characterized by a steel structure of branched columns, that supports a lightweight canopy made of ETFE pneumatic cushions fixed to a continuous system adapting itself to the underlying supporting structure. The ETFE components are composed of a double layering of Texlon: one of the layers is transparent while the other is printed with a 3 mm silver dot pattern to limit the solar incidence for the pavilion building below. Considering the role of new technologies in architecture, the principle of customization that stands behind the roof canopy is particularly interesting. A series of 3D printed sheaths were designed to surround the structural joints that connect the steel columns and the respective branches supporting the ETFE canopy (Fig. 4.23). The structural constraints deriving from the existing building determined a specific design for each structural joint of the roof, requiring a unique and rigorous form finding process to achieve an elegant structural solution that is coherent and integrated with the design language of the building (Fletcher Priest Architects 2012).

6, Bevis Marks' design was driven by the use of 3D modeling software throughout the whole process, involving both the design and the construction phases. Indeed, 3D modelling was exploited to achieve the desired quality for the roof system: starting from the structure and the patterning of the ETFE pillows to the design and production of the nodes between the columns and the canopy. With the aim to reach the desired aesthetic specifications for the rooftop joints, several manufacturers and fabricators have been involved in the project. Starting from the intent of a traditional process of steel casting, the use of 3D printing technology was

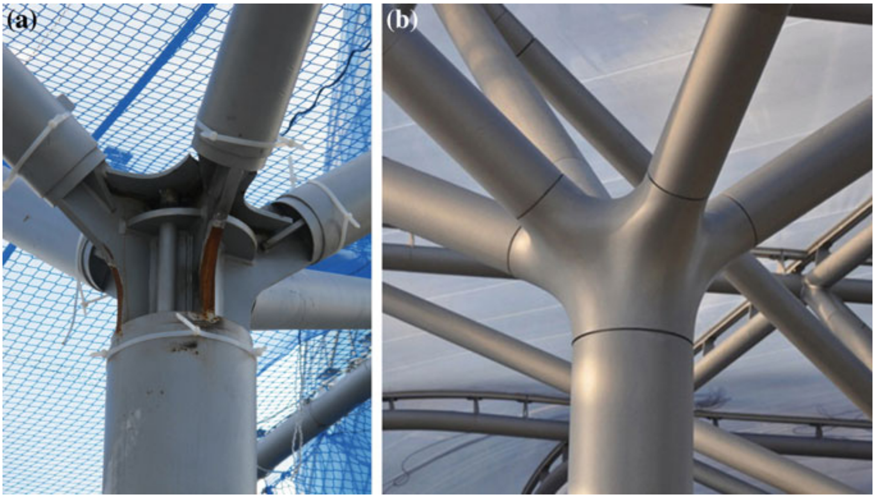


Fig. 4.23 **a** Rooftop steel column joints: the *picture* shows the structural node joint without covering the sheaths (Reproduced with permission of Fletcher Priest Architects). **b** Rooftop steel column joints covered with the 3D printed polyamide sheaths (Vector Foiltec)

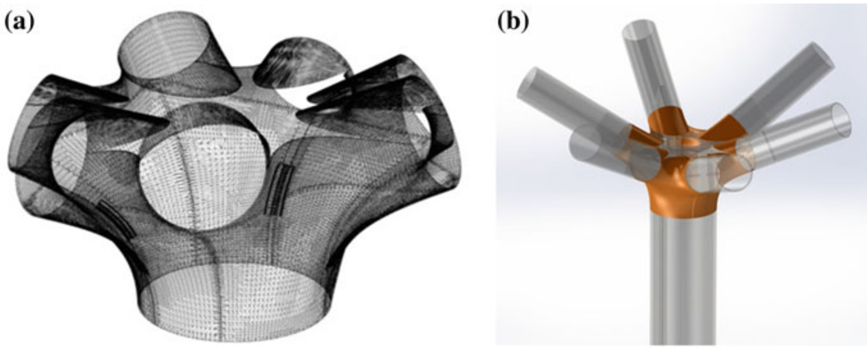


Fig. 4.24 **a** Digital model of the sheath for the structural joints (Vector Foiltec). **b** Digital model of the system integrating columns with the 3D printed shroud for the structural joints (Vector Foiltec)

considered as it offered optimization in terms of time and cost. 3D modeling was employed to simulate the complex and organic shape of the joint sheaths and to extract the required information later transferred to the printing machine (Fig. 4.24). The idea of mass-produced customized sheaths constituted an innovative and optimal solution to coherently integrate the structural elements with the building design language. Furthermore, the production process allowed to fabricate the components at more affordable prices in respect to the traditional methods (Fletcher Priest Architects 2012).

To achieve a satisfactory solution, an iterative process alternating digital and physical simulations was adopted: during the design phase mock-ups were developed in order to inspect the aesthetics of the elements and to ensure a smooth construction process on site. The sheaths fabrication was realized by Selective Laser Sintering (SLS) employing polyamide 12 as a material to produce the joint covering components. This material is a specific type of nylon particularly suitable for exterior application as it is resistant to ultraviolet radiation and offers filtering properties. It is able to absorb moisture and gain strength over time even if it needs to be waterproof before being used for outdoors. In this case, the 3D printing machine size constituted a limitation as the nodes needed to be printed in sections before being applied to cover the canopy joints. As the mesh definition of the element needed to be subdivided into several parts, the 3D model was further employed to identify the precise sections before printing them. The components fabricated with polyamide were assembled together in the factory, in order to avoid mistakes on the site, and later were mechanically fixed to the steel structure of the rooftop. The printed sheaths are composed of a double 3D printed layering to reinforce the joints and to avoid collapsing or cracking.

This case represents a concrete and feasible solution to provide specific architectural language and technological performance with the potentiality enabled by the emerging additive manufacturing process.

4.3.2 Bespoke In-house Optimization Tools

Massimiliano e Doriana Fuksas—Shenzhen Bao'an International Airport, Shenzhen

Located in the southern Chinese region of Guangdong, Shenzhen is one of the fastest growing cities in the world and has the fourth largest airport in China following Beijing, Shanghai and Guangzhou. Thus, replacing the already "old" 2002 structures with a new airport extension was of critical importance for the city and the surrounding region as a booming business and tourist destination. In 2008, Massimiliano and Doriana Fuksas won the international competition for the expansion of the airport with a third terminal, which would increase the capacity by 58 %, allowing the airport to handle up to 45 million passengers per year (Williams 2014).

Bao'an International Airports new terminal evokes the image of a manta ray wrapped in a honeycomb double skin, and with its 300,000 m^2 three-dimensional folded façade it is one of the largest parametrically defined buildings in the world. It has been built in only 3 years, completed in November 2013, following a rapid design process (Fig. 4.25).

Accustomed to deal with large and complex projects, the Rome-based architects had a clear key purpose: controlling the huge scale of the building in order to keep comfortable and livable the ambiences while building a landmark for the territory giving a discernible unity to the overall design. The "manta ray" terminal is vast

Fig. 4.25 The manta ray terminal is 500,000 m^2 vast, 1,250 m long and 642 m wide (© Leonardo Finotti)

500,000 m^2, 1,250 m long and 642 m wide. From the entrance located under the large “tail” passengers access the terminal where white conical supporting columns rise up to the roof. On the ground floor, luggage, departure and arrival areas are located, as well as coffee houses and restaurants, offices and business facilities. The double and triple height spaces of the departure areas establish a visual connection between the internal levels, allowing natural light to filter through.

The whole building is characterized strongly by the internal and external double skin that wraps the structure: thanks to its double layering the skin allows natural light to enter, thus creating light effects within the internal spaces (Fig. 4.26). The cladding is made of alveolus-shaped metal and glass panels of different sizes that can be partially opened. The same honeycomb motif is transferred and replicated in the interior design which Doriana and Massimiliano Fuksas designed with a sober profile: shop boxes reproduce the alveolus design on a larger scale and recur in different articulations along the concourse, while a stainless steel finish reflects and multiplies the motif of the internal “skin”. Sculptural objects—big stylized white trees—have been designed to supply air conditioning all along the terminal and the concourse replicating the planning of amorphous forms inspired by nature. This is also the case for the baggage-claim and info-point “islands” (Fuksas 2013).

It is well known that the ideal condition during the design process is the full cooperation between engineers and architects to work together from the very beginning. This is even more relevant today for projects with complex geometries

Fig. 4.26 The interior is strongly characterized by the dynamism of the punctured tube which acts as walls and roof (Courtesy of © Archivio Fuksas)

because programming and code development are an important part of architectural design and engineering.

In this case, however, when the structural engineers began to work, the organic shape of the airport was already established by Massimiliano and Doriana Fuksas. Given its complexity and formal quality, optimizing the overall shape was nearly impossible: minor adjustments to the form only led to slight decreases in the total amount of steel used. This approach, called "fixed-shape approach", has the advantage of keeping the architect completely free in his creativity as structural efficiency and production abilities come second.

The main challenge for the architects and the structural engineers has been the geometrical development of the steel structure and the façade:

> The generation of the façade and roof elements of the Shenzhen Bao'an International Airport, has been automated with bespoke in-house software tools. This enabled to generate a double truss structure over a given free-form surface, including the above mentioned aspects of sustainability, day light control, energy gain and architectural design intends were influencing the final design which required several adjustments of façade layout. The only possible way to deal with this kind of task is to parametrically define the entire structure so that with each change of the form all elements can be generated within hours, or even minutes (Scheible and Dimcic 2014).

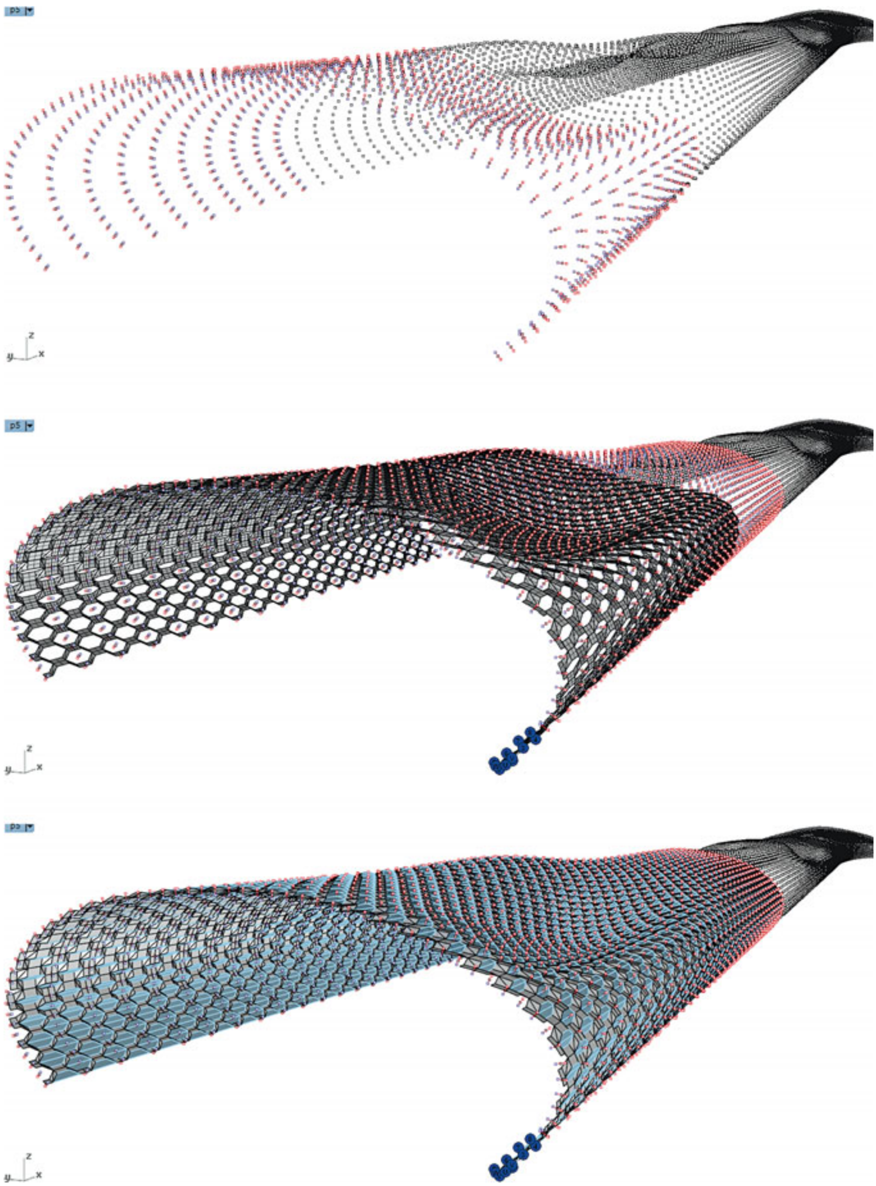


Fig. 4.27 Parametric definition of the façade geometry (Courtesy of © Archivio Fuksas)

The initial modelling surface was firstly described with a point cloud. The points were arranged in four layers: the two inner layers served as the basis for a double-layered grid structure while the two outer layers for the generation of façade elements (Fig. 4.27).

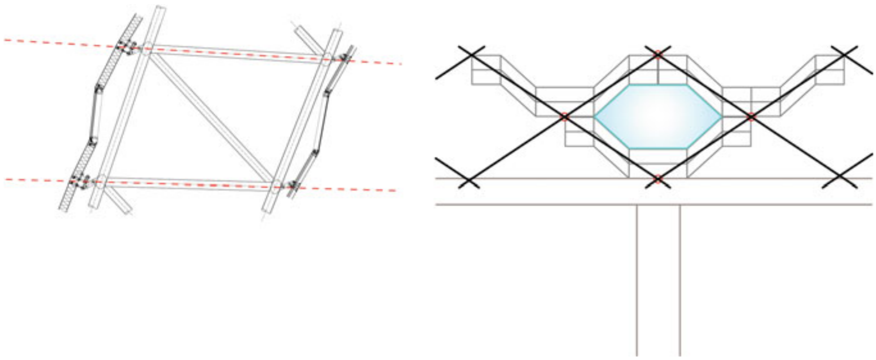


Fig. 4.28 Structure of the façade system (Courtesy of © Archivio Fuksas)

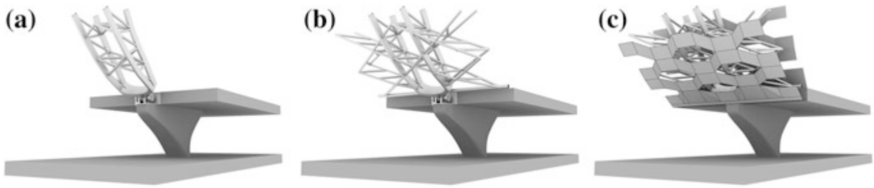


Fig. 4.29 The bearing point: concrete bracing with the structural arches (a), the reticular wall (b) and the double skin (c) (Courtesy of © Archivio Fuksas)

The surface was unrolled so that the façade elements could be represented in an Excel spread sheet: since there were 20 different types of façade panels (with different angles and openings), architects simply had to fill the spread sheet with different colors and numbers corresponding to the different elements (Fig. 4.28). The software written for this purpose was able to extract the information from the Excel file, generate appropriate façade elements on the desired sector and fix all problems that arose in the process. Fixing problems refers to the adjustment of the connections between different elements and automated geometry perturbations performed in order to always keep the glass element of the façade planar—which was one of the main conditions and one of the biggest challenges, considering the double curvature of the surface and the complexity of the elements (Scheible and Dimcic 2014).

In Shenzhen Bao'an International Airport the structure is an integral part of the multilayered and multi-functional building envelope: walls and roof create a continuous tube shaped form and due to the geometrical complexity and restraints all structural components are proposed to be built by steel (Fig. 4.29). This decision was made taking in consideration the wide experience already gained by the

Fig. 4.30 The steel structure before installation of the inner skin (Courtesy of © Archivio Fuksas)

Chinese steel industry in constructing highly complex projects, such as the Bird's nest and Watercube in Beijing for the Olympic Games and the Expo Boulevard in Shanghai for The Expo.

The roof structure consists of a spatial framework with varying heights between the lower and upper chord level, wide enough to allow access by maintenance workers. The outer layer is made of flat panels of metal and glass: the weatherproofing, the sound and thermal insulation embodied in the outer skin serve as a barrier to aviation noises and excessive thermal exchange, while the high-performance glazing units reduce solar heat gain during the summer. The parallel inner layer is a three-dimensional lattice of folded metal pieces forming hexagonal openings which improve ventilation and pull warm air away from the people in the building—a critical factor in the hot climate typical of Shenzhen. The inside skin acts as a frame for services distributions, but also employs reflection and shading patterns to reduce the visual impact and shield the interior from excessive solar heat gain, while providing daylight to the main hall and concourse area (Fig. 4.30). Aesthetically, the three-dimensional nature of the openings offers different views depending on the position of the visitor. Shenzhen Bao'an International Airport shows how integrating different software enables an efficient cooperation between architects, designers and engineers.

4.3.3 Non-standard 3D Printed Bricks

Brian Peters—Building Bytes, Amsterdam

The Building Bytes research project was developed in the autumn of 2012 by Brian Peters (DesignLab Workshop), professor at the College of Architecture and Environmental Design at Kent State University in Kent, Ohio, USA. This project investigates the potential of 3D printing technology in architecture, in particular studying a traditional construction component, the brick, re-invented as a product of the available contemporary manufacturing technologies. Potential applications include interior partitions, façade components or structural elements (Fig. 4.31). The design team developed the concept of 3D printed brick-like components by testing different characteristics and applications and demonstrating above all how they can perform as structural elements (Figs. 4.32 and 4.33). Recently, several projects have been focusing on the potentials of large-scale 3D printing. In contrast, Building Bytes researches in the opposite direction towards the use of small-scale, economically accessible printers (Peters 2012).

Building Bytes is focusing on the idea of non-standard construction blocks, customized with variable characteristics and shapes. The research conducted explores how to differentiate ceramic brick forms with interlocking joints and inconstant three-dimensional profiles. This system allows the potential to incorporate the necessary electrical or mechanical infrastructures within the bricks. Brian Peters designed four different assembling typologies in order to test and demonstrate the advantages of this fabrication system and its employment in both interior and exterior contexts. One of the brick typologies are the Honeycomb Bricks, which are modular and can be combined in different ways and orientations. This type of block can be applied to both interior spaces as well as exterior elements, i.e. for privacy or sun screen walls. Interlocking Bricks, instead, are characterized by internal bracing and interlocking joints that provide stability and allow the assembly of several bricks in a more complex structure, suitable for building large domed structures. Ribbed Bricks are instead conceived for columns, with a vertical sequence of prototypical bricks characterized by an outer surface that is both structural and ornamental. The last typology, X-Bricks, maximizes visual opacity through walls, optimizes material and printing time and explores non-modular construction and assemble creating an undulating surface by using unique blocks per row (Fig. 4.34).

The bricks design has been developed using the parametric design plug-in Grasshopper for Rhinoceros. Here, an algorithmic definition was used to describe a general wall structure, while the individual brick characteristics were obtained as a variation of a predefined set of parameters. The information required for the 3D printing was then directly obtained from the Grasshopper algorithm. Parameters such as exterior skin, interior skin, internal structure and interlocking joint details could be changed or modified through the parametric software and directly transferred to the printing machine. The final script of Grasshopper could be translated into a G-code, which is the programming language read by 3D printers. Thanks to the advantages of the parametric

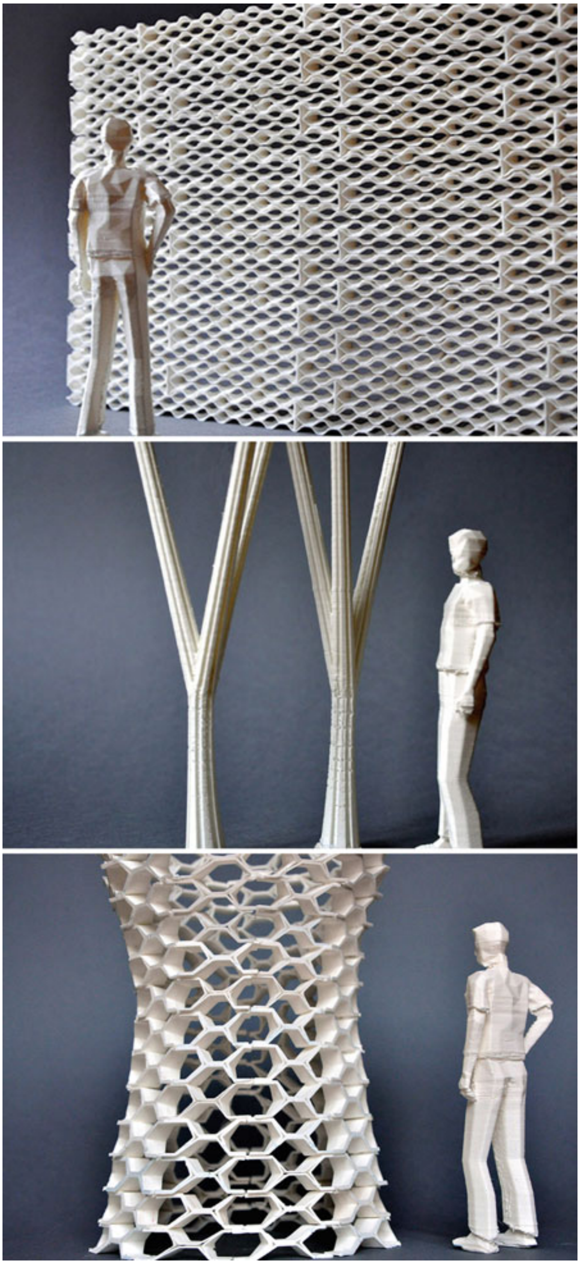


Fig. 4.31 Several applications of 3D printed bricks in *structural* and *vertical* elements. The models show how the printed components can be assembled in a printed wall, branched columns, or a porous partition system (Reproduced with permission of Brian Peters)

software, further information for each single brick could be estimated, such as material cost, printing time and structural data. If the overall structural form needed to be modified, the single bricks would automatically update.

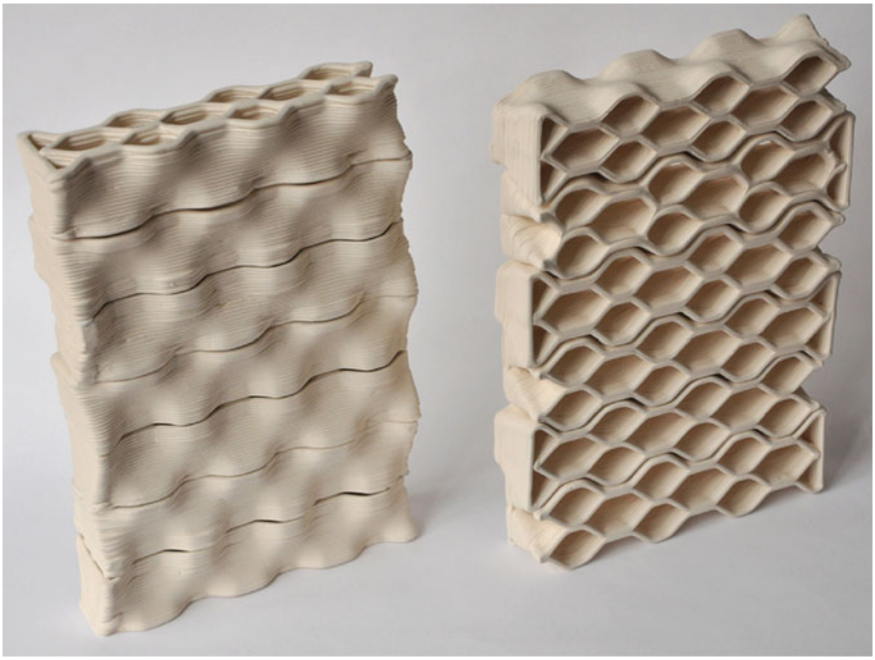


Fig. 4.32 Different orientations of the Honeycomb Bricks produce different results in terms of both geometry and structural performance (Reproduced with permission of Brian Peters)

Fig. 4.33 The Interlocking Bricks assembled in a structural system (Reproduced with permission of Brian Peters)

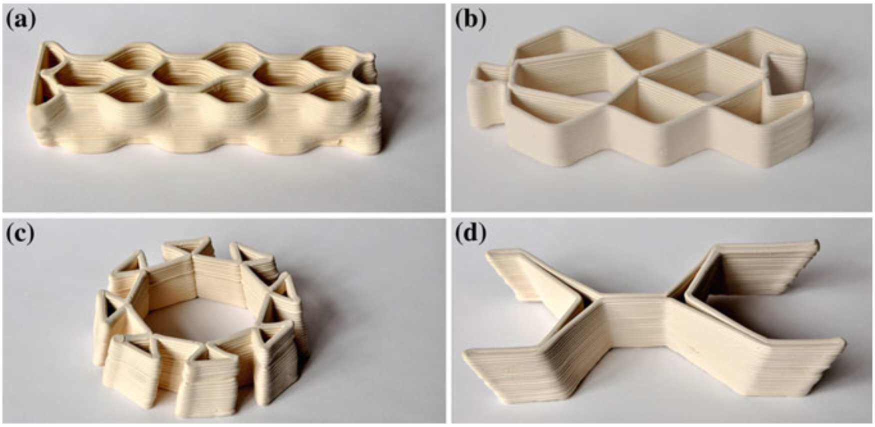


Fig. 4.34 3D printed brick types: **a** Honeycomb Bricks, **b** Interlocking Bricks, **c** Ribbed Bricks, **d** X Bricks (Reproduced with permission of Brian Peters)

Among the various 3D printing techniques currently developed, Building Bytes utilized a desktop Fused Deposition Modeling (FDM) 3D printer. These types of machines are inexpensive and widely available on the market with a relatively small printing size: approximately 20 × 20 × 20 cm. However, within this research the printing dimensions were not considered as a limitation but rather one of the design parameters that characterized the final production. One of the main challenges of the research was the desire to use ceramic materials, which meant the specific configuration of a desktop machine. Focusing on this purpose, the plastic extrusion system, also defined as the "print head" of a standardized 3D printer, was replaced with a bespoke one that worked with air pressure.

Several recipes were tested throughout its execution in order to define the ideal viscosity, drying time and shrinkage of the composite. The final printed material was derived from a cast recipe of earthenware ceramics extruded through the air pressurized "print head". During printing, the required speed for extrusion, related to the air pressure, was constantly monitored to ensure a continuous extrusion process. The printing path followed a series of overlapping layers constituted by a printing path polyline that needed to be continuous and unbroken to ensure structural stability (Fig. 4.35). The printing process lasted about 15–20 min for each brick, and in the end each printed component needed to be air dried for 1 day and then fired in a kiln at 1,100 °C for 12 h.

As the project is highly experimental, it was fundamental to proceed with an iterative process in order to obtain continuous feedback by testing both the physical and digital simulations which informed the final design. According to the designer, specific factors, such as the flow of material, speed of printing, material viscosity, material slump, amount of layer overhang, stability during printing, and layer height were taken into consideration while developing the different physical models. One of the limits faced during the research phase was the viscosity: the bricks tended to collapse throughout the 3D printing process as the material used for the prototypes

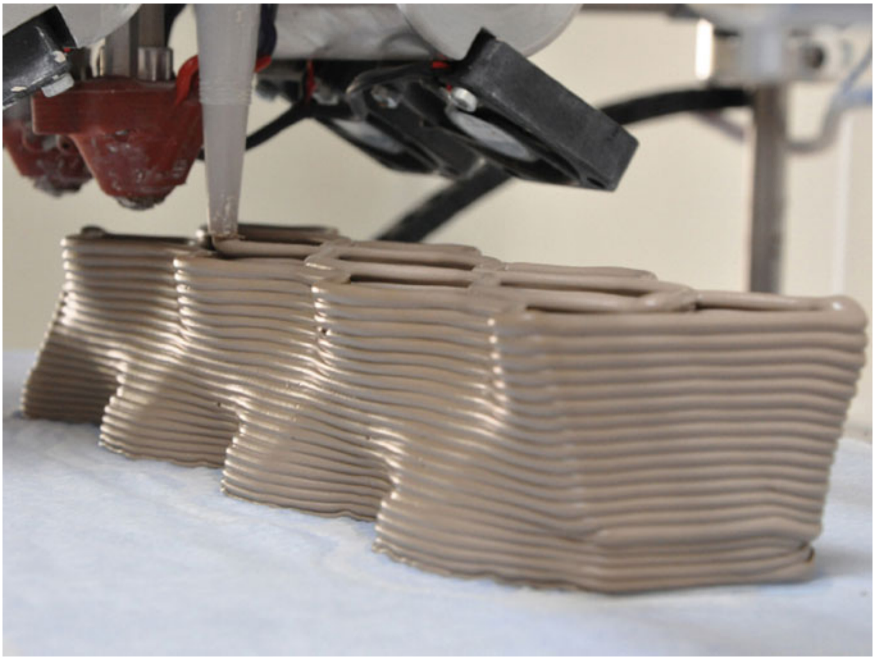


Fig. 4.35 3D printing process: the machine is overlapping layers of ceramic material (Reproduced with permission of Brian Peters)

was unstable. As a matter of fact, the bricks design was reconsidered to enhance the component stability. In order to support the printing process, more articulated forms were developed, including intricate interior patterns and undulating exterior skin patterns.

4.3.4 3D Printing Research-by-Doing

DUS Architects—3D Print Canal House, Amsterdam

The 3D Print Canal House has been developed by the Amsterdam-based architectural firm DUS Architects and has been opened to the public since March 2014. The intent of the designer was to print a full-sized canal house in Amsterdam, with the aim to find new and improved solutions for the additive manufacturing of large structures. One of the driving principles of the project was based on the idea of developing new fabrication processes, techniques and materials, sometimes altering the project design according to new research findings, following a "research-by-doing" approach (DUS Architects 2013).

Fig. 4.36 3D printed components of the 3D Print Canal House, open to visitors (Reproduced with permission of DUS Architects)

The 3D Print Canal House does not simply constitute an experimental building based on 3D printing technology, rather it is an open exposition site, where designers and project partners collaborate to constantly improve the buildings construction. The site opened its doors to the visitors on the first of March 2014, becoming a type of event space, given that the house components are printed directly on-site, employing a purpose-designed printer called KamerMaker (Vinnitskaya 2012) (Fig. 4.36). The house is located in the northern area of Amsterdam, along the Buiksloterkanaal in a developing area of the city, and it works as an open center of architectural research in 3D printing. Indeed, the large-scale 3D printer is placed on the construction site of 3D Print Canal House and every printing process is exhibited to the public. 3D Print Canal House can be considered a continuously evolving exhibition space, where visitors can be informed about the technology employed, the new solutions and techniques experimented, and where they can attend the printing and construction process. The project modifies its own configuration every week according to the newly developed solutions: since it is an ongoing research project, the design is altered according to the printing experiments in terms of both materials and techniques (DUS Architects 2013).

The new printing machine—KamerMaker, literally meaning "room maker", is a large-scale version of a portable desktop 3D printer. It is placed inside a stripped movable shipping container and is the result of a cooperative effort between DUS Architects, Ultimaker and Fablab Protospace, among others (Fig. 4.37). KamerMaker is approximately 6 m high and can print objects as large as $2.2 \times 2.2 \times 3.5$ m^3,

Fig. 4.37 The 3D printed components of the 3D Print Canal House are produced directly on site by the KamerMaker (Reproduced with permission of DUS Architects)

therefore 1:1 scale components are printed and directly employed in the building construction. The 3D Print Canal House has several rooms made up of different elements designed with 3D modelling techniques, printed and assembled on-site. The room parts, as large Lego-like blocks, are firstly printed at 1:20 scale to be tested and verified and later printed at full scale for the assemblage. In this way, the building has the advantage to be easily re-assembled and relocated elsewhere. The printed chunks constituting the 3D Print Canal House contain hollow areas designated for cables, pipes, and wiring, designed to be later filled with a second material for reinforcement and insulation. Regarding the structural aspects, both digital software and physical testing were constantly employed and developed in collaboration with the structural engineers of Tentech. In order to test the supporting properties of the printed components, some elements are shaped with folds, which increase their structural performance. According to the designers' descriptions, both sides of the structural elements are characterized by different patterns, with different shafts and inclinations. The design teams have experimented with supporting elements that develop inclined shafts,

> The new house-pieces we print contain a double layer of shafts, one side running in one direction, the other side in the other direction (DUS Architects 2014),

assuring in this way an improved structural behavior.

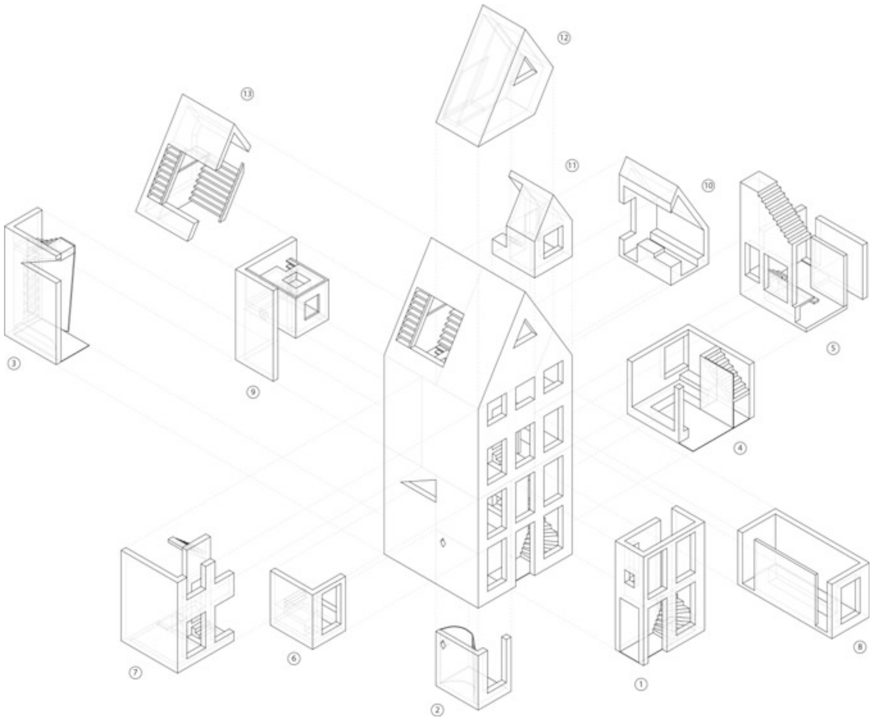


Fig. 4.38 The 3D Print Canal House constitutes an envisioning sample of an entirely customized architecture (Reproduced with permission of DUS Architects)

The use of parametric software is fundamental throughout the research, providing the possibility to rapidly adapt and modify dimensions and design parameters. The material employed for the additive manufacturing is a particular type of plastic, developed by the German chemical firm Henkel, mainly obtained from natural sources, which supports one of the main intents of the architects in using recyclable and sustainable materials, including bioplastics.

As the 3D Print Canal House is an experimental project, the aim of the research is far from simply demonstrating the employment of plastic for future housing construction. At the moment this proved to be the most appropriate material according to the current additive manufacturing developments, but the designers intend to experiment and test a wider range of materials for the printing process (Zimmer 2014). The 3D Print Canal Houses construction is supposed to take about 3 years and is being developed in collaboration with Heijmans, the building partner of the project.

This project experiments with sustainable solutions in printing block components made of recycled materials, in order to significantly reduce waste and transportation costs. Moreover, the building components are conceived in order to be re-combined and re-assembled in other sites (Fig. 4.38). All of these features suggest a promising scenario for the future applications of 3D printing in architecture.

4.4 Interior Interfaces

This section describes various cutting-edge projects that have implications for interior applications. The first set of case studies represents the typical condition of contemporary architecture: continuous spaces which integrate different functional and expressive elements together through the use of different material systems.

Stone fluidity with design interoperability is an outstanding example of spatial fluidity using stone panels, which is the result of a profound integration of competences, made possible by an integrated platform of BIM and parametric software. The reference project is the Louisiana Sports Hall of Fame and Northwest Louisiana History Museum by Trahan Architects.

Wooden Parametric Inflections analyzes One Main Street by dECOI Architects where a sort of interior landscape, parametrically reacting to functional requirements, is discretized through a sequence of unique wooden sections.

Printing unlimited complexity by Michael Hansmeyer and Benjamin Dillenburger—Digital Grotesque, an experimental case of a room-scale 3D printed model which shows the dramatic potential of additive manufacturing for addressing continuous and hyper articulated spaces.

A second group of projects deals with responsive interior interfaces, highlighting an interesting form of customization which is not only limited to physical features, but also regards interactive behaviors of architectural interfaces.

Kinetic electroacoustic ceiling addresses Resonant Chamber, by RVTR, a successful research project that deals with sensing, processing, robotic and electroacoustic technologies applied within custom design as well as fabrication limits and potentials.

Interactive surface examines Temporal Synapse by PROJECTiONE, which constitutes a significant application of advanced technology for both the fabrication process and the capacity of an interior wall panel to interact and entertain visitors.

4.4.1 Stone Fluidity with Design Interoperability

Trahan Architects—Louisiana Sports Hall of Fame & Northwest Louisiana History Museum, Louisiana

The Louisiana Sports Hall of Fame and Northwest Louisiana History Museum has been designed by a New Orleans-based architecture firm, Trahan Architects, in collaboration with Method Design, David Kufferman Structural Engineers and CASE which provided specific competences in terms of software for both design aims and construction requirements.

The building is placed in an old settlement of Louisiana facing the banks of the Cane River Lake, at the boundary of the Red River valley. According to Trahan Architects the building geometry refers to the natural character of the surrounding

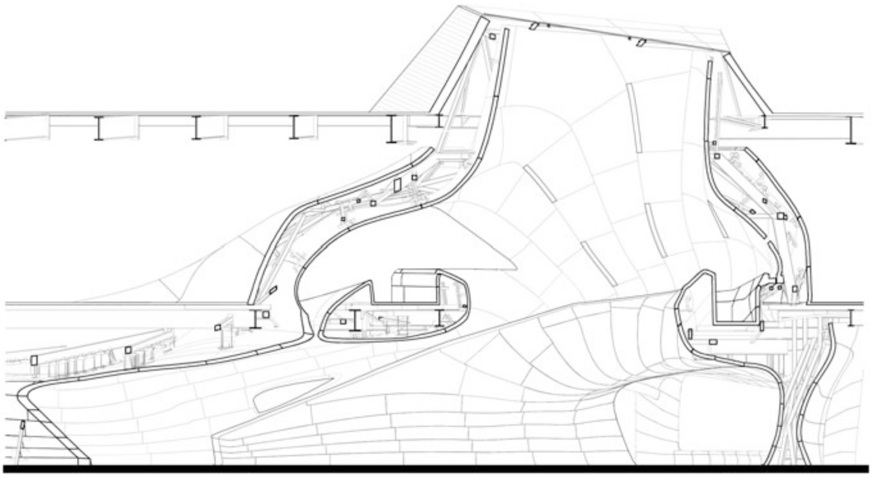


Fig. 4.39 The cross section of Louisiana Sports Hall of Fame & Northwest Louisiana History Museum shows the organic interior space featured by complex supporting steel structure and customized stone paneling (Reproduced with permission of Trahan Architects)

area: interior spaces clearly recall the fluid shapes of the river and its meanders. The Louisiana Sports Hall of Fame and Northwest Louisiana History Museum merges two apparently separate subjects, as it pertains to North Louisiana's profound history and the process of becoming a contemporary venue within the world of sports. A regular façade, derived from the local context, encloses the interior fluid structure with a complex form (Fig. 4.39). With complex shapes in mind, Trahan Architects involved both Method Design and David Kufferman Structural Engineers in the design process to develop the customized stone cladding that characterizes the interior spaces of the building. Indeed, to design and build the free-form interior space specific software and optimizing methods were needed. CASE was selected by the architects as an expert in Building Information Modeling (BIM) technology. An advanced digital support was essential to control the quality of the design and the fabrication of such a complex structure (Trahan Architects 2013).

As mentioned above, the project is inspired by the surrounding landscape and is derived from the area's geomorphology and the river's hydromorphology. As a matter of fact, the circulation system and the exposition spaces of the building are inspired by the fluid shapes that characterize the braided channels of the river separated by interstitial masses of land. The building design conceptually refers to the idea of balance between past and future, combining together history and sports. Interpreting athletics as part of the national culture, the fluid spaces are configured to make the visitors visually and physically explore the connections between sports and regional history. The design team declares that the main intention of the project was related to the client's desire to exhibit sports and history together so that the visitors can go through the subjects either separately or simultaneously. Considering the local site, Trahan Architects decided to integrate the internal spaces with the existing

Fig. 4.40 The interior of Louisiana Sports Hall of Fame & Northwest Louisiana History Museum (Reproduced with permission of Trahan Architects, © Courtesy of Tim Hursley)

context. The visitors pathway is ramified as a fluid space going through the exhibition galleries and rooms and terminates with a veranda that overlooks, and virtually connects, the new fabric to the historic town square. The architectural language represents the mediation between the city and the natural environment, combining a regular exterior urban container with the fluidity of the interior, highlighting the contrast between the rigid geometry of artificial urban fabrics and the ancient river's fluvial geomorphology. 1,100 unique CNC milled cast stone panels compose the organic surfaces that embrace the interior space and seamlessly integrate all the building systems; its clear that the fluidity of the space clearly refers to its digital genesis (Fig. 4.40). The customized stone panels are lit by the daylight from above, and are also used as screens for films and to exhibit projections (Betsky 2013).

Specialized contractors were involved in the design process to guarantee the desired level of quality for the cast stone panel surfaces and the supporting steel structure. Indeed, the interior space not only represents the core part of the project but also comprises a significant example of customization, therefore adequate software and advanced technologies played an essential role throughout the project development. Specialty Steel Consultant, Engineer David Kufferman P.E. and Method Design worked as geometry and detailing consultant to engineer a highly sophisticated structural steel system that connects each stone panel with its necessary custom connections (Fig. 4.41). According to David Kufferman the cast

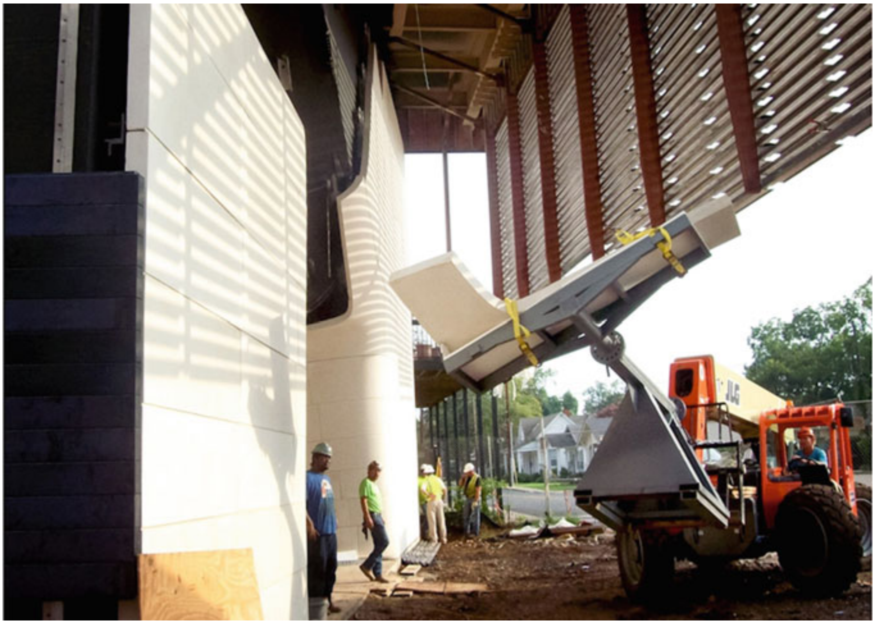


Fig. 4.41 Installation of the customized stone paneling (© 2011 CASE Design, Inc.)

stone surface can be compared to a-1051-piece 3D puzzle and each piece is made according to its unique and digitally defined pattern different from any other piece. The challenge is even greater considering that the interior surfaces needed to be supported by dedicated and customized steel structures (Fig. 4.42). The task of this project is further complicated by the fact that the cast stone is a fragile material and cannot tolerate much movement without the risk of cracking: this means that the structure must be designed in such a way to avoid any movement of the panels.

In order to manage this complexity with adequate technological tools the design team employed 3D modeling software from the very beginning. The original design of the internal surface was developed by Trahan Architects with the 3D modeling software Rhinoceros and was then panelized in several sequences by CASE using the 3D model and BIM software CATIA. Method Design and David Kufferman Structural Engineers focused on the development of the structural geometry of the supporting steel frame. Different teams worked with the digital model in Rhinoceros and developed the geometry definition using the parametric software Grasshopper (Stasiuk 2013). Through this working process, all the stone panel anchor types and locations were defined and shared with CASE working team that employed BIM technology and was able to obtain the information needed for the cast stone panel production.

The design team states that the use of advanced software such as Grasshopper, Karamba and Geometry Gym was fundamental in the process to convert the Rhinoceros model into a Robot supported file for the fabrication and assembly phases.

Fig. 4.42 Detail of the supporting steel structure showing the complexity that characterizes the interior space (© 2014 Method Design)

SDS/2 software was employed to extract shop drawings and specific information about steel detailing while other software was further exploited to obtain the three-dimensional structural analysis (Method Design 2013).

This workflow allowed Trahan Architects, CASE, Design Method and David Kufferman Structural Engineers to develop a feedback and testing system, and thus to transfer geometrical data across multiple software. The final result was a fully detailed 3D model providing all the required information for both production and installation of the steel support structure and the cast stone cladding. Specifically, Kufferman and Method Design worked with Global Steel Detailing for the production and installation of the support steel structure. The steel components were later produced and erected by Champion Steel of Louisiana and CMC of South Carolina. To avoid installation mistakes a digital reference to the BIM model was used to locate steel during the construction phase so that every anchor point and custom connection system was accurately secured to the related stone panel. The same system was used to precisely place the custom stone panels, erected and installed by Masonry Arts (Fig. 4.43).

The Louisiana Sports Hall of Fame and Northwest Louisiana History Museum presents a successful case as different teams of architects, engineers and various experts collaborated together from the beginning, according to a common workflow, continuously exchanging information and further developments.

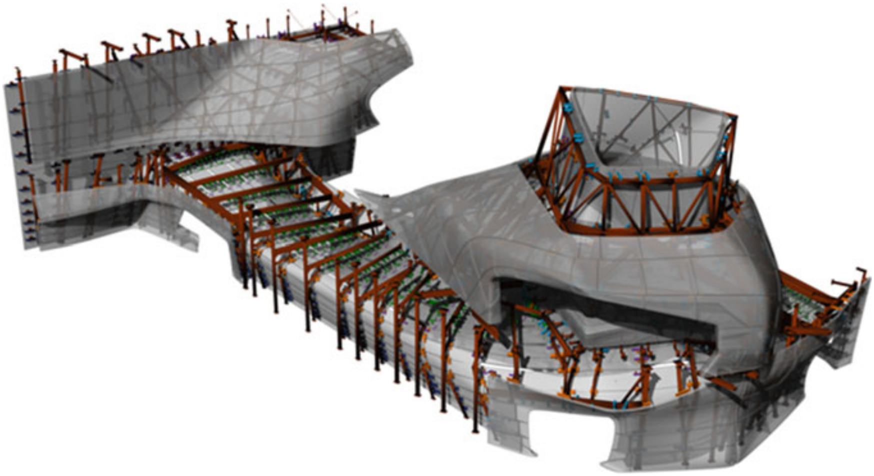


Fig. 4.43 The interior structure of Louisiana Sports Hall of Fame & Northwest Louisiana History Museum was developed using BIM technology (Reproduced with permission of Trahan Architects, Courtesy of © Method Design)

4.4.2 Wooden Parametric Inflections

dECOI Architects—One Main Street, Boston

For the renovation of its offices, CChange Investments/Zero+, an investment group interested in clean energy and green buildings asked for a radical interior design, that would differentiate it from traditional ones. The architects in charge, dECOI, came up with a fascinating solution where walls, floors, ceilings, furniture and even door handles were obtained from sustainably forested CNC milled plywood. The project is essentially working on two mirroring planes—the floor and the ceiling—both articulated as continuous surfaces inflected by functional activities. The curvilinearity expresses the digital genesis and the seamless fabrication logic, which involved the architects providing the actual machine files to the fabricator (Fig. 4.44).

The main idea is the demonstration of the design versatility and efficiency achievable by CAD/CAM design/build processes. The shape emerges directly from the continuous machining logic, where a numeric command machine executes curved cuts with equal precision as straight lines, essentially indifferent to the complexity or number of cuts. Thus, walls are transformed into surfaces that, from the floor, become a reception desk, or, from the ceiling, blend into structural columns (Fig. 4.45). The edges of the floor extend and curl to provide perimeter

Fig. 4.44 The curvilinearity of the project clearly expresses the digital genesis and the seamless fabrication logic (Reproduced with permission of dECOI)

Fig. 4.45 Ceiling and benches during the installation (Reproduced with permission of dECOI)

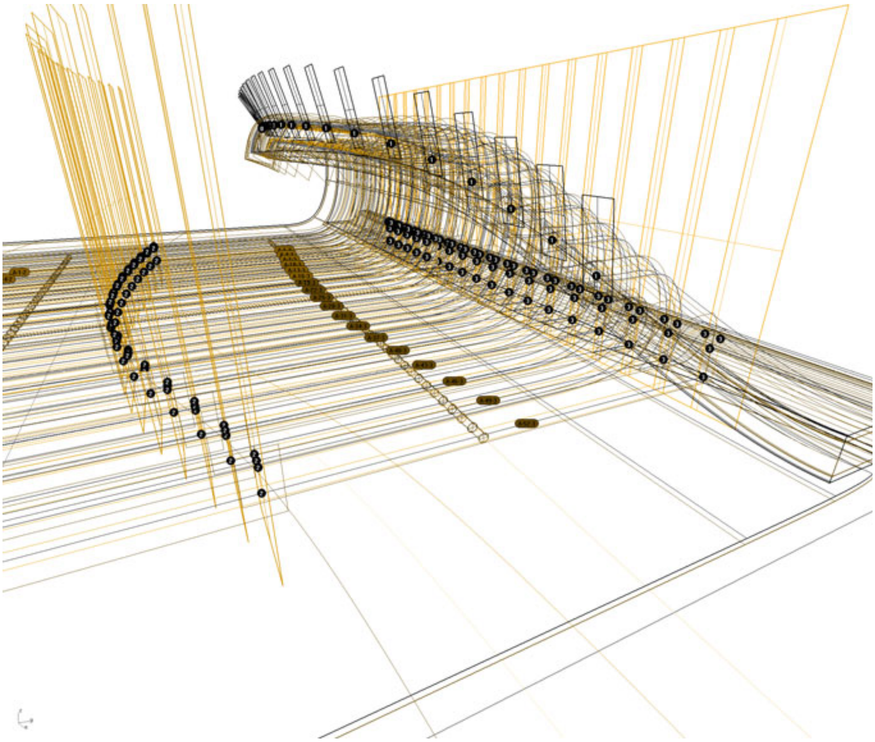


Fig. 4.46 Scripting process generating milling information (here, the benches) (Reproduced with permission of dECOI)

benches in a continuous-surface formalism. In a secondary scale, surfaces host functional services punctured by vectors of light while tables open to offer electrical outlets.

> This suggests an "alloplastic" latency as an emergent aesthetic, where architectural surfaces and spaces legibly "trace" functional attributes (dECOI Architects 2011).

The project surfaces deform to perform technically. Functional attributes were developed as parametrically variable elements, adapting locally to the base surface conditions and shaping their geometry as an automatic feedback to suit their host site (Fig. 4.46). Where the glass wall is longer, so the structural fold of the floor heightens to augment its grip, the entire series of bumps vary by a second-order constraint. Where air-flow is increased locally, the vents elongate to baffle the flow proportionally, flaring the ribs of the ceiling wider.

The main requirement of manufacturing was to streamline the current milling process, and this goal was even more compelling as the lowest tender came from a millwork fabricator who used only a single 3-axis CNC machine. The architects developed a series of scripted milling protocols that would analyze the surface

Fig. 4.47 Milled elements of the benches ready for assembly (Reproduced with permission of dECOI)

geometry and automatically divide the parts, generating tool paths instead of actual geometric information. The fabricator was provided directly with the actual milling files, already nested onto plywood sheets to minimize waste.

Finally, these cutting instructions had to be issued digitally to the numeric command machine resulted in more than 300,000 linear meters of cut to be manufactured. Traditional methods of representing architecture has been replaced by an abstract machine instruction that does not display the final form but a “ghost” of it. In this way the architects had every detail of their work in full control.

Each part of the interior has been designed and automatically fabricated by a single 3-axis numeric command milling machine. Ceilings, walls, floors and fixed furniture have been fabricated as sectional elements cut from flat plywood sheets. Other functional elements like ventilation grills, light pockets and door handles have been formed directly by milling the mass of wood (Fig. 4.47).

The traditional building stages have been completely annulled by a more efficient and unique process in which large and highly accurate prefabricated parts are quickly installed on site without the need for multicomponent assembly. The 1,000 m^2 project nested onto 1,200 plywood sheets of 3.8 cm thick, 1.2 × 3.6 m milled locally. A basic renewable natural resource, the spruce plywood, was used. This a fast-growing softwood trees have been sustainably harvested in Finland to offer optimal yield to laminate sheets. The carbon dioxide captured by the trees exceeds by far the carbon emitted by the energy used for transportation and fabrication, since the cutting and assembly use lightweight and efficient machines. Wastage was about 10 %—pulped and recycled. Thus, the lifecycle calculation demonstrated the good choice of the material and even of the planning process. The architects executed the projects paperless, neither plans nor sections were created, and used only 3D instructional files proving the comprehension of digital processes (dECOI Architects 2011).

4.4.3 Printing Unlimited Complexity

Michael Hansmeyer & Benjamin Dillenburger—Digital Grotesque, Zurich

The research project Digital Grotesque, also known as 3D Printed Grotto, has been conducted by Michael Hansmeyer and Benjamin Dillenburger throughout 2013 within the CAAD group at the Swiss Federal Institute of Technology (ETH) in Zurich.

Digital Grotesque is based on the key principles of the latest evolutions in architecture: digital fabrication through additive manufacturing and computational design. The structure is a fully enclosed room entirely 3D printed with massive sandstone defining a solid, human-scale structure. The 3D printed Grotto is articulated by millions of microscopic forms obtained through the additive process binding millions of sand grains to stone and creating a solid and highly detailed structure. The structure presents details at the threshold of human perception, entirely obtained through the employment of custom algorithms that allow the production of a highly differentiated and complex architecture (Menocal 2013) (Fig. 4.48).

This case study is an envisioning sample of how 3D printing technology can be applied at the architectural scale, in particular unveiling emerging applications in the context of articulated interior environments. The designers have been inspired by the natural process of cell division and consequently developed an algorithmic definition to divide and transform the primitive geometry of a pure cube through several iterations. This simple principle guided the design concept of the overall project, including its complex forms and highly articulated geometries. The

Fig. 4.48 Digital Grotesque is a human scale 3D printed structure, detailed at the threshold of the human perception (Reproduced with permission of Michael Hansmeyer & Benjamin Dillenburger)

structure consists of two individual halves (Aediculae) that form a volume, which is described on the outside as a flat cubical volume while its interior features a complex geometry consisting of millions of individual facets (Fig. 4.49). The final output is both an ornament and a structure. If typical computational architecture is based on the idea to create smooth and minimal surfaces, the 3D Printed Grotto is instead focusing on the maximal articulation of geometries, creating differentiated microscopic textures, allowing lights to be reflected in a million different directions and rejecting the boundaries of the structure. The project is clearly referring to classic architecture, offering a range of multiple scales of information contained in its own forms, showing progressive and hierarchical levels of detailing. As it happens with buildings of the classic period, the closer one gets to the structure, the more details one discovers; at the same time Digital Grotesque differentiates itself from the classic artifacts by being created through a single process—an algorithmic design—to "sculpt" both the overall shape and the details.

The research project shows hundreds of millions of individual facets printed at a resolution of a tenth of a millimeter, constituting a 3.2 m high, 16 m^2 long room. With the employment of parametric software a simple input form is recursively refined and enriched to define the entire system, a system composed of 260 million facets that are individually defined through the potential of the algorithmic

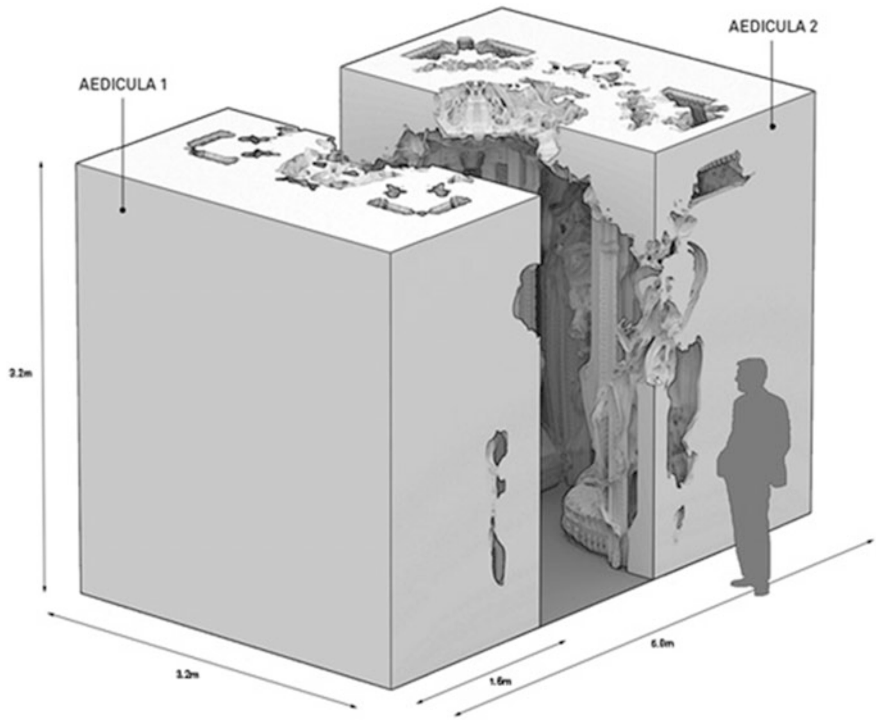


Fig. 4.49 The design consists of two individual halves (Aediculae) that form a volume, which is described on the outside as a flat cubical volume, while the interior is featured by complex geometry, consisting of millions of individual facets (Digital Grotesque)

definition (Fig. 4.50). The process and software employed allowed the precise generation and control at different scales of the definition, from the general form and its curvature, to the local surface and minute textures. Such a level of definition and detailing would not be achievable through simple 3D modeling software or traditional drawing tools. Actually, the CAD software available on the market is not able to process this large amount of data without a loss of information, especially because it needs to be converted into a language compatible with the printing machines.

As the Grotto represents the first high-resolution 3D printed architecture, the construction process and details needed to be developed in their entirety. According to the designers, the limits of the fabrication process were due to the transportation and assembly of the printed blocks that constitute the entire massive structure rather than the dimension of the printable volume. For this reason the whole room has been printed in 60 elements designed to fit into 120 × 120 cm pallets and to be lifted by four people (Fig. 4.51). The entire design has been addressed to face these difficulties: structural analysis tools were utilized during the design phase to reduce

Fig. 4.50 The structure is made by a geometric mesh, containing 260 million highly detailed facets, that are individually defined through an algorithmic design and fabricated with 3D printing technology (Reproduced with permission of Michael Hansmeyer & Benjamin Dillenburger)

Fig. 4.51 The whole room has been printed in six large elements, designed to be transported and assembled together (Demetris Shammas, Achilleas Xydis)

the wall thickness of non-critical areas and minimize the weight of the components. Each of the printed elements was manufactured with specific details to both join different pieces together and to lift them: truncated cones and funnels allowed consistent and stable vertical alignment. Additionally, an internal grid was introduced to increase the structural stability.

The structural fabrication was based on sand-printing. This experimental technology, recently offered the potential to overcome some limits of 3D printing like the material cost, the limited dimensions of the typical machine areas and the requirements of printed materials in terms of stability and resistance. Sand-printing is particularly appropriate for architectural applications as it allows the fabrication of large-scale elements with high resolution at a competitive price and in short periods of time. This manufacturing technology allows printing up to 8 m^3. According to the properties of the applied material, the product obtained through sand-printing can conduct to self-supporting elements, be assembled in solid construction or even applied for structural purposes. As the 3D printed Grotto needs to be self-supporting, this manufacturing process comprises an optimal solution. Indeed, 3D printed sandstone has similar properties to the natural sandstone which has been traditionally used in architecture as an easily workable material. In order to further strengthen the micro-details and to increase its structural properties, the printed sandstone is infiltrated with resin that closes the pores of the artificial sandstone.

With the development of additive manufacturing, the fabrication processes are transforming in an irreversible way, engaging continuously updated and refined technologies and tools to improve several sectors, including the architecture and construction fields. Digital Grotesque is one of the most resounding demonstrations of 3D printing in architecture as it shows the possibility to fabricate not only small-scale models or iterative and assembling components, but rather an entire room. Moreover, the level of details that characterize the structure evokes the potentialities of the new technologies availability, reproducing and improving the flaunt that only in past eras was handcrafted, and achieved with highly qualified competence. Digital Grotesque, rather, provides a highly detailed and differentiated structure obtained with the same production process and reduced cost. The combination of computational design and 3D sand-printing allowed the fabrication of a unique architecture and inevitably modified the role of the designer and the logic of architectural design. As the designer states,

> in computational design, the architect no longer develops form by pen on paper or by mouse in CAD program, but instead defines procedures to generate form. Shifting the design process onto this abstract level has a dramatic impact: Forms can be designed with a complexity and richness that would be impossible to draw by hand. Now these complex forms can be brought out of the computer using additive manufacturing. Bits and bytes can be rendered directly into reality (Hansmeyer and Dillenburger 2013).

Considering the advanced tools and the latest fabrication technologies, nowadays, architectural projects need to be developed directly in three dimensions and then translated into materialized and physical geometries with unseen levels of detail and control. Additionally, with the employment of 3D printing technologies and advanced digital tools, there is no longer a cost associated to the level of complexity or customization, as printing a highly detailed model costs the same as printing a primitive cube. Nor is there a cost for customization: fabricating highly individual elements costs no more than printing a standardized series. Ornamental complexity and formal expressionism are now legitimized.

4.4.4 Kinetic Electroacoustic Ceiling

RVTR—Resonant Chamber, Ann Arbor

Resonant Chamber is a research project by Ann Arbor and the Toronto-based design firm RVTR, through a process that employs both computational design and full-scale prototype testing. The research has been developed during 2011 and 2012 at the University of Michigan, in Ann Arbor, through internal funding from the Taubman College "Research Through Making" Program, the U-M center for Wireless Integrated Microsystems and external funding from the Social Science and Humanities Research Council of Canada (SSHRC).

Resonant Chamber represents a synthetic design process that implicates simultaneous computational and physical studies that inform each other through various feedback and control systems. The project combines performative acoustic panels forming a kinetic ceiling dynamically adapting the acoustic signature of an interior space (Fig. 4.52). The interactive structure is integrated with a system of acoustic sensors, its form is based on the geometric principles of rigid origami and constitutes a successful application of responsive technologies to interior architectural space. The design was developed through three streams of iterative research, exploiting both computational software and physical prototyping, according to the different phase of the research. The initial phase of the process investigated Dynamic Surface Geometries employing both parametric design tools and physical supports for testing; the second phase of the research dealt with Performative Material System investigating the material properties and the specific characteristics needed to optimally perform the acoustic alteration; while the last phase focused on Variable Actuation and Response studying the adequate adaptive system and technologies required.

The designers affirm:

> our aim is to create an instrument at the scale of architecture, flexible enough that it might be capable of being played (RVTR 2013),

and Resonant Chamber is actually a complex electroacoustic instrument that transforms its kinetic performance, responding to the acoustic environment, in an architectural product that interacts with inhabitants. Through the process, RVTR developed a system that is able to modify the acoustic surroundings, through dynamic spatial, material and electroacoustic technologies, exploiting digital tools, physical and effective logics, geometric and material behaviors and opportunities

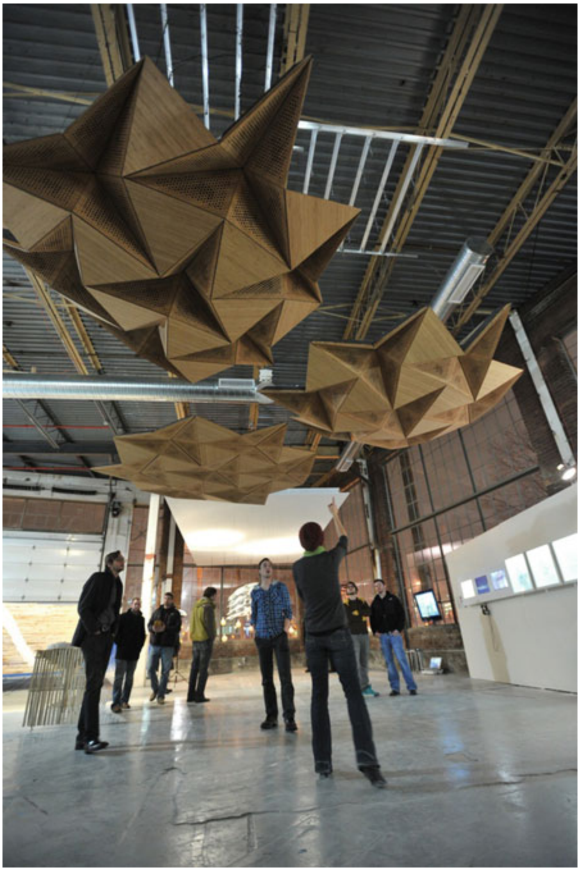


Fig. 4.52 Resonant Chamber consists of kinetic acoustic panels creating an interactive ceiling surface (Reproduced with permission of RVTR)

and considering at the same time limits and constraints. Resonant Chamber offers an interior paneling system composed of reflective, absorptive and electroacoustic panels that can interactively modify their shape in order to produce the optimal acoustic performance relative to the different sound inputs of the space (Fig. 4.53). The origami structure alters its geometric configuration, exposing or concealing its surfaces, and in this way responds to the sonic external inputs and transforms the acoustic environment (RVTR 2013).

The research team evaluated the formal, spatial, material and fabrication logics of Resonant Chamber, through a simulation and prototyping process, in order to improve acoustic performance and formal results. Particularly interesting is the design approach, characterized by adaptive feedback between the different digital and physical platforms employed. The computational workflow included sophisticated tools, exploited during the research process, to evaluate both acoustic requirements and geometrical performances, studied through predictive modeling of the physical behaviors and material performance. Spatial volume and proportion, critical distance, reverberation time, noise reduction coefficient, reflection density noise levels,

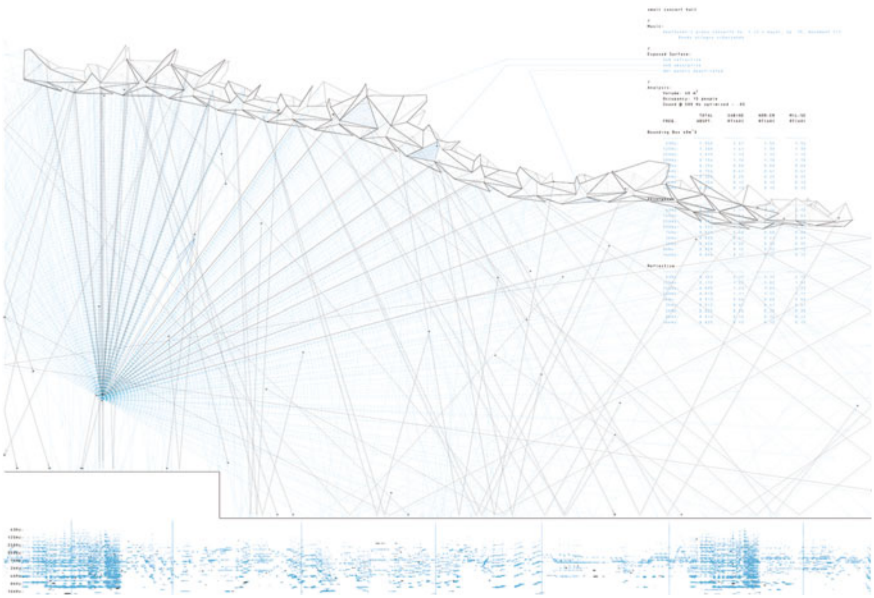


Fig. 4.53 Resonant Chamber acoustic model, exploited to study the interactive behaviour of the interior ceiling (Reproduced with permission of RVTR)

material surface characteristics (smoothness, texture), surface exposure and electroacoustic amplification are just a few of the factors considered in order to evaluate the acoustics through digital simulation and physical testing. The research team engaged different simulation software to test several geometric configurations and to evaluate different combinations of material distribution. In particular, an initial analysis was produced by ray-tracing the digital surface model developed together with an acoustic sound pressure study through the use of CATT software, with the aim to configure the initial geometric configuration of the origami structure. Focusing on the generation process of the geometry, the folding surface was predictively modeled with the 3D modeling software Rhinoceros combined with parametric software, such as Grasshopper and Kangaroo, particularly useful to test the physical relationship between vertices and applied forces. In this project, the rigid origami was explored as a flexible geometric system capable of delivering predictable spatial configurations through its surface properties of change (folded from a single sheet), flat fold-ability (ability to fold into a flat shape) and degrees of freedom that can be transformed into kinetic three-dimensional structures (Fig. 4.54).

With the aim to translate the digital model to an interactive prototype, required information was extracted from the Rhinoceros model and transferred via the Firefly plug-in to the Arduino board, which received inputs through Pulse-Width Modulation (PWM) signals actuating the system's kinetic components and

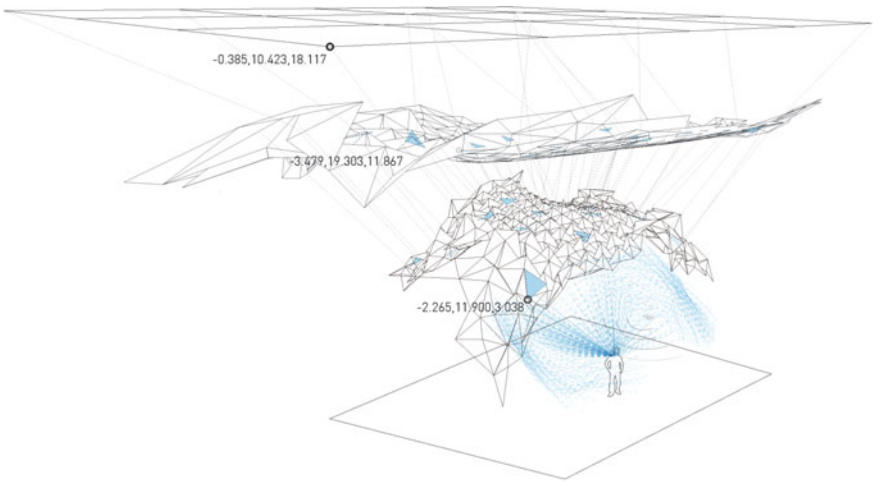


Fig. 4.54 The system's kinetic components are actuated based upon acoustic inputs received through a variety of sensors, processed through a proprietary software developed by RVTR and Arup, then translated into spatial instructions via the FireFly plug-in to generate numeric positioning commands packaged and wirelessly transmitted to activate stepper motors and linear actuators controlling the panel orientation and the position of the ceiling (Reproduced with permission of RVTR)

controlling different physical actuators connected to a folding cell. Both linear actuators and stepper motors were employed to simultaneously transform both surface orientation (addressing late acoustic energy) and overall volumetric enclosure within the space (addressing early acoustic energy). In order to verify the assumptions derived from the digital simulation study, physical prototypes were fundamental to test the acoustic behavior of specific materials and geometries. Furthermore, a dedicated software called Vivo was employed during the research phase to convert the digital model information into displacement and positioning data to achieve the panels exact orientation and to coordinate folding actuation. To modify the origami component's configuration, acoustic sensors, linear actuators and motor controllers were placed within a standardized panel containing amplification devices of one or more distributed mode loudspeakers (DML) (Fig. 4.55). A distributed mode loudspeaker is also fixed to each of the electroacoustic panels, allowing sound to not only be reflected but also produced by the units themselves. The design team explains that this is obtained by introducing vibrations through an electroacoustic exciter (Thün et al. 2012).

One of the main aesthetic objectives of the design team was to define a homogenous material surface to be seen from the underlying space and, according to this challenge, the material properties of the exposed surface required both acoustically reflective properties and electroacoustic capacity. The designers

Fig. 4.55 The final result of the Resonant Chamber is achieved through fabricating component parts that could be assembled into a composite panel. By creating a face panel separate from the frame, each panel type could be uniformly bonded to the continuous membrane that comprises the hinge. A cap on the frame encloses either a DML exciter component, electronics controls or a solid reflective panel (Reproduced with permission of RVTR)

investigated several materials including extruded honeycomb aluminum, glass, glass-fiber reinforced gypsum, plexiglas and bamboo plywood with the aim to identify the optimal solution for panels. Various joint profiles, material thicknesses, lamination techniques and membrane hinges were tested and according to this research approach the prototype materials and geometries were defined, and a further series of manufacturing and physical tests were developed. The physical testing revealed that bamboo plywood was the material providing a higher quality performance in mid-tone frequencies utilized in electroacoustic amplification and able to be milled to various depths to achieve different panel compositions.

The design team involved as specialist consultant in the fabrication process, ARUP Acoustics, tested a series of geometric shapes and sizes and then translated the results into the geometric evaluation to optimize the origami pattern and its potential spatial deformations.

At the end of this intensive and iterative process, Porous Expanded Polypropylene (PEPP) was selected as the best material to couple with the Bamboo Plywood Frames and inserts to provide the capacity for reflective, electroacoustic and absorptive variation within the system. PEPP provided the required level for panel rigidity and, additionally, it could be milled in order to fabricate the custom components for the desired origami configuration. Furthermore, this material revealed an optimal sonic performance as it provided the acoustic absorption coefficient desired for sound dampening effects (Figs. 4.56 and 4.57).

The research approach offers the capacity to modify aesthetic form while simultaneously manipulating the acoustics of a space and investigating all the necessary aspects—simulation and testing to material limits and behaviors to geometric, technological and manufacturing limitations or constraints. Although there are precedents to control both height and orientation of a ceiling reflector, Resonant Chamber proposes a folding structure, which through its dynamic

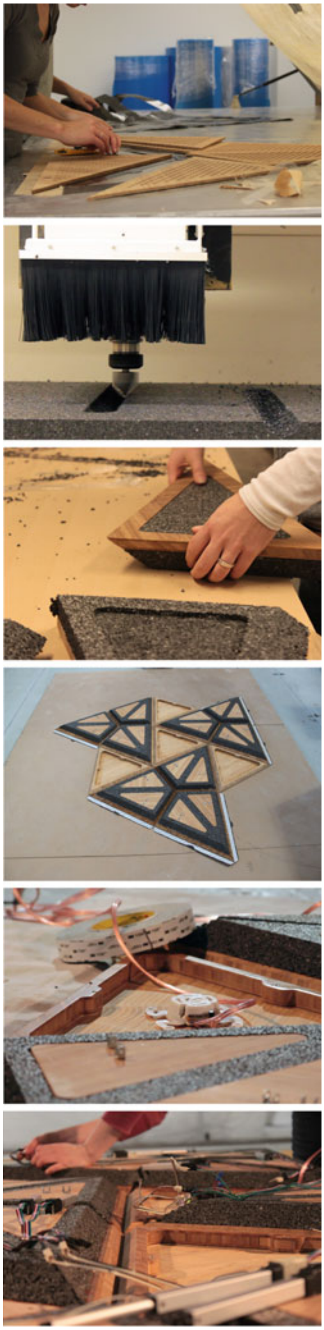


Fig. 4.56 Fabrication process. From the *top* panels perforation with 25 % exposure; PEPP milling; PEPP absorption panels assembled with milled plywood frame; composite cell tessellated with reflective panels DML Application; actuation mounting (Reproduced with permission of RVTR)

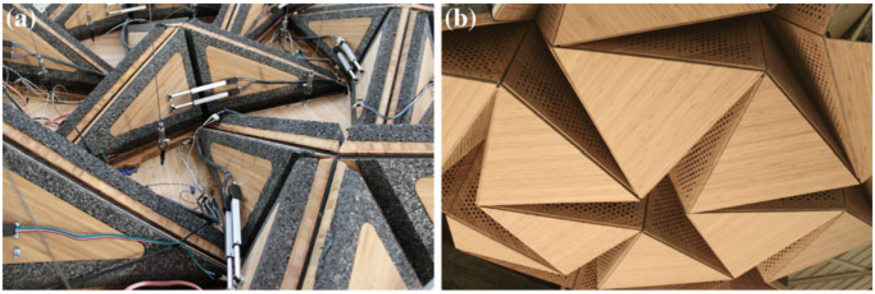


Fig. 4.57 The fabrication process pictured and described above led to the complete assembly of the interactive surface. From the *left* **a** PEPP panels, plywood frames and electronic devices are not visible by the inhabitants, since they are oriented towards the concealed side of the surface; **b** A homogeneous material surface is seen from the underlying space (Reproduced with permission of RVTR)

geometrical deformations, offers an innovative solution exploiting a kinetic system to moderate sound wave levels and velocity—dynamically shaping acoustic space. The research project represents an unprecedented architectural application of robotic potentials and responsive envelopes.

4.4.5 Interactive Wall

PROJECTiONE—Temporal Synapse, Indianapolis

The Temporal Synapse project has been developed by the design firm PROJECTiONE for the elevator lobby walls of the Eskenazi Health center in Indianapolis. PROJECTiONE is a design and fabrication studio formed a few years ago by recent graduates from Ball State University's College of Architecture and Planning, Adam Buente and Kyle Perry. PROJECTiONE collaborates with two other members, Elizabeth Boone and Eric Brockmeyer, working on digital tools, full-scale prototypes, research processes and collaboration with other disciplines (PROJECTiONE 2014).

The project is a highly customized interactive interior wall, which makes use of innovative software and digital fabrication processes. The aim of the project is to create an emotional space, giving the hospital users the possibility to interact with it and, at the same time, provide a pleasant distraction to the patients. Considering its own name, the driving conceptual principle of Temporal Synapse refers to the biological process that permits communication among nervous system cells. The design team elaborates:

> Temporal Synapse takes this anatomical concept and recognizes the linkage between our body and continually developing technology (PROJECTiONE 2014),

Fig. 4.58 Temporal Synapse, interactive function (© 2009 PROJECTiONE LLC.)

considering the technology as an essential element of contemporary living and interpreting communication as an inseparable aspect of our society.

The wall is based on an interactive mechanism which is able to create a direct link between the technology and the hospital inhabitants, translating their movements into sophisticated LED lighting patterns (Fig. 4.58). The surface tessellation recalls biological cellular structures, creating, in this sense, a link to the noble essence of the hospital and reinforcing its identity as a place devoted to the care of the human body. Advanced computer programming and Computer Numerically Controlled machinery allowed the traditional walls to transform into reactive lighting elements that respond to the human body. A flow of light appears on the exposed surface and visually represents data about the space and its users.

The elevator lobby of the Indianapolis Eskenazi Health center is now featured by the gestural system which creates graphic patterns that refer to bio-cellular structure and continues through all the floors. The idea of making the hospital elevator lobby an interactive space is related to the aim to provide a positive experience to the patients. Indeed, an elevator lobby is traditionally characterized by the alternating presence of individuals and within a hospital it often assumes the role of a waiting area, leading the patients to dwell on negative thoughts or encourage anxiety and stress.

The interactivity of the walls can stimulate interest, attraction and curiosity or even promote a conversation between strangers, in this way redirecting the patients' focus. The designer, Eric Brockmeyer, has been heavily involved in the design process in order to deal with the software and hardware programming, given that he

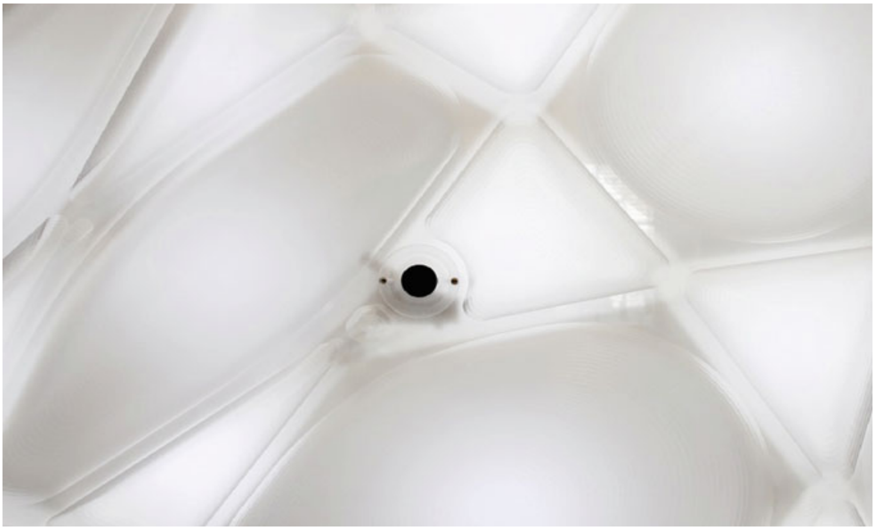


Fig. 4.59 Temporal Synapse, sensor camera detail (© 2009 PROJECTiONE LLC.)

is specialized in digital fabrication, interaction, lighting and touch sensing technologies and parametric design. A fish-eye camera is mounted in the middle of the wall capturing people's motions. Through sensors the movements are then communicated to a computer system that sends signals to hundreds of LEDs that slowly power on and off in different parts of the wall (Fig. 4.59).

In terms of material characteristics, the project deals with specific requirements, particularly for the optical properties and light stability that are needed throughout the material composition. Acrylic material was employed in the external layer of the project and, specifically Acrylite®, was chosen as the optimal product to bring the specific appearance and translucent properties considering the lighting effects. The bespoke support system was made of milled aluminum. The aluminum panels were cut employing a CNC milling machine and then assembled in the final form of the cellular pattern. Uniform in height, aluminum stripes were obtained through the milling process, incised with folding cuts to be bent in the form of each cell. Once the cell boundary structure was produced, all the elements were assembled together and fixed to a continuous metal sheet that covered the patterning gap between the cells. Considering the scale of the Temporal Synapse walls and the dimension constraints due to the available machines, it was not possible to build a single panel for a whole wall. Each wall was subdivided into four portions in order to produce manageable panels, also keeping in mind the transportation and assembling limits (Evonik Industries 2014).

The Acrylite® sheets were customized into the desired patterned panels and the milled form emphasizes the depth of the pattern to accentuate the lighting quality of the material. The white translucent panels were sculpted through CNC routers, creating different engravings within each cell of the whole pattern, and later applied over the aluminum structure, embedding a prefabricated network of electronic

Fig. 4.60 Temporal Synapse, CNC milled acrylic sheet and cellular pattern detail (© 2009 PROJECTiONE LLC.)

devices and acting as a container for the LED system (Fig. 4.60). The metal panels were assembled together with their sustaining frame, directly on-site, on a dedicated supporting welded aluminum grid structure that hosts the electronic central control panel, connected with the LED system embedded in each cell. Before covering the electronic components with the cellular structure, the builders assured the correct connection and functioning of the lighting system.

This project constitutes a significant application of advanced technology for both the fabrication process and the functioning theme. As customized components obtained through CNC machinery are more and more diffused, the idea to apply lighting sensors to interior space is rather unexplored. Moreover, Temporal Synapse is an exemplar in terms of the production and assembling process, considering the high level of customization that characterized the design of the walls.

Projects Credits

4.2.1 Italy Pavillion, Milano Expo 2015

Designers: Nemesi & Partners srl, Michele Molè, Susanna Tradati
Location: Milano, Rho-Pero Area, Italy
Designed in: 2013
Completed: to be completed in 2015
Area Palazzo Italia: 13,275 m^2 (on 6 levels)
Cost: n.d.

Client: Expo 2015 SpA
Architects: Nemesi & Partners, Arch. Michele Molè, Arch. Susanna Tradati (from preliminary design to working drawings)
Design team: Alessandro Miele (Coordinator), Alessandro Belilli, Claudio Cortese, Daniele Durante, Enrico Falchetti, Alessandro Franceschini, Davide Giambelli, Alessandra Giannone, Paolo Greco, Mariarosaria Meloni, Fabio Rebolini, Giuseppe Zaccaria, Kai Felix Dorl, Matteo Pavese, Paolo Maselli
Model maker: Officina06, Gianluca Brancaleone
Engineering and Cost Management: Proger SpA
Structural and plant engineering: Bms Progetti Srl
Sustainability Energy: prof. Livio De Santoli
Consultants: ABeC (Glass Facade engineering), Mario Nanni (Lighting design), Dario Paini (Acustics), Systematica Srl (Flows), Energo SpA (Fluid dynamic), GTA Srl (Environmental feasibility), Zomraude Chantal Chalouhi (Fire system), Samuele Sassi- FSC Engineering srl/Ramboll Group (Fire engineering), Studio Montanari & Partners S.r.l. (Food manager)
Contractors:
Foundations: Mantovani Group
Building: Italiana Costruzioni S.p.A. with Consorzio Veneto Cooperativo S.C.P.A.
External facade: Italcementi SpA with Styl-Comp Group
Shingle: Stahlbau Pichler

4.2.2 Ofenhalle, Brickfaçade of Keller AG Headquarter

Designer: Gramazio & Kohler
Location: Pfungen, Switzerland
Designed in: 2010
Completed: 2012
Area: façade area: 167 m^2
Cost: CHF 339,000
Client: Keller AG Ziegeleien
Design Team: Philipp Hübner (project lead), Matthias Helmreich, Kathrin Hiebler, Marion Ott, Sarah Schneider
Local Partner: N.A.
Façade Engineering: Engineering Steel façade: Bona + Fischer Ingenieurbüro AG, Winterthur
Building Physics Glass façade: Raumanzug GmbH, Zürich
Structural Engineering Brick Elements: Keller AG Ziegeleien
Fabrication data creation: R-O-B Technologies AG, Zürich
Selected contractor: brick façade: Basement Brick-AG, Pfungen
Steel façade: Geilinger windows and façades AG, Winterthur

4.2.3 Tori Tori Restaurant

Designer: Rojkind Arquitectos
Location: Mexico City, Mexico
Designed in: 2009
Completed in: 2011
Cost: Confidential
Client: Confidential
Area: 629 m^2
Architects: Rojkind arquitectos, Michael Rojkind, Gerardo Salinas
Project Team: Tere Levy, Agustín Pereyra, Raúl Araiza, Carlos Alberto Ríos, Isaac Smeke J., Enrique F. De La Barrera, Daniela Dustamante, Daniel Hernández
Esrawe Studio: Héctor Esrawe [principal in charge]
Project Team: Ricardo Casas, Basia Pineda, Ian Castillo, Karianne Rygh, Alejandra Castelao, Jorge Bracho, Alejandro Zárate, Marcela Muñoz, Edgar Sánchez, Rodrigo L. Franco
Design Computational Consultants: Kokkugia [Roland Snooks, Robert Stuart-Smith]
Construction: Zda Desarrollo + Arquitectura [Yuri Zagorin]
Structural Engineering: Ing. Juan Felipe Heredia
Façade Engineering: Grupo Mas [Ing. Eduardo Flores]
MEP: quantum diseño
Lighting Design: luz en arquitectura [Arq. Kai Diederichsen]

4.2.4 Zahner Factory Expansion

Designer: Crawford Architects
Location: 1400 East 9th Street, Kansas City, Missouri, USA
Designed in: 2009
Completed in: 2011
Cost: $1 million
Client: Zahner
Local Partner: Crawford Architects, Kansas City, Missouri, USA
Structural Engineer: Wallace Engineering, Kansas City, Missouri, USA
Mechanical Engineer: M.E. Group, Inc.
Electrical Engineer: M.E. Group, Inc.
Façade Engineering: Zahner, Kansas City, Missouri, USA

4.2.5 New York by Gehry

Designer: Gehry Partners, LLP
Location: New York, USA
Designed in: 2004–2006

Completed in: 2012
Cost: $680 million–$90 million for the curtain wall
Client: Forest City Ratner Companies, USA
Environmental Engineer: Mueser Rutledge Consulting Engineers
Main Contractor: Kreisler Borg Florman General Construction Company
Structural Engineer: WSP Cantor Seinuk
MEP Engineer: Jaros Baum & Bolles
Curtain Wall: Permasteelisa Group

4.2.6 Arboskin

Designer: ITKE (Institute for Building Construction and Structural Design)
Location: Stuttgart, Germany
Designed in: 2013
Completed in: 2013
Cost: Confidential
Client: Speculative Research
Designers: ITKE University
Project Management: Dipl.Ing. Carmen Köhler
Construction Management: Dipl.Ing. Manfred R. Hammer
Structural Design: Dipl.Ing. Thiemo Fildhuth
Student Design Team: Martin Loučka, Peter Kohlhammer, Adrian Grygar
Geometry Programming Martin Loučka
Realisation: Adrian Grygar, Serge Deisner, Maximilian Kurz, Martin Loučka, Paco Motzer, Jan Tondera, Dennis Gerlach, Alexander Mironov, Dominik Heizmann, Svenja, Felis, Maximilian Schäfer, Benjamin Fritsch supported by Michael Tondera (Fakultätswerkstatt Architektur)
Façade Materials: Dr. Michael Schweizer, TECNARO GmbH, Ilsfeld-Auenstein
Pyramid production: Frank Braun, Hans-Peter Braun, BAUER THERMOFORM-ING GmbH & Co. KG, Talheim
Material Consultant: Institute for water engineering, water quality and waste management, ISWA.

4.3.1 6, Bevis Marks

Designer: Fletcher Priest Architects
Location: 6 Bevis Marks, London, UK
Designed in: December 2008
Completed: Spring 2014
Cost: £52 million
Client: AXA, BlackRock, Wells Fargo and CORE

Design Team: Ed Williams, Sam Craig, Anne Schroeder, Christina Stellmacher, Evonne Tam, Jonathan Hodge, Mareike Langkitsch
Main Contractor: Skanska
Facade Engineering: NET, Lindner, Vector-Foiltec
Structural Engineering: Waterman Building Structures, David Dexter Associates

4.3.2 Shenzhen Bao'an International Airport

Designer: Massimiliano and Doriana Fuksas
Location: Bao'an District, Shenzhen, Guangdong, China
Designed in: 2008
Completed in: 2013
Area: 500,000 m^2 in phase 3
Cost: €734 million
Client: Shenzhen Airport (Group) Co., Ltd.
Interior Design: Fuksas Design (internet-point, check-in "island", security-check, gates, passport-check areas, shop box, baggage-claim "islands", info-point, ventilation trees, signage, commercial desk and washrooms)
Structures, Façade and Parametric Design: Knippers Helbig Engineering, Stuttgart, NY
Architect of Record: BIAD (Beijing Institute of Architectural Design), Beijing
Lighting Consulting: Speirs & Major Associates, Edinburgh, London
Developer: Shenzhen Planning Bureau; Shenzhen Airport (Group) Co., Ltd.
General Contractor: China State Construction Engineering Corporation Limited, China Construction Eighth Engineering Division
Steel Contractor: China Construction the Third Engineering
Façade Contractor: Shenzhen Sanxin Façade Engineering Co., Ltd; Shenzhen Ruihua Construction Co., Ltd; China Fangda Group Co., Ltd.

4.3.3 Building Bytes

Designer: Brian Peters (DesignLabWorkshop)
Location: European Ceramic Work Centre, Hertogenbosch, Netherlands
Designed in: 2012
Completed in: Ongoing
Cost: Confidential
Client: Speculative Research
Architects: Brian Peters, DesignLabWorkshop, Kent, Ohio, USA
Local Partner: N.A.

4.3.4 3D Print Canal House

Designer: DUS Architects
Location: Badhuiskade 11, Amsterdam North, Netherlands
Designed in: 2013
Completed: Ongoing
Cost: N.A.
Client: Self-initiated project by DUS Architects
Premium Partners
DUS Architects, Henkel; Heijmans; Stichting Doen; Amsterdam Fonds Voor De Kunst; Gemeente Amsterdam/EZ.
Partners
Amsterdam Smart City; Alliander; Ultimaker; Fiction Factory; Tentech; Rooie Joris;
Amsterdam Energie; Breedband Nederland/Aaldering ICT; Westpoort Warmte; Aon; Rsa; Protospace; Buko.

4.4.1 Louisiana Sports Hall of Fame & Northwest Louisiana History Museum

Designer: Trahan Architects
Location: 800 Front St, Natchitoches, Louisiana, USA
Designed in: 2010
Completed in: 2013
Cost: $12.6 million
Client: State of Louisiana, Office of Facility, Planning & Control
Design Team: Victor F. "Trey" Trahan III, FAIA; Brad McWhirter, AIA; Ed Gaskin, AIA; Mark Hash; Michael McCune, AIA; Sean David; Blake Fisher; Erik Herrmann; David Merlin, AIA; Benjamin Rath; Judson Terry
Interior Designer: Lauren Bombet Interiors
General Contractor: VCC
M/E/P/FP Engineer: Associated Design Group, Inc.
Structural Engineering: LBYD, Inc.
Civil Engineering: CSRS, Inc.
Geotechnical Engineer: GeoConsultants
Landscape Architect: Reed Hilderbrand LLC
BIM Manager and Technology Consultant: CASE
Cast Stone Support Steel Geometry and Detailing: Method Design
Cast Stone Support Steel Engineer: David Kufferman PE
Cast Stone Manufacturer: Advanced Cast Stone
Cast Stone Installer: Masonry Arts
Steel Structure Installers: Champion Steel (Louisiana) and CMC of (South Carolina)

4.4.2 One Main Street

Designer: dECOi
Location: Boston, USA
Completed: 2009
Cost: Confidential
Client: CChange Investments/Zero+
Architects: dECOi Mark Goulthorpe, Raphael Crespin (Project Architect), Gabriel Blue Cira, Matt Trimble, Priyanka Shah
MIT: Kaustuv de Biswas
Mathematics: Prof Alex Scott (Oxford University)
Consultants: Helen Heitman, Pablo Garcia (Gensler Associates)
General Contractor: Paul Jacobson (Tricore)
Local Partner(Millwork Contractor): Shawn Keller (CWKeller)

4.4.3 Digital Grotesque

Designer: Michael Hansmeyer & Benjamin Dillenburger
Location: CAAD department, Swiss Federal Institute of Technology ETH, Zürich, Switzerland
Designed in: 2012
Completed in: 2013
Cost: Confidential
Client: FRAC Centre museum, Orléans
Fabrication: Maria Smigielska, Miro Eichelberger, Yuko Ishizu, Jeanne Wellinger, Tihomir Janjusevic, Nicolás, Miranda Turu, Evi Xexaki, Akihiko Tanigaito
Video & Photo: Demetris Shammas, Achilleas Xydis
Partners and Sponsors: Chair for CAAD—Prof. Hovestadt, ETH Zurich—Department of Architecture, Voxeljet AG, FRAC Centre, Strobel Quarzsand GmbH

4.4.4 Resonant Chamber

Designer: RVTR
Location: Liberty Research Annex, 305 W Liberty St. Ann Arbor, MI, USA
Designed in: 2011–2012
Completed: 2012
Cost: $25,000—prototype construction
Research Funding: 2011 Taubman College Research Through Making Program, 2011 U-M Office for the Vice President of Research, 2012 SSHRC Research Creation Grant
Client: The University of Michigan

Design Team: Geoffrey Thün, Wes McGee, Kathy Velikov (leads) Lisa Sauvé, Mary O'Malley, Adam Smith, Colin Ripley, David Lieberman (design research collaborators) Katie Wirtz, Ian Ting, Lief Millar (prototyping)
Collaborators: Raj Patel, Terence Caulkins and Dave Rife—ARUP Acoustic Consultants Jerome Lynch, Devki Desai, Mike Kane (Embedded Sensing and Wireless Integrated Microsystem Integration)
Consultants
Digital Fabrication: Wes McGee, Matter Design, Ann Arbor/Boston
Acoustic Engineering: Raj Patel, Terence Caulkins and Dave Rife ARUP Acoustics, New York
Embedded Sensing and Wireless Integrated Microsystem Integration: d
Jerome Lynch, Devki Desai, Mike Kane (University of Michigan)

4.4.5 Temporal Synapse

Designer: PROJECTiONE
Location: Eskenazi Health centre, 1001 W 10th St, Indianapolis, USA
Designed in: 2013–2014
Completed: 2014
Cost: Confidential
Client: Eskenazi Health centre in Indianapolis
Design Principals: Kyle Perry and Adam Beunte
Hardwares and Software consultant: Eric Brockmeyer

References

Betsky A (2013) Hall of Fame. Trahan Architects brings a regionally inflected modernism to the small town of Natchitoches, in the form of the Louisiana Sports Hall of Fame and Northwest Louisiana History Museum. In: Architect. The magazine of American Institute of Architects. http://www.architectmagazine.com/cultural-projects/hall-of-fame.aspx. Accessed 14 May 2014

Carr E (2011) Using technology and innovative designs to build complex architectural envelopes. ISSN online: 2239-0243, 2011 Firenze University Press. In: Techne 02. http://www.fupress.net/index.php/techne/article/viewFile/9937/9182 Accessed 15 May 2014

Crawford Architects (2014) Press Release

dECOI Architects (2011) One main street. dECOi Architects. http://www.decoi-architects.org/2011/10/onemain/ Accessed 25 May 2014

DUS Architects (2013) Press Kit. 3D Printed canal house. http://3dprintcanalhouse.com/ Accessed 28 May 2014

Evonik Industries (2014) ACRYLITE® http://www.acrylite.net/sites/dc/Downloadcenter/Evonik/Product/ACRYLITE/acrylite%C2%AE-used-to-create-revolutionary-art-measuring-patients%E2%80%99-motions—temporal-synapse.pdf Accessed on 06 May 2014

Fletcher Priest Architects (2012) 6 Bevis Marks. http://www.fletcherpriest.com/our-work/architecture/key-projects/6-bevis-marks/ Accessed 05 March 2014

Fuksas M (2013) Shenzhen Bao'an International Airport - Terminal 3. 2013, China, Shenzhen. http://www.fuksas.it/#/progetti/1405/ Accessed 22 March 2014

Gramazio F, Kohler M (2014) Gramazio & Kohler, Architekten ETH SIA BSA. http://www.gramaziokohler.com Accessed 18 June 2014

Griffiths A (2013) Arboskin pavilion made from bioplastic by ITKE. In: Dezeen. http://www.dezeen.com/2013/11/09/arboskin-spiky-pavilion-with-facademade-from-bioplastics-by-itke/ Accessed 06 April 2014

Hansmeyer M, Dillenburger B (2013) Digital grotesque. http://www.digital-grotesque.com/ Accessed on 17 May 2014

Helbig T, Kamp F (2014) New terminal 3 for Shenzhen Bao' an Airport: a 1250 m long structure. http://www.knippershelbig.com/sites/default/files/pdf/new_terminal_3_shenzhen_boa_an_airport_th_fk1.pdf Accessed 23 March 2014

Hurst N (2013) Building on the cloud: Gehry and Box Overhaul Architecture with new paperless service, Design, Wired. In: Wired.com. Conde Nast Digital, 08 Apr. 0013 http://www.wired.com/2013/04/frank-gehry-hates-paper/ Accessed 05 May 2014

Knippers J (2013) ArboSkin: Durable and recyclable bioplastics facade mock-up. Faculty of architecture and urban planning University of Stuttgart, Germany. United news network GmbH. http://www.pressebox.com/pressrelease/tecnaro-gmbh/ArboSkin-Durable-and-Recyclable-Bioplastics-Facade-Mock-Up/boxid/634594 Accessed 06 April 2014

Loria K (2012) Inside the cutting edge. In: Green Building and Design. http://gbdmagazine.com/2012/crawford-architects/ Accessed 20 May 2014

Menocal CG (2013) Digital grotesque: a 3D printed room by Michael Hansmeyer. In: DesignBoom. http://www.designboom.com/architecture/digital-grotesque-a-3d-printed-room-by-michael-hansmeyer/ Accessed on 18 May 2014

Method Design (2013) LSH - Louisiana State Sports Hall of Fame + Regional History Museum. http://www.methoddesign.com/lsh/ Accessed 14 May 2014

Minutillo J (2010) Behind the curtain wall. McGraw-Hill Construction. http://continuingeducation.construction.com/article_print.php?L=5&C=695 Accessed 15 May 2014

Peters B (2012) Building bytes. 3D printed bricks. http://buildingbytes.info/ Accessed 18 March 2014

PROJECTiONE (2014) Temporal synapse. http://www.projectione.com/temporal-synapse/ Accessed on 06 May 2014

RVTR (2013) Resonant Chamber. http://www.rvtr.com/research/resonant-chamber/. Accessed 30 March 2014

Scheible F, Dimcic M (2014) Parametric engineering. Everything is possible. http://www.programmingarchitecture.com/publications/ScheibleDimcic_IASS_2011.pdf Accessed 22 March 2014

Shelden D, Kashyap S (2012) BIM in the Big Apple, In: Construction business owner magazine. http://www.constructionbusinessowner.com/topics/software/project-management/bim-big-apple Accessed 05 May 2014

Stasiuk D (2013) Louisiana State Museum and Sports Hall of Fame. In: Grasshopper. Algorithmic modeling for Rhino. http://www.grasshopper3d.com/profiles/blogs/louisiana-state-museum-and-sports-hall-of-fame. Accessed 14 May 2014

Thün G, Velikov K, Sauvé L, McGee W (2012) Design Ecologies for Responsive Environments: Resonant Chamber, an Acoustically Performative System. In: Synthetic Digital Ecologies: Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture. 373–382. ACADIA. San Francisco: California College of the Arts

Trahan Architects (2013) Featured work: Louisiana State Museum. http://www.trahanarchitects.com/158624/1645131/featured-work/louisiana-state-museum Accessed 14 May 2014

Vinnitskaya I (2012) KamerMaker: Mobile 3D printer inspires potential for emergency relief architecture. In: Archdaily. http://www.archdaily.com/274798/kamermaker-mobile-3d-printer-inspires-potential-for-emergency-relief-architecture/ Accessed 28 May 2014

Virginia Tech Interior Design (2012) Two minutes with Michel Rojkind, of Rojkind Arquitectos. In: Interior design, Interviews. http://interiordesign.arch.vt.edu/home/twominutes-with-michel-rojkind-of-rojkind-arquitectos.html Accessed 27 March 2014

Williams A (2014) Air Max: Terminal 3 at Shenzhen Airport by Studio Fuksas Architetto. In: The architectural review. http://www.architectural-review.com/buildings/air-max-terminal-3-at-shenzhen-airport-by-studio-fuksas-architetto/8658141.article Accessed 22 March 2014

Zahner (2012) Zahner headquarters. The North dock expansion at the Zahner campus headquarters. http://www.azahner.com/portfolio/zahner-campus Accessed 20 May 2014

Zahner Press Office (2013) Company known for iconic architecture announces free software. Press release

Zimmer L (2014) 3D-printed canal house pops up in Amsterdam. May Start New Housing Trend. In: Inhabitat. http://inhabitat.com/dus-architects-3d-prints-canal-house-prototypes-in-amsterdam/ Accessed 28 May 2014

Chapter 5
Towards a 100 % Customized Architecture

Abstract The chapter envisions an agenda for a 100 % customized architecture to increase quality and performance of the built environment. Advanced machines connected to computational applications encourage an understanding of architectural design as an *information flow*. Design teams use, and in some cases develop directly, tailored tools to extract the design from specific data, such as material characteristics, customer expectations, performance options and fabrication features in order to develop projects at any scale. The growing interest of architects to experiment with advanced fabrication methods has outlined the synergy between digital and material processes in design and construction as a concept of emerging importance. This new paradigm has been defined as *digital materiality*, able to synergically connect data and material, programming and construction. This novel material awareness suggests the potential development of new families of integrated architectural systems, overcoming the limitations of contemporary construction typologies. The perspective of the radical diffusion of mass customization is discussed with an analysis of supporting conditions necessary in order to strengthen the impact of this cutting-edge research over the next decade, such as the development of accessible computational tools and digital fabrication facilities, the specification of new education systems and the definition of novel professional competences. In particular, a discussion about how the AEC sector would benefit from re-organizing its own system of contractual regulations is presented as well as how to overcome the legal constraints which are currently limiting the diffusion of advanced customized architecture.

Keywords Customized architecture · Digital materiality · Information-driven design · Information flow

5.1 The Role of Information-Driven Design

Advanced customized architecture has largely been promoted by the new tools designers are able to use nowadays. Most of the works and approaches described in this book have been developed through the use of state-of-the-art machines

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connected to computational applications, which encourage an understanding of architectural design as "information flow", rather than the more traditional concept based on geometrical objects. Designer teams use, and in some cases develop by themselves, tailored tools to streamline the design from specific data, such as material characteristics, customer or performative options and fabrication features, in order to develop projects at any scale. Computation is pervasive in terms of diffusion, and accessible if we look at the ease of use of present-day tools, within the professional field and in everyday applications.

In technical disciplines, the increased diffusion of advanced software represents one of the biggest cultural changes, which is also affecting the AEC sector. What interests us in this context is the way in which these tools activate the creation of customized architecture. One major aspect is indeed the way material and fabrication characteristics, behaviors, requirements and constraints, can drive the formation of architecture. This information does not limit the holistic behavior of the design to preconceived ideas, but inspires it to emerge, along with forms, from the integration of design constraints. On large scale projects this bottom up approach does not entirely replace the traditional one, but complements it with an increased level of information from the very beginning. In this sense, we partially substitute the traditional concept of design optimization as a linear process, with a new model of design workflow based on the parallel development of the actual idea and its feasibility. Fabrication characteristics are then anticipated, and considered as a new dimension to the three classical geometrical ones.

The cutting edge approaches described in this book envision a promising future: morphological freedom, new materials, alternative tectonic systems and bespoke production workflows have the potential to radically change, on a diffused level, the way we conceive architecture. However, making buildings, even before making architecture (if we can assume for a second a clear separation between the two) is one of the primary human needs, and thus has to be streamlined enough to be applicable in a diffused manner. This posits the inevitable question of what will be the possible impact of these advanced methods on the AEC sector. The optimistic nature of this book does not attempt to avoid some of the existing critical points to be faced.

If we broaden this perspective beyond the boundary of a (growing) niche of cutting-edge research, we can easily evaluate how complicated the mission of making architecture is in the context of growing worldwide problems. The global market cannot stand inefficiencies any more: economic crisis, reduced budgets, high quality demands and a forever increasing performance expectation require high quality design, an optimized construction process and efficient technical systems. The AEC sector is evolving towards more accurate and reliable procedures of contract allotment, aiming at controlling the relation between cost and advancement in the buildings construction with a limited degree of uncertainty. We believe the answer to these market expectations will inevitably pass through the redefinition of the architectural practice and profession, towards a one-off design-to-construction model able to satisfy articulated requests without compromising the sustainability of the process. To do so, the process of *advanced customization* should start from considering specific tools, ideas and approaches.

Architectural practices are called to embrace new operative models, oriented to an information-driven design. This implies the use of highly detailed parametric models from the early stages of the design, with the same degree of precision as the final model, and able to interface with Building Information Modelling (BIM) platforms to collaborate with multidisciplinary teams. Moreover, the manufacturing machinery outlined in this book allows architects and designers to experiment directly with bespoke building components. This is increasingly sustainable as technology is rapidly evolving and getting economically accessible, with designers developing their own systems to control sophisticated fabrication machinery. The collection, accuracy and availability of information in the design phase and during the whole process, becomes crucial in this context (Fox 2009). Dedicated computational applications create the natural "environment" to develop this process, but as David R. Scheer correctly points out, imprecise computer code does not produce evocative images as an imprecise sketch might. It simply does not work. A high degree of precision is required in the computational design processes from the onset, as seen in the collection of case studies in this book. This contrasts with the drawing-based design process in which vagueness and ambiguity are essential. The designer's task is then to design an algorithmic process that reflects the design problem and leads to a stable solution, not to envision the solution directly (Scheer 2014). Moreover, Cynthia Ottchen reminds us of the need to find a way to inform the project using "soft forms of data" as well, such as aesthetics, political and cultural aspects which both modelling and BIM software are unable to process (Ottchen 2009).

5.2 A New Material Awareness

Connecting digital design with digital manufacturing allows the designer to understand material and fabrication characteristics in advance, through direct experiments, and eventually consider them in a generative way within the project development. The increased diffusion of advanced machinery, and the growing interest of architects to experiment with it, has outlined the synergy between digital and material processes in design and construction as a concept of emerging importance. This new paradigm has been defined as *digital materiality*, from the interweaving of data and material, programming and construction. Material is thus not just considered in terms of physical or aesthetic properties to enrich our conceptual design, but thoroughly explored and shaped by digital information (Gramazio and Kohler 2008).

The idea of advanced customization, informed by this novel material awareness, suggests the potential development of a new family of integrated architectural systems, overcoming the modernist tradition that classifies construction elements by pre-determined typologies of forms, structures and materials (Oxman 2012). This typological standardization was the expression of the need of automation in construction, but finally ended up in creating an architecture of mass production: assembled and built using replicated modules. Contemporary machines and design research, on the contrary, have enabled the automation of the bespoke, and the opportunity to easily explore integrated designs in a consistent and sustainable process.

The collection of case studies included in *How to build* (*almost*) *anything customized*, (Chap. 4) shows multiple examples of this tendency. Projects like the Brickfaçade of Keller AG Headquarter by Gramazio and Kohler, Arboskin Pavillion in Stuttgart by ITKE, and Building Bytes by Brian Peters have investigated specific material systems and their application in state-of-the-art construction techniques, which were impossible to achieve in an automated way just a few years ago. Nowadays, these advancements are also feasible thanks to the breakthroughs in the field of chemistry, and particularly in nanotechnologies and material properties studies.

The common research line among these (and other) projects is inevitably bringing us back to an ancient notion of craft, in which architectural elements were the result of the interaction between the craftsman and the material. The capacity of innovative machines, and robots in particular, permits us to re-discover these material implications in a very controlled way, and to overcome the humanistic nature of modern design, which imposes ideas over materials (Carpo 2014). The most evolved digital fabrication techniques allow architects to combine the intuitivity of the millenary-old material crafting, with the contemporary rationality control over the design. The outcome is a new type of architecture which is new and antique at the same time, because it is an emergent expression of the interaction between intrinsic material behaviors and computationally controlled machinery.

It is then interesting to question the possible impact of this material-based approach in architecture in a mid-time range. The major contribution of these empirical works that research novel architectural systems is, most likely, yet to be found in the significant push they offer to the evolution of the discipline of architectural design and construction. Experiments facilitate the development of different construction prototypes, innovative techniques and cutting-edge processes at a faster pace, and even if still in a research phase, their cultural impact is growing due to their effectiveness. This is probably the factor of major importance for architecture: advanced customization lets us design and build innovative concepts and products in a direct way, overcoming the typical resiliency of the overall sector towards innovation, which is often attributed to the interest of investors and contractors in maintaining the status quo, avoiding risks and holding on to their economic interests. The support of these works is already noticeable today in the increasing number of buildings adopting innovative solutions, and it is realistic to hypothesize a higher frequency, as well, in contractors specifications of innovative material and customized components at affordable cost.

5.3 Evolution of the Professional Competences

In the last few years the role of the architect has evidently been changing to meet the increasing need for competences introduced by the use of digital fabrication processes. With the evolution of construction and design disciplines, architects are required to not simply think in terms of forms and geometries achieved through the use of sophisticated machines, but to focus on the design of the behavior and responsiveness of the machines themselves (Menges 2014). The disciplines are evolving along with the technological progress and the use of innovative machinery. There are different research groups, mainly involved at the academic level (which today have a large impact on the pragmatic evolution of the field), and specializing in the fundamental development of tailored tools, both physical and virtual.

It is becoming increasingly difficult to consider digital modelling and advanced fabrication as two separated phases of the architectural process, with the progressive merging of design and production, and the perspective of a "massive customization" in the field supported by the industrial shift. Architects are requested to develop definite competences: programming skills, deep understanding of fabrication techniques and working on the material engineering. The education system in the field is nowadays severely challenged to provide the needed skills, which are often developed externally from the standard academic environment. Advanced customization concerns mastering digital tools in order to design and to build, and in this sense scripting and coding skills might be considered as the new literacy, to bend digital technology to one's needs and purposes (Prensky 2008). Designers will soon be pushed to control and deeply comprehend the human-machine interaction, as well as to be acquainted with the details and the specific features of the field, as they used to be with drawing and sketching in the past.

In recent years, the professional identity and the established workflow of architectural firms have been seriously challenged by the introduction and diffusion of innovative information and communication technologies (Jaradat 2012). Operators related to traditional and strictly defined contractual roles are changing towards less characterized and more trans-disciplinary roles, that can enter at different levels in the design and construction process with their competences. The traditional boundaries among different professions will cease to exist in favor of interdisciplinary work environments that involve holistic perspectives and dialogue between specialists.

An issue of Architectural Design (AD, March/April 2009), with the programmatic title *Closing the Gap* was dedicated to the complex relationship between various professional figures, in this shifting scenario of technologies and tools for the project (Ottchen 2009). The interaction between the possibilities given by the digitally controlled tools and the actual construction process is limited by traditional contracts that are rigidly segmented and regulated heavily the production of architecture. Contracts are nowadays the weak ring of the information chain, relying excessively on outdated construction methods, favoring the clear distinction between the design and construction phases. To strengthen the impact of this cutting-edge research it is now fundamental that architects re-discuss their own system of regulations at the boundary with other disciplines, to overcome the last obstacle towards a diffused model of advanced customization.

5.4 Towards a 100 % Customized Architecture

The book promotes the goal of a 100 % customized architecture in a provocative way, considering how it would positively impact the quality and performance of architectural solutions. With this perspective, we can use a "what if analysis" to reflect on the actual constraints and to predict possible scenarios of development of a fully customized design and construction process.

What if innovative software products would allow designers and users to tailor advanced project solutions in an intuitive way? This could encourage the spread of computational potential in design, and extend the limits of the traditional construction process.

What if the cost of advanced manufacturing could be lowered enough to compete with mass production costs? Construction systems could be differentiated and unique in any project, raising the level of architectural originality, performance and efficiency.

What if final users in AEC could be directly involved in the design process, and could participate in raising the quality of the systems they are buying, similarly to what is happening now in the fields of furniture and fashion design? The actual level of involvement is still low due to many constraints typical of the manufacturing process, but new fabrication methods will allow more participative designs.

What if major contractors could esteem the effective value of optimizing the construction process? The contractual phase of design would be significantly different and performance oriented instead of quantity oriented, as it often happens now.

What if, finally, legislation would make the use of digital information compulsory along each phase of the design and the construction chain? This would help the dialogue among the different stakeholders, which could perform different operations from a common digital platform, ensuring higher levels of interaction and quality of the construction. Indeed, the imposition of regulations is often the only way to boost innovation in construction.

Advanced methods of production are not intended to entirely replace the traditional ones, which would remain the most appropriate solutions for some applications. This is not necessarily a limitation if we consider the deeper human-machine interaction envisioned by many as an inevitable step towards *The Fourth Industrial Revolution*, where robots and humans will work hand in hand on interlinking tasks, utilizing smart sensor Human Machine Interfaces (Blanchet et al. 2014).

With this perspective, we think the above mentioned *what if* scenarios would become effective in the next decades. *Towards* 100 % *customized architecture* is therefore not only an optimistic vision, but a realistic agenda for advanced, high performance architecture.

References

Blanchet M, Rinn T, Thaden G, Thieulloy G (2014) Industry 4.0. The new industrial revolution. How Europe will succeed. In: Think Act. Beyond mainstream. Roland Berger Strategy Consultants GmbH. http://www.rolandberger.de/media/pdf/Roland_Berger_TAB_Industry_4_0_20140403.pdf Accessed 12 August 2014

Carpo M (2014) In conversation with Matthias Kohler. In: Gramazio F, Kohler M (2014) Fabricate: Negotiating design and making. p. 12–21, gta Verlag, ETH Zurich, Zurich

Fox S (2009) Factory 2.0. Highly distributed sustainable ideation, propagation, and creation of physical products. In: Paoletti I (2009) Innovative design and construction technologies. Maggioli Editore, Santarcangelo Di Romagna, pp. 475–485

Gramazio F, Kohler M (2008) Digital Materiality in Architecture, Lars Muller Publishers, Baden

Jaradat S (2012) The architect's role and the interactions in BIM-enabled projects. In: Javernick-Will A, Mahalingam A (2012) Proceedings—EPOC 2012 Conference. Rheden, The Netherlands

Menges A (2014) In conversation with Philip Beesley. In: Gramazio F, Kohler M (2014) Fabricate: Negotiating design and making. p. 156–165, gta Verlag, ETH Zurich, Zurich

Ottchen C (2009) The future of information modelling and the end of theory: Less is limited, more is different. In: Garber R (2009) Closing the gap. Information models in contemporary design practice. Architectural Design AD Journal 79: 22–27. doi: 10.1002/ad.845

Oxman N (2012) Material computation. In: Fabvolution. Disseny Hub Barcelona (Ed.), A Barcelona City Council Publication, Barcelona

Prensky M (2008) Programming is the new literacy. In: Edutopia Web. http://www.edutopia.org/literacy-computer-programming Accessed 18 August 2014

Scheer D R (2014) The death of drawing: Architecture in the age of simulation. Routledge, New York

Glossary

Algorithm A procedure or formula for solving a problem. In the context of digital design, it is a set of clearly defined steps describing a computational process. Algorithms usually take inputs, perform a process and create an output.

Automation The use of various control systems for operating equipment such as machinery, processes in factories, with minimal or reduced human intervention. Automation has been achieved by various means including mechanical, hydraulic, pneumatic, electrical, electronic and computers, usually in combination.

BIM (Building information modelling/Building information model) A computer-aided method for generating project data and managing it throughout the entire building life cycle. With the use of 3D modelling software a building information model (BIM) is produced. The BIM contains not only the geometry but also information about the spatial relationships, the geography, the quantities and the characteristics of the building components of the project.

CAD/CAAD (Computer-aided design/Computer-aided architectural design) A software that is used by architects, engineers and designers to create precision drawings or technical illustrations. CAD software can be used to create two-dimensional (2-D) drawings or three-dimensional (3-D) models.

CAM (Computer-aided Manufacturing) The use of computer software as a tool to control a machine or a fabrication process. A CAD file is required to control a CAM machine.

CNC (Computer numerical control) machine A machine that is using computer controls in order to process three-dimensional objects and surfaces out of solid materials. It is translating programs of specific number and letters to move the spindle to various locations and depths. CNC systems are used for any process that can be described as a series of movements and operations including laser cutting, welding, ultrasonic welding, flame and plasma cutting, bending, spinning, hole-punching, pinning, gluing, fabric cutting, sewing, tape and fiber placement, routing, picking and placing (PnP), and sawing.

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Fab Lab (Fabrication laboratory) A small-scale workshop offering (personal) digital fabrication. It is generally equipped with an array of flexible CNC—tools that cover several different length scales and various materials, with the aim to make "almost anything". These devices can be tailored to local or personal needs when using mass production methods are not practical or economical.

Firefly It is a set of comprehensive software tools dedicated to bridging the gap between Grasshopper, the Arduino microcontroller and other input/output devices like webcams, mobile phones, game controllers and more.

G-Code One of the most widely used numerical control (NC) programming language.

Gantry robot Also called Cartesian or linear robot, it is an industrial robot that consists of a manipulator mounted on an overhead system that allows movement across a horizontal plane. They are usually large systems that perform "pick and place" applications, but they are also used in welding and other applications.

Genetic algorithm In computer programming, it is an algorithm that uses the metaphor of natural evolution to search for the fittest solution to a specific problem.

Grasshopper™ It is a graphical generative algorithm editor tightly integrated with Rhinoceros 3-D modeling tools. Algorithms are created by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components. Grasshopper's components create 3D geometry and process different type of data including numeric, textual, audio-visual and haptic applications.

HAL robot programming It is a Grasshopper http://www.grasshopper3d.com/ plugin for industrial robots programming supporting ABB, KUKA and Universal Robots machines. Its large library allows designers to simulate, program, control and monitor simple or multi-robots cells in near real-time.

Jet cutting/Waterjet An industrial tool cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. In this process, the CNC-controlled procedure is very precise and efficient.

Kangaroo It is a live physics engine for interactive simulation, optimization and form-finding directly within Grasshopper.

Laser cutting machine A machine that is directing the output of a high-power laser at a material in order to slice through it or to engrave a pattern on its surface, using a CAD file.

Manufacturing The production of merchandise for use or sale using labor and machines, tools, chemical and biological processing, or formulation. The term may refer to a range of human activity, from handicraft to high tech, but is most commonly applied to industrial production, in which raw materials are transformed into finished goods on a large scale.

Mass customization The use of flexible computer-aided manufacturing systems to produce custom output. This type of systems combine the low unit costs of mass production processes with the flexibility of individual customization.

Maya autodesk software It is used to create interactive 3D applications, including video games, animated film, TV series, or visual effects. Users define a virtual workspace (scene) to implement and edit media of a particular project. Maya exposes a node graph architecture. Scene elements are node-based, each node having its own attributes and customization. As a result, the visual representation of a scene is based entirely on a network of interconnecting nodes, depending on each other's information.

Mock-up A scale or full-size model of a design or device, used for teaching, demonstration, design evaluation, promotion etc. A mockup is a *prototype* if it provides at least part of the functionality of a system and enables testing of its design.

Moulding A process of manufacturing by shaping liquid or pliable raw material using a rigid frame called a mold or matrix. A mold is the counterpart to a cast.

Nesting The process of laying out cutting patterns to minimise the raw material waste. To reduce the amount of scrap raw material produced during cutting a flat sheet a nesting software can be used to determine how to optimize cut geometries.

Nibbling A type of punching production procedure for perforating and processing metal panels. Using this process complex forms are blank cut with multiple CNC-controlled applications of a simply formed tool.

Open-source hardware Open source hardware consists of physical artifacts of technology whose design in addition to the software that drives the hardware, are all released with the FOSS approach.

Parametric design A design process based on algorithmic logic that enables the implementation of parameters and rules that define, encode and clarify the relationship between design intent and design response. Parametric softwares provide the user with the opportunity of creating associative connections between the generated geometries thus a higher level of intelligence and flexibility of the process is achieved.

Plug-in In computing, a plug-in (or addon) is a software component that adds a specific feature to an existing software application. When an application supports plug-ins, it enables customization.

Rapid prototyping Printing in three dimensions using a CAD file. The object is built by layering, each new layer is bonded or melted to the previous one.

Rhinoceros 3D software It is a 3-D modeling software, developed by Robert McNeel & Associates that specializes in free-form non-uniform rational B-spline (NURBS) modeling. The software is commonly used for industrial design, architecture, jewelry design, automotive design, CAD/CAM, rapid prototyping, reverse engineering, etc. There are over 100 third-party plugins developed, some of them for CAM and CNC milling, allowing for toolpath generation directly in Rhino. It features a scripting language, based on the Visual Basic language, and an SDK that allows reading and writing Rhino files directly.

Robotic arm A type of programmable mechanical arm with similar functions to a human arm. The links of such a manipulator are connected by joints allowing either rotational motion or translational (linear) displacement. The links of the manipulator can be considered to form a kinematic chain. The terminus of the kinematic chain of the manipulator is called the end effector and it is analogous to the human hand.

Scripting The development of small program extensions which display the analysis of a variety of possible solutions to a specific problem. This process leads from an original formulation of a computing problem to executable programs which involve activities such as analysis, understanding, and generically solving problems resulting in an algorithm.

Selective laser sintering An additive manufacturing technique used for the low volume production of prototype models and functional components. Selective Laser Sintering uses lasers as its power source to sinter powdered material, binding it together to create a solid structure.

Shear cutting A separation of a construction material by two cutters which pass across each other in other words separation through the use of shear forces.

STL format STL (STereoLithography) is a file format native to the stereolithography CAD software created by 3D Systems. STL is also known as Standard Tessellation Language. It is widely used for rapid prototyping and computer-aided manufacturing. STL files describe only the surface geometry of a three-dimensional object without any representation of color, texture or other common CAD model attributes.

Thermo cutting A procedure for shaping foam materials into a desired shape using a heated steel tool and then heat-sealing them to other foam particles by butt-welding with heat reflectors.

Digital assembly line A digital chain in conjunction with computerized construction processes that enable an efficient flow between drafting, preliminary design, fabrication and construction processes.

3D printer A 3D printer is a type of industrial robot that is capable of carrying out an additive process under computer control. It prints three-dimensional solid objects of virtually any shape from a digital model using a plaster-based material bonded with glue.

3D scanner A device that digitally records the three-dimensional properties of an object, collects data on its shape and appearance (e.g. colour) and creates a CAD 3D—model that can be manipulated and reproduced. 3D laser scanning machines use line- or grid-based scanning methods in order to measure objects.

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