ROBOTIC ARMS IN THE FUTURE OF ARCHITECTURE

Lilach Porges
Instructors: Prof. Arch. Etan Kimmel,
Arch. David Robins,
Arch. Jonathan Dortheimer

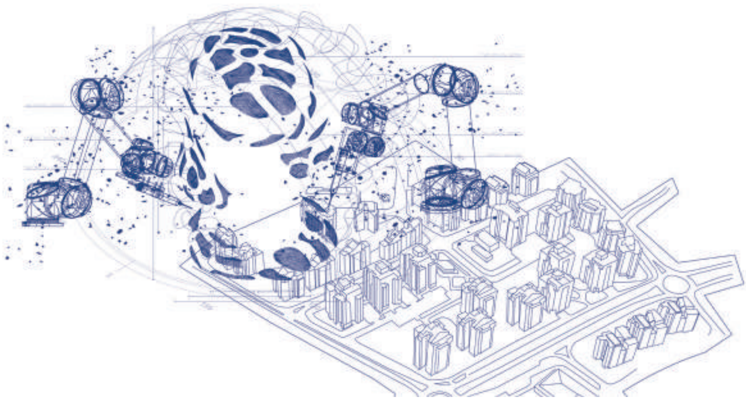
Given additive manufacturing by a robotic arm, what climatic and aesthetics opportunities could be suggested to the building's façade design?

TECHNION
Israel Institute
of Technology

ROBOTIC ARCHITECTURE

Robotic arms in the future of architecture

Lilach Porges



TECHNION
Israel Institute
of Technology

Lilach Porges

ROBOTIC ARCHITECTURE

Final Project

Technologic Studio

Instructors | Prof. Arch. Etan Kimmel, Arch. David Robins

Research Seminar

Instructors | Arch. Jonathan Dortheimer

Architecture and Town Planning Program

Faculty of Architecture and Town Planning, Technion

2021

TECHNION
Israel Institute
of Technology
Faculty of
Architecture and Town Planning

Content

Figure 1: Many cities look the same, full of generic buildings

Introduction

When driving Israel's roads, many cities look the same, full of generic buildings, which are seen all over the country – a duplication of each other (figure 1). While we are not the same, our apartments share the same plan. The environment changes from one place to another (figure 2), but the buildings repeat themselves in every city (Dickinson 2018). Each place's uniqueness has been damaged for reasons of low-cost production of repetitive architectural and construction elements by industrial techniques. Those generic building methods were satisfactory until now. However, future technology holds the promise to allow the production of buildings with many advantages over the old ones, such as uniqueness, adaptation to different building's uses, Climatical efficiency, and consideration of the environment.

Many parts and elements of a building could be the core of this project, including interior partitions, exterior walls, photovoltaic systems, windows, balconies, and interior designs (figure 3). Each of these components, and of course, many more, can be the main building element to examine, aiming to create it with the technology of additive manufacture by a robotic arm. A building element that would affect many aspects of the building, including its exterior and interior design, is its façade (figure 4). This element serves the inside of the building, where people live or work, and the outside, where the city's urban design is influenced.

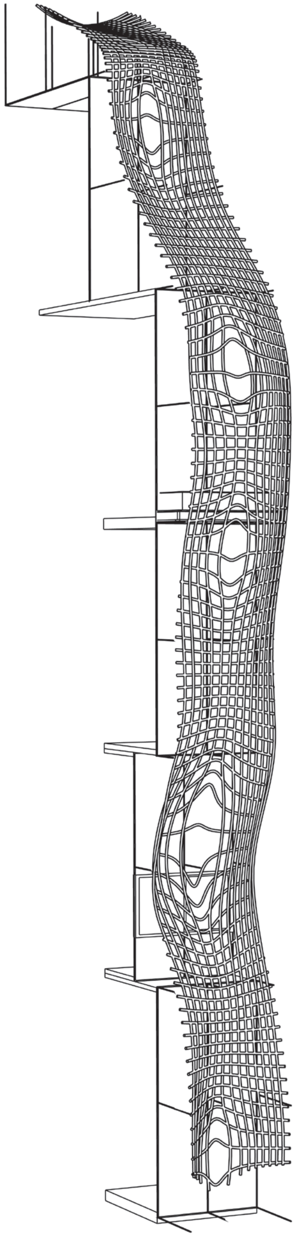


Figure 4: Façade

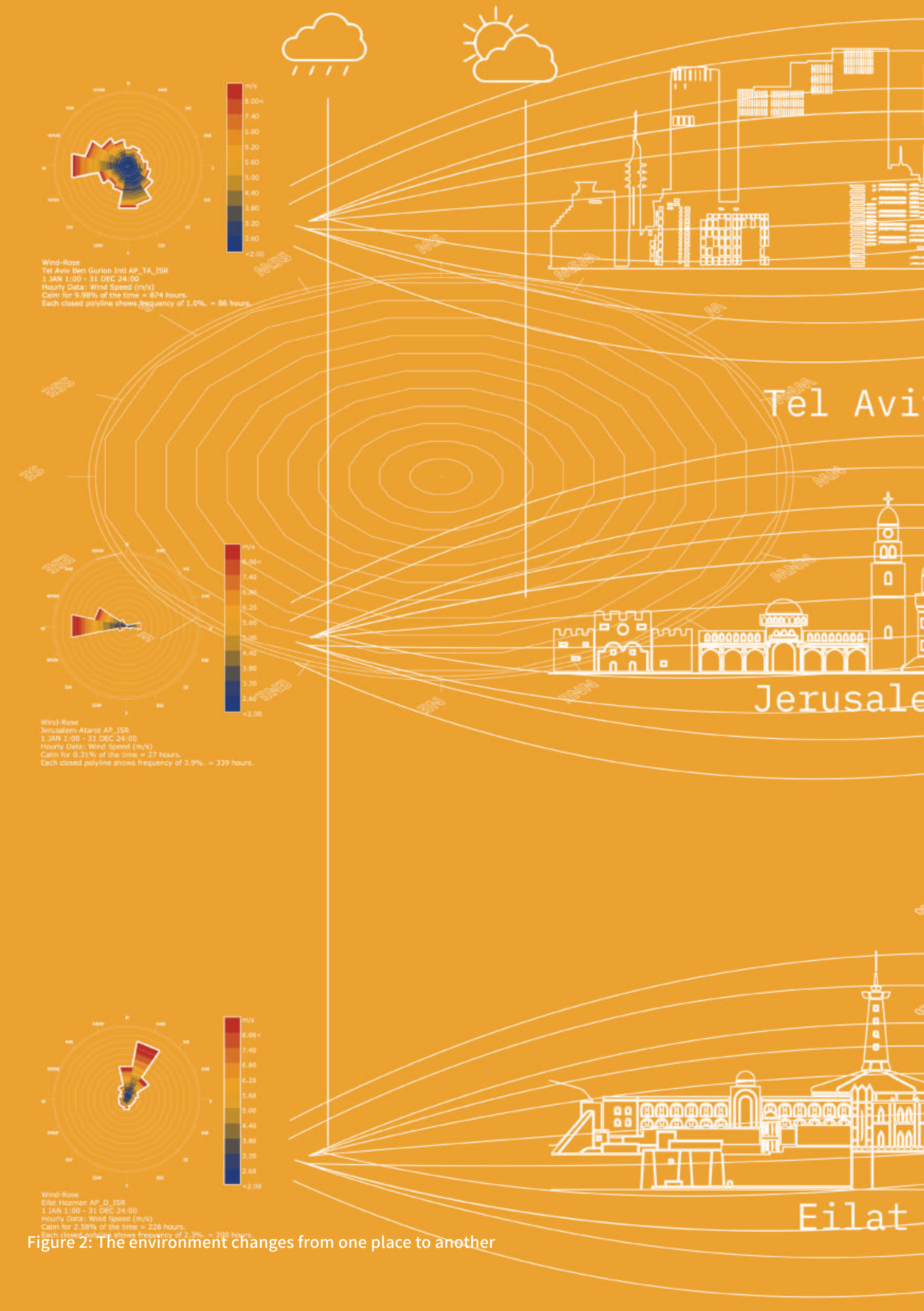
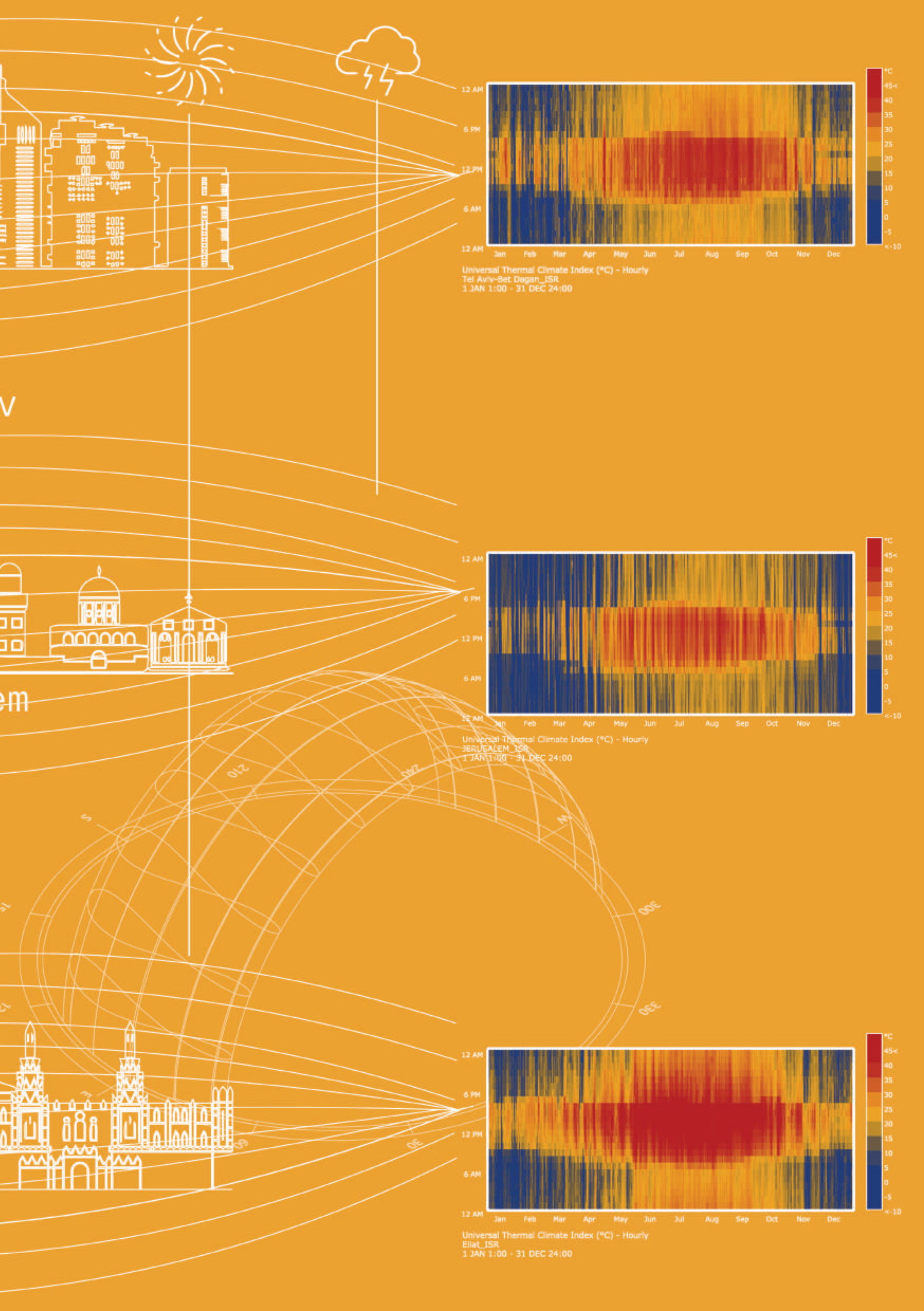


Figure 2: The environment changes from one place to another



Universal Thermal Climate Index (°C) - Hourly
Tel Aviv-Bet Dagan_ISR
1 JAN 1:00 - 31 DEC 24:00

Universal Thermal Climate Index (°C) - Hourly
JERUSALEM_ISR
1 JAN 1:00 - 31 DEC 24:00

Universal Thermal Climate Index (°C) - Hourly
Eilat_ISR
1 JAN 1:00 - 31 DEC 24:00

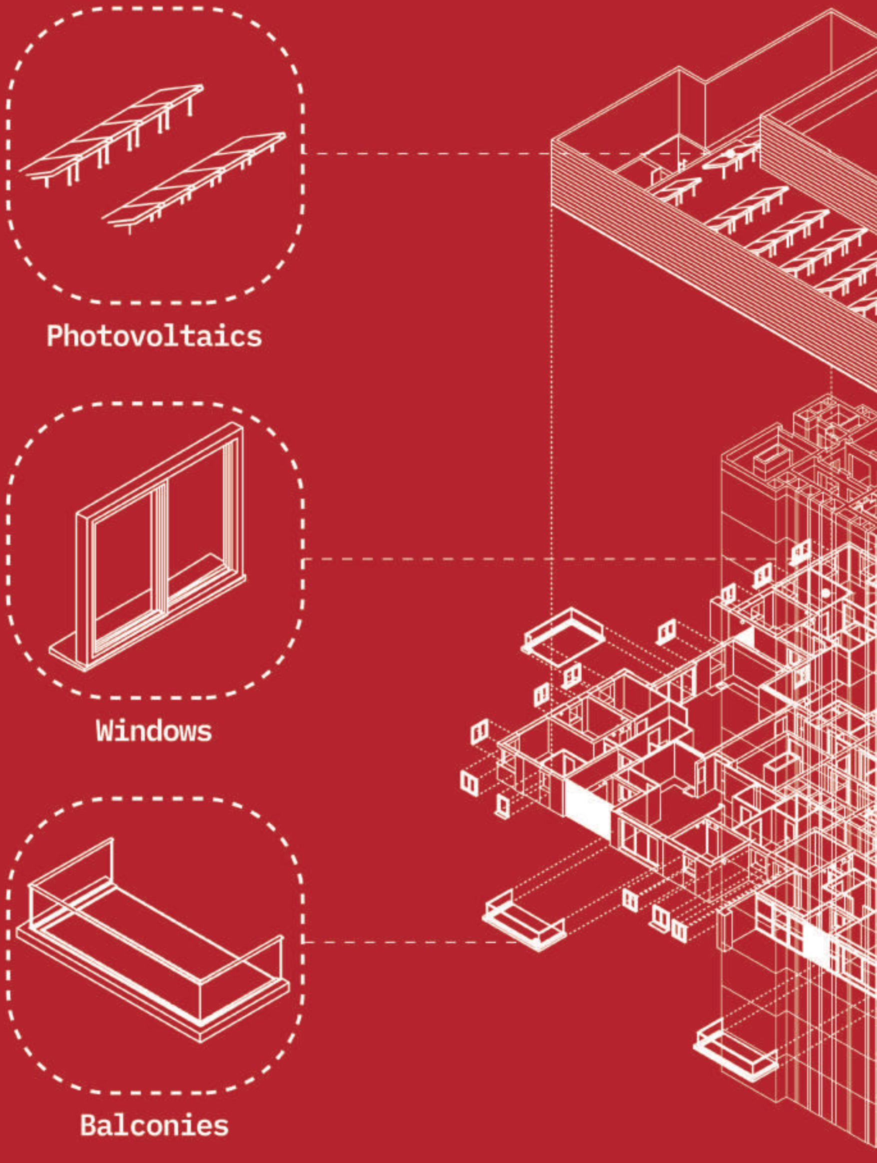
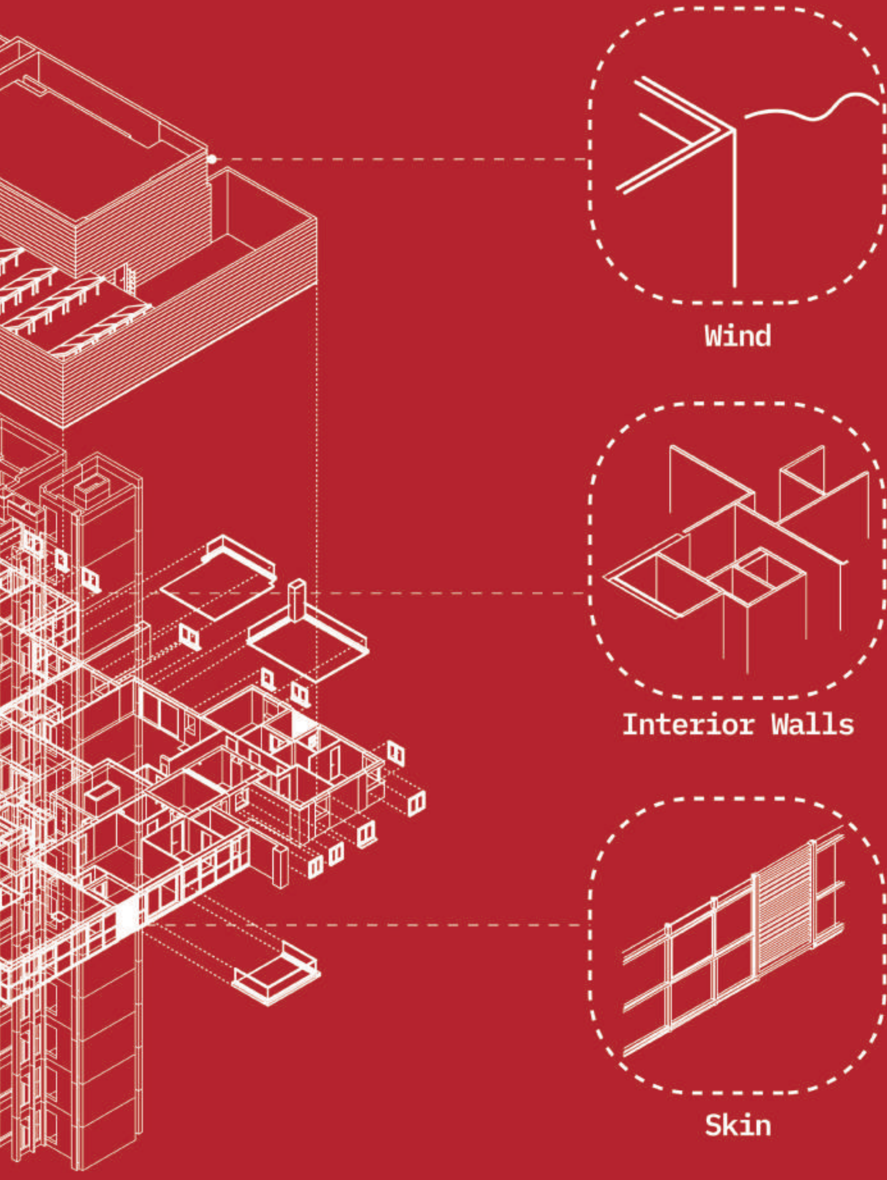


Figure 3: Parts and elements of a building


Wind
Interior Walls
Skin

The potential in additive manufacturing by a robotic arm and digital design may produce other alternatives for future building (Paoletti 2017). The project's research question is: Given additive manufacturing by a robotic arm, what climatic and aesthetics opportunities could be suggested to the building's façade design?

To address this question, a review of relevant literature and precedents was conducted, resulting in an exploration of alternative mixed-use building designs. Finally, one alternative was chosen and demonstrated.

Lack of climatic and aesthetic consideration

The building's aesthetic has significant importance. One building's design can completely change the urban perception. For example, the Guggenheim Museum in Bilbao transformed an industrial city into a popular tourism site (Ockman 2018). The distinction between cities worldwide is determined by their urban design, monuments, architectural symbols, and cultural aesthetics. Therefore, concerns about the aesthetics of the building are significant to the city experience and atmosphere.

Nevertheless, aesthetics is not enough. In recent years, architects and engineers promote principles of sustainability (Del Grosso and Basso 2010) concerning the extensive destruction of the environment and nature by humanity. As Architects that lead the builders' society, it is urgent to stop this destruction (Yeang 1998). The awareness of energy efficiency has increased following some ecology crises; therefore, energy-saving, natural ventilation, and sun protection have become more critical. Moreover, principles such as lighting, human-building interaction, and many more became the center of architectural thinking (Del Grosso and Basso 2010).

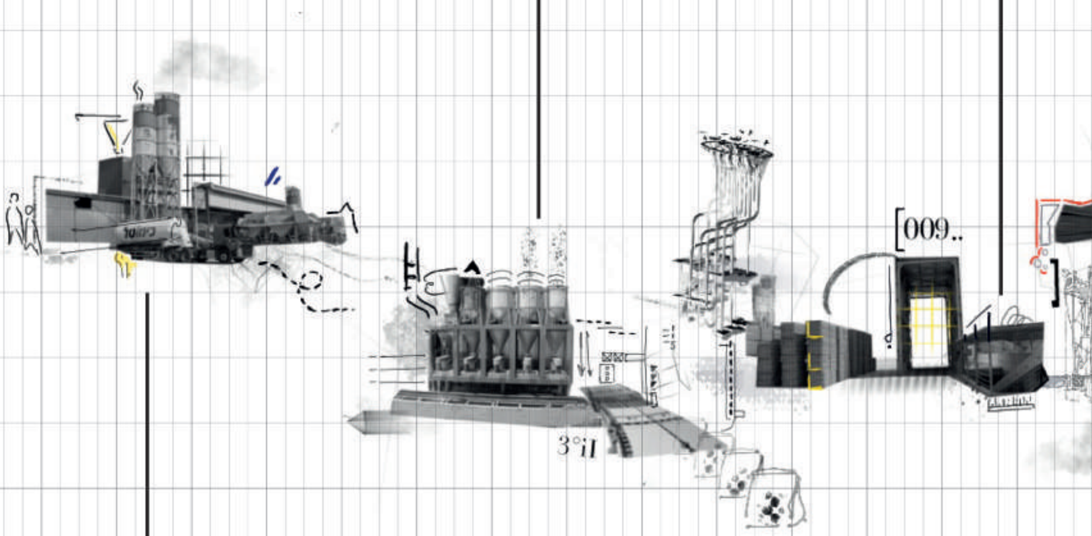
While many architects attempt to address these challenges, many buildings end up generic. One of the reasons for that is the low-cost production by industrial methods (figure 5). The notion of industrialization is to speed up building processes while reducing costs. The industrialization of building elements and construction materials allows builders to supply many buildings in less time because of the fast manufacturing of identical elements. When there is a severe lack of homes and offices, low cost and time become the leading construction principles to impact the building's design. As a result, the architectural quality of the building's design is subtracted; therefore, buildings are replicas of one another (Maas et al. 2017), and they do not fulfill many principles regarding energy efficiency and human-building interaction.

However, there are some climatic benefits in generic buildings, such as air and light directions. For instance, the building's core of the H-prototype building, which is seen a lot in Israel, is positioned in the middle of the floor and arranges the apartments around it, so each apartment receives two or three air and light directions. Still, there is a lack of energy efficiency principles, such as solar radiation and wind power consideration, which can shape the building to work together with the conditions in order to create a more sustainable and comfortable environment for humans.

The first example of the lack of climatic consideration in the generic buildings is their usual shape, which is mainly orthogonal; therefore, they do not deal well with the wind's forces, especially on the top floors (Alaghmandan et al. 2016). Residents of such buildings, especially on the upper floors, complain about the wind's noises. If the building had been rounded, they would have suffered less from the wind because rounded structures let the wind pass without feeling it (Alaghmandan et al. 2016). An example of such a

The industrialization of building's elements and construction materials offers builders to supply many buildings in less time because of the fast manufacturing of identical elements

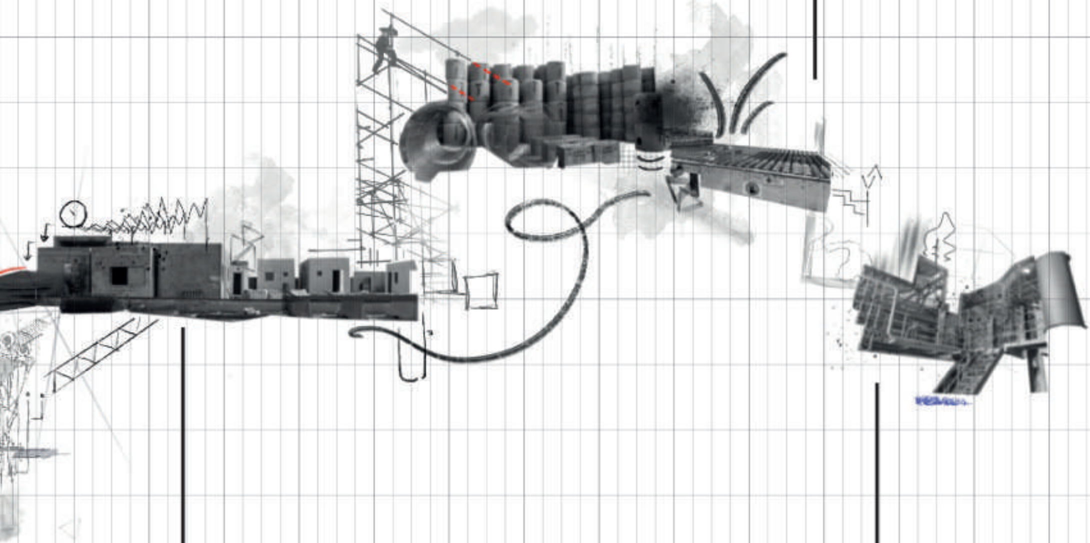
The building's shape is determine by the shape of it raw materials, the Itong brick.



Each place's uniqueness has been damaged for reasons of low-cost production of repetitive architectural and construction elements by industrial techniques.

Figure 5: Low-cost production by industrial methods

As architects, it is our obligation to prevent a repetitive unchanging world.



The generic buildings replicate one another, as the repetitive manufacture of bricks, predominantly residential and office buildings.

When there is a severe lack of homes and offices, low cost and time become the leading construction principles to impact the building's design and planning.

building is 30 St Mary Axe, also known as the Gherkin, by Foster and partners (Foster + Partners 2003). Different architectural shapes affect the wind flow differently (figure 6) (Kormaníková et al. 2018); therefore, it should be a priority when planning the building's overall shape.

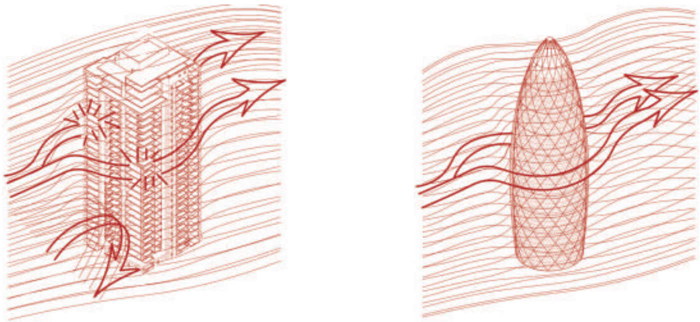


Figure 6: Different architectural shapes affect the wind flow differently

The second example is expressed by the positioning of the floors, which is not ideal to the light direction (figure 7). Sometimes there is too much solar radiation on the wrong window or balcony. One side of the building receives too much radiation, while the other side receives too little. That is because the architecture relates to different sides with the same materials and architectural elements.

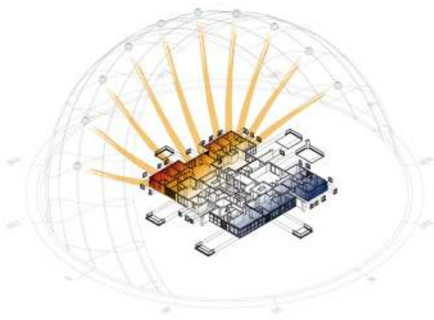


Figure 7: The positioning of the floors is not ideal to the light direction

The third example is expressed by photovoltaic cells usually installed on the rooftops of the generic buildings to heat the apartments' shower water. Using new technologies, buildings with photovoltaic façades can allow solar energy instead of electricity throughout the building, for instance, EPFL Quartier Nord in Switzerland (figure 8) (Richter Dahl Rocha & Associés 2014). Moreover, recent technologies of micro solar cells that are smaller than 1 square centimeter can be placed on the façade of a building (Cossu et al. 2016).

Figure 8: EPFL Quartier Nord in Switzerland (Richter Dahl Rocha & Associés 2014)

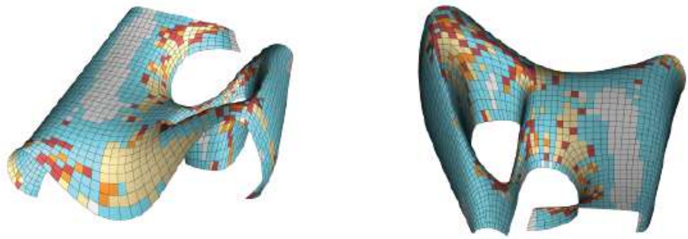
New technology developments may solve these issues. Digital design could offer a new way to plan a building's façade by sustainability principles, such as wind impacts, climate comfort, and energy efficiency. In addition, additive manufacture by a robotic arm may suggest the method to produce those designs.

Related works

In the last two decades, there is a tendency to create different forms of architecture. Architects shape buildings in the aesthetics of the twenty-first century according to new techniques of computational design. Those methods have provided some of the missing things in the industrialized era, but this technology is still incomplete. In particular projects like Prada in Tokyo (figure 9), Herzog and de Meuron have created concave windows, but they are identical because they were made according to specific molds (Herzog and de Meuron 2017).

Figure 9: Prada in Tokyo (Herzog and de Meuron 2017)

Another example of the attempt to create irregular shapes is Heydar Aliyev of Zaha Hadid in Baku (figure 10). However, she had to optimize the number of different components to produce to reduce the number of molds (Eigensatz et al. 2010). The production of many molds makes this kind of architecture more expensive (Elkabany, Elkordy, and Sobh 2020). Robotic construction will produce irregular shapes without molds and allow even more complex structures (Paoletti 2017).



cost/mold	0	2	18	24	30
cost/panel	1	2	5	5	5

molds	-	91	101	57	112	6
panels	224	1660	282	78	150	6

Figure 10: Molds scheme of Heydar Aliyev by Zaha Hadid in Baku (Eigensatz et al. 2010)

In the new age of technology, when robotic arms replace construction workers and tools (Horesh 2020), there will be a change in building and its product. It will no longer have to be industrialized because new technologies and production methods will become cheaper and more accessible over the years. Moreover, there has been a significant development in robotic fabrication within architecture research worldwide in recent years (Wit and Daas 2018). This new development introduces new possibilities of complex geometries and new materiality in architectural design with robotic arms and additive manufacturing technologies (figure 11).

Advanced manufacturing techniques include various 3D printers that build objects in three dimensions, layer above the layer on a horizontal base (Lu, Zhu, and F. Yuan 2018). Researchers and companies around the world have developed large 3D printers on the scale of a building. For example, with their project Olympus (figure 12), ICON aims to print structures on Mars (ICON 2020). Others have already printed houses on earth, for instance, Apis Cor (figure 13), with their technology of 3D printing of horizontal structure (Apis Cor 2020).

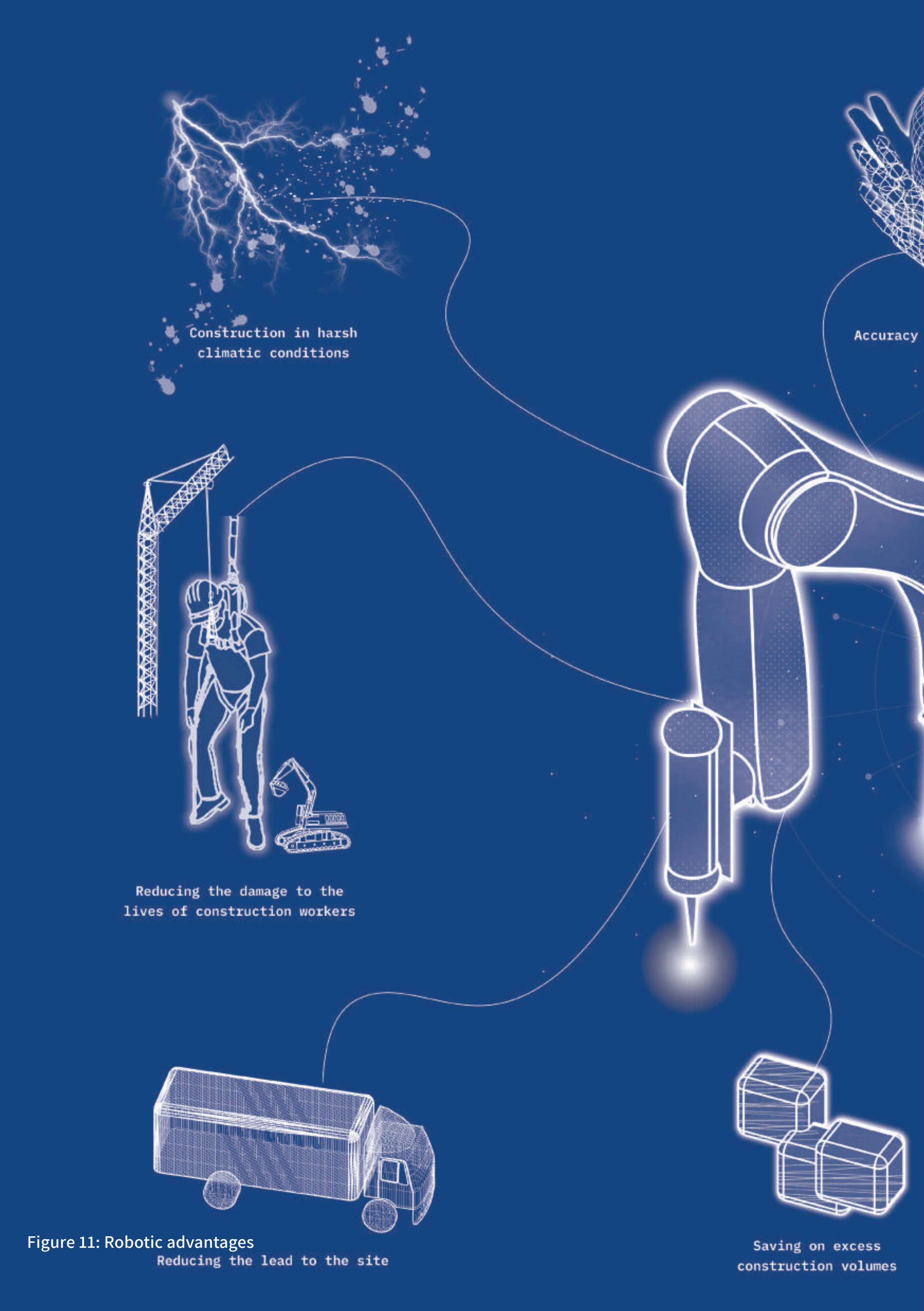
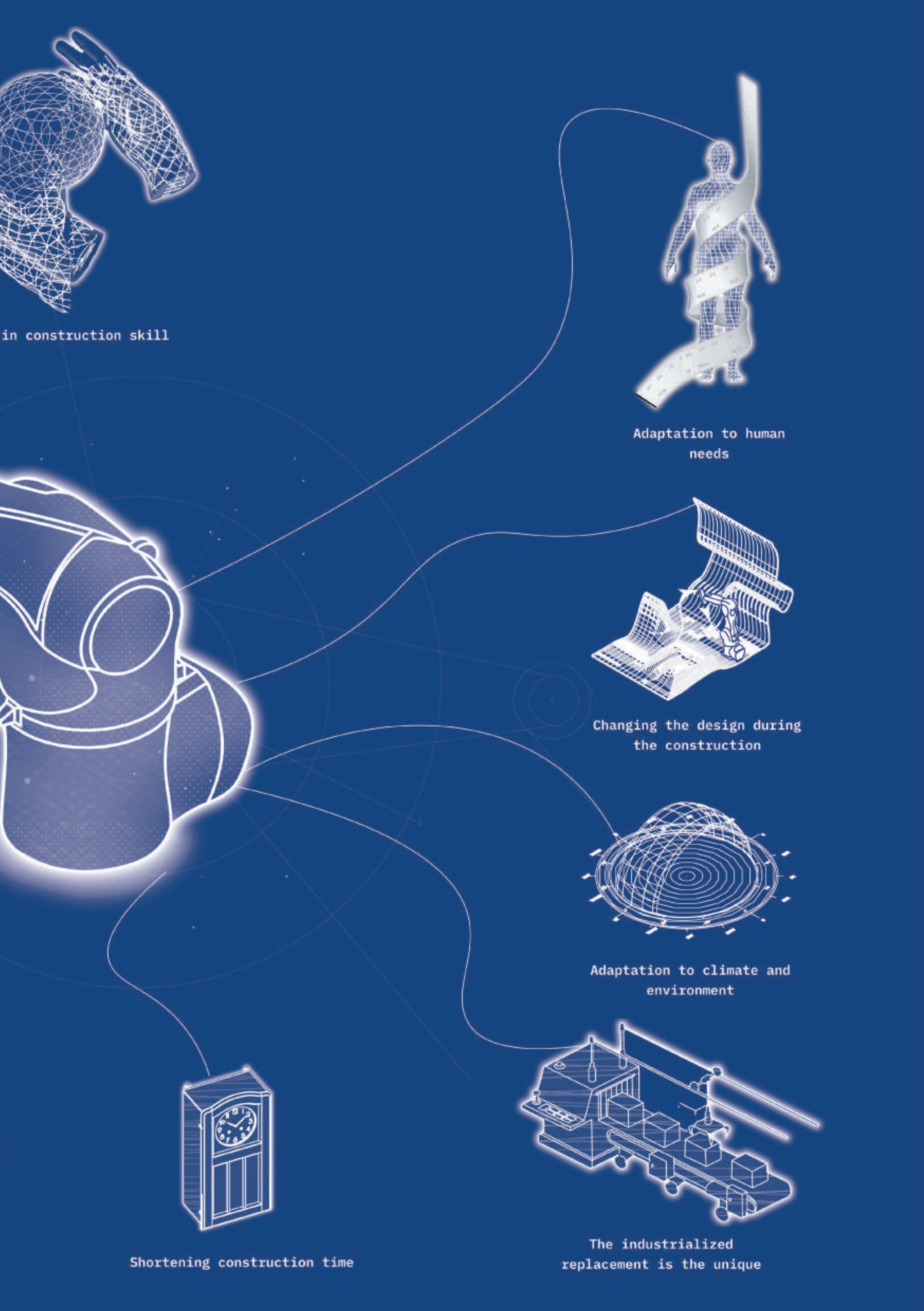


Figure 11: Robotic advantages


in construction skill
Adaptation to human needs
Changing the design during the construction
Adaptation to climate and environment
Shortening construction time
The industrialized replacement is the unique

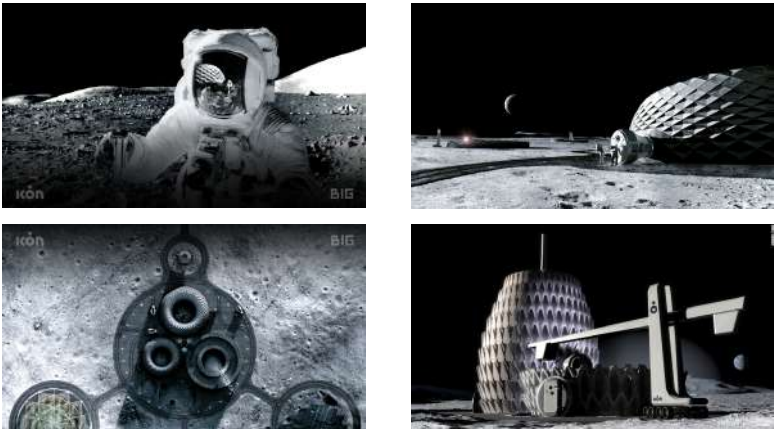


Figure 12: Project Olympus (ICON 2020)

Figure 13: The world's Biggest 3D printed building in Dubai (Apis Cor 2020)

Additive manufacturing is a technique that adds materials; it includes 3D printings on a horizontal base, but not necessarily. Additive manufacturing can be done by other types of machines, for example, robotic arms. The robotic arm has some advantages over 3D printers: It can print in more directions than X, Y and Z, because it can move freely in space and change direction simultaneously. It can be placed on a table, on a floor, or any surface one needs it to be; therefore, it can print on any surface shape. Some large robotic arms can print large-scale elements, such as the scale of a building, for prototyping and production (Paoletti 2017).

The suitable material and the right equipment hold the promise to create irregular forms. While most companies print according to gravity forces, Mataerial has a radically new additive manufacturing method – gravity-neutral 3D printing (figure 14). By their method, 3D printed objects can be created on every surface, with no additional support structures and tools (Novikov and Jokic 2013).

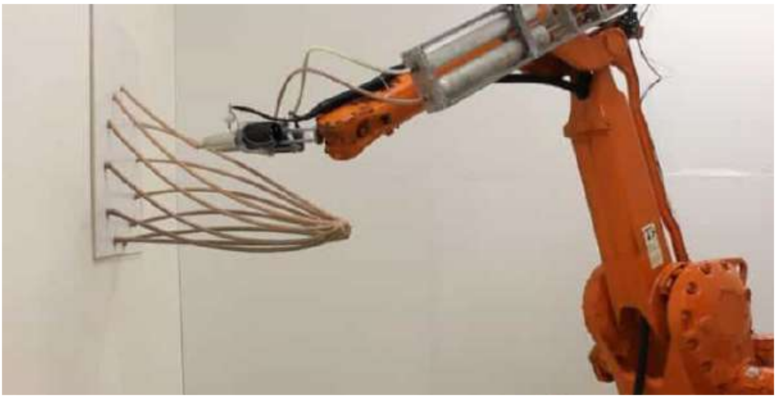
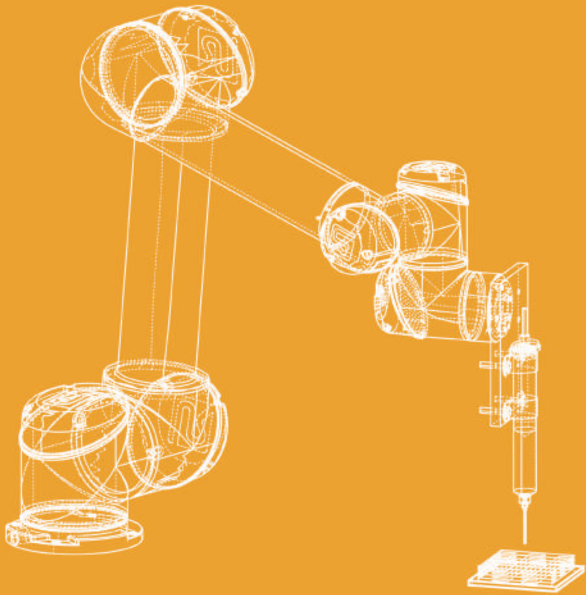
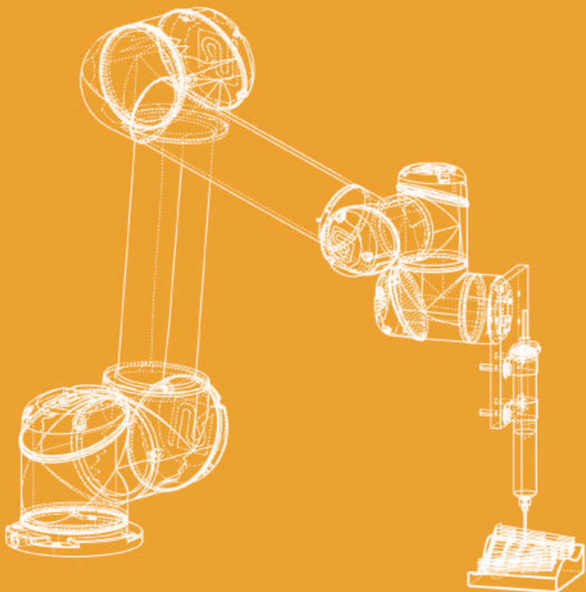


Figure 14: Additive manufacturing method – gravity-neutral 3D printing by Mataerial (Novikov and Jokic 2013)

Those researchers and companies have used additive manufacture in various methods, which defines two robotic arm printing techniques: one is similar to a 3D printer, a horizontal print in layers from bottom to top, and the second is a vertical print upright to the wall. The vertical 3D print uses the real advantage of a robotic arm over a 3D printer (figure 15).

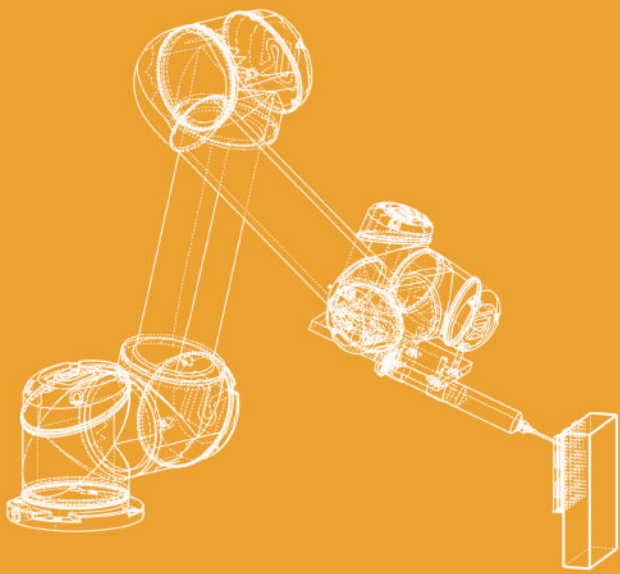


Horizontal additive manufacturing
on a flat surface

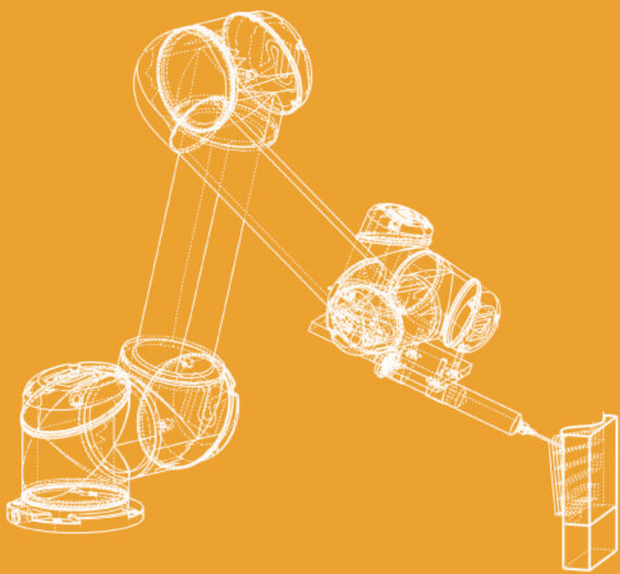


Horizontal additive manufacturing
on a curved surface

Figure 15: Robotic arm printing techniques



Vertical additive manufacturing
on a flat surface



Vertical additive manufacturing
on a curved surface

The next level of additive manufacture would be to print on a curved horizontal surface (figure 15). Schipper et al. (2017) used a robotic arm additive manufacture technique to print concrete on double curved, non-planar surfaces. These surfaces were used as a support to the printed concrete during the process of additive manufacture. The surfaces were different from each other; however, there was no wasted material in their creation (Schipper et al. 2017). On the other hand, Costanzi (2016) created adjustable surfaces on a system of pins in different heights, which communicates with the computer, so the physical surface appears digitally; therefore, the robot can print in the exact place of the three-dimensional space (Costanzi 2016).

Concrete was also added on a horizontal curved surface which was 3D printed in advance (Weiguo et al. 2018). Another team researching 3D printing of curved concrete structures created the base to print on from reusable aggregate. They shaped the aggregate with a robotic, computerized tool and printed horizontally on this double curved surface they have created (Battaglia, Miller, and Zivkovic 2019).

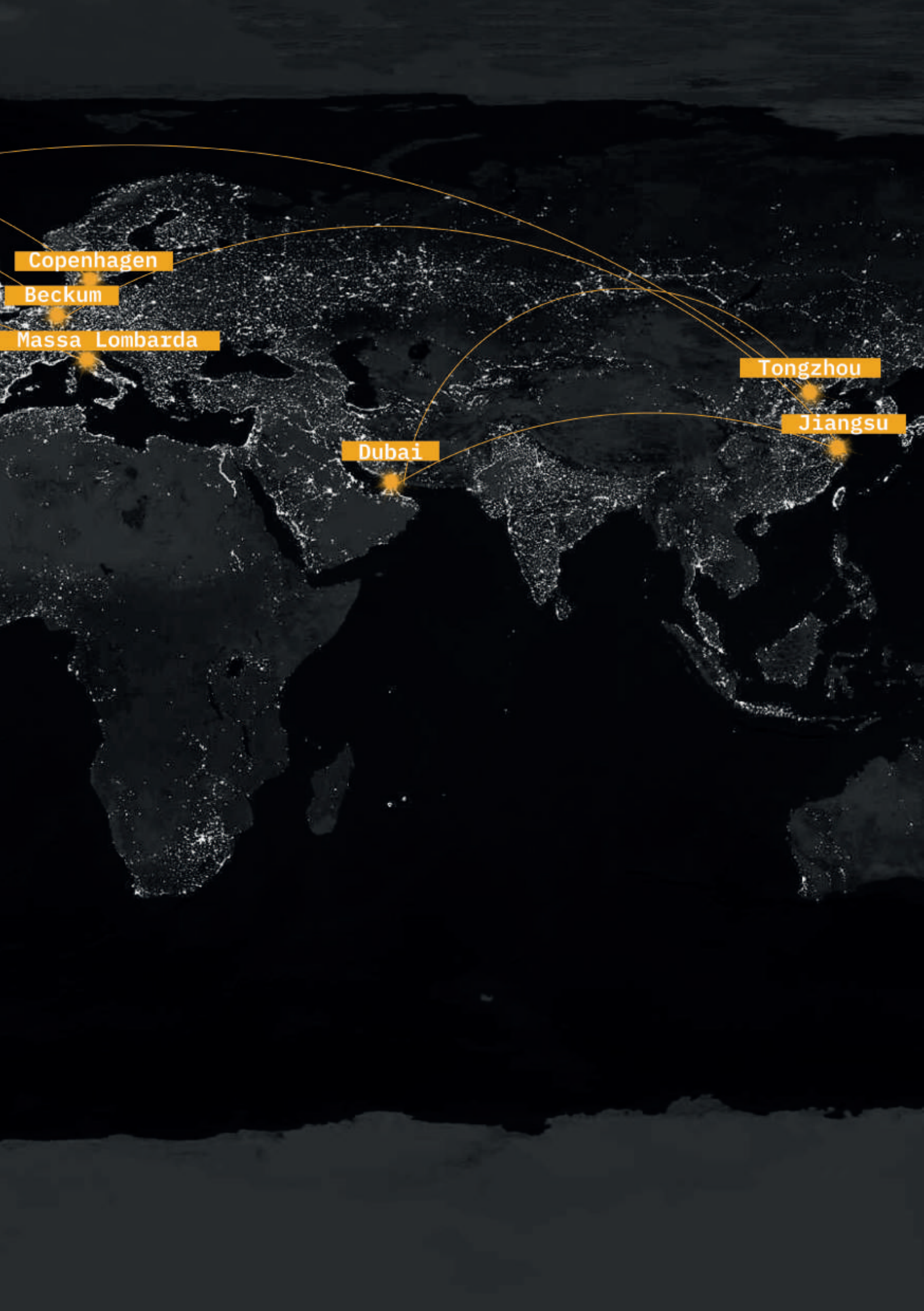
This technology is not in the far future in a distant world (figure 16). Beyond3D developed a catalog of a new generation of concrete building products utilizing robotic manufacturing technology in Israel. Beyond3D offers various products that can be customized by shape, dimensions, colors, and surface finishing. They claim to reduce production machinery costs, manual labor, manufacturing time, waste, and product damage and prevent potential risks and hazards (Beyond3D 2020).

According to automated manufacturing methods, residential and office buildings will look different from the buildings we know today. There are many possibilities for these buildings, and they can be designed by parameters we did not use before, such as sustainability properties. The architecture of the future will not be shaped according to the manufacturing methods of today.

The robotic arm's product shape is usually rounded; for instance, the Blossom vase collection (figure 17), 3D printed, demonstrates this kind of curved form. This vase imitates the fluidity and movement of a fabric (Ai Build 2020). Moreover, computational design and 3D printing technologies achieve an accurate and sophisticated production without formwork or molds, for example, the 3D-print concrete columns (figure 17), which were developed by Anton et al. (2019), are nine individually designed columns, which indicates the unique possibilities of horizontal 3D printing and the potential of computational design and digital fabrication for the future building (Anton et al. 2019).

The robotic arm can follow any kind of line, from straight to curved. This line can change according to any parameter and design. This line composes the robotic arm path, which is computerized; therefore, it is a lot more accurate than the human hand attempting to make the same path (Després et al. 2020). For example, Thallus Installation (figure 17), created by automated additive manufacturing by six-axis robotic printing technology, "demonstrates what can now be achieved in the architecture, construction, and engineering industries" (Zaha Hadid Architects 2017). Someday in the future, robotic arms will print almost any

Figure 16: Robotic arms construction companies worldwide


Copenhagen
Beckum
Massa Lombarda
Dubai
Tongzhou
Jiangsu

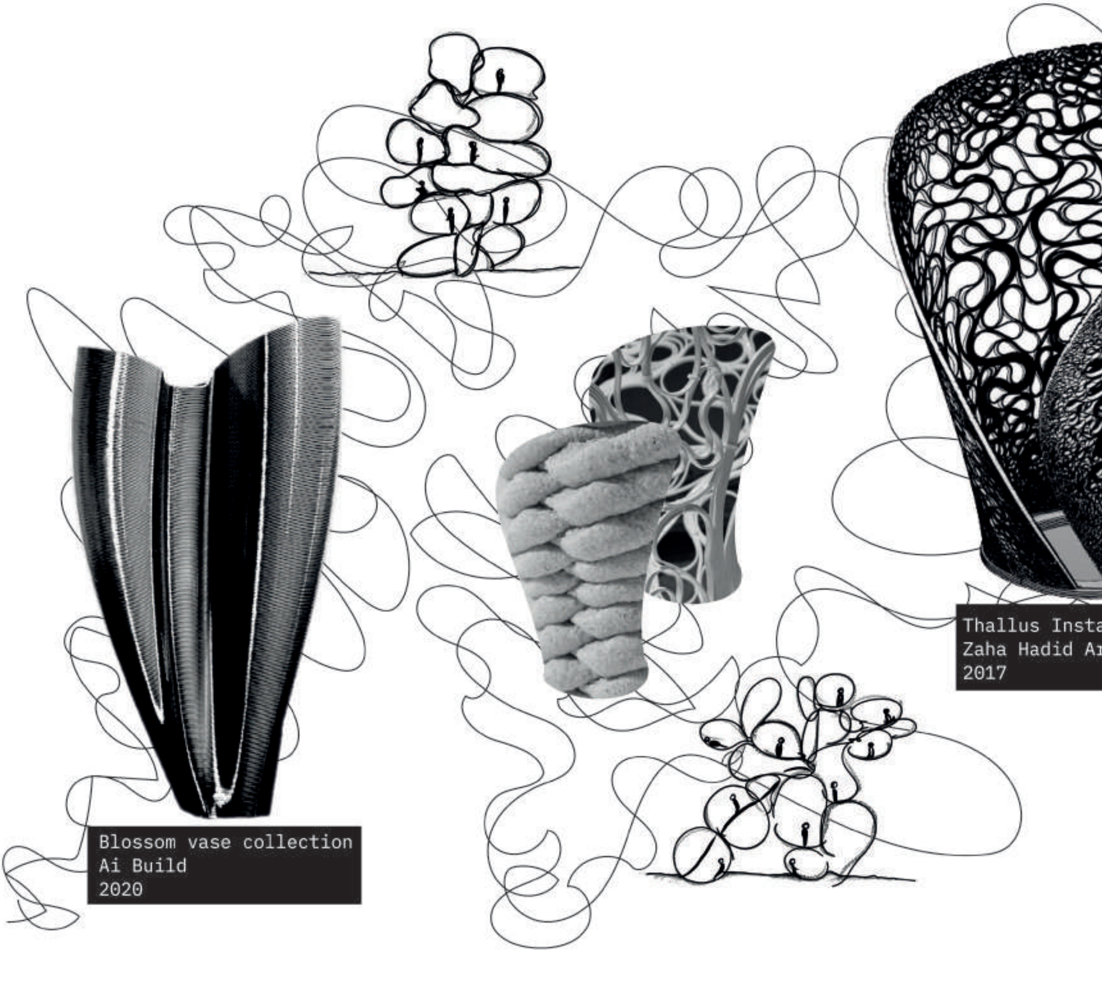
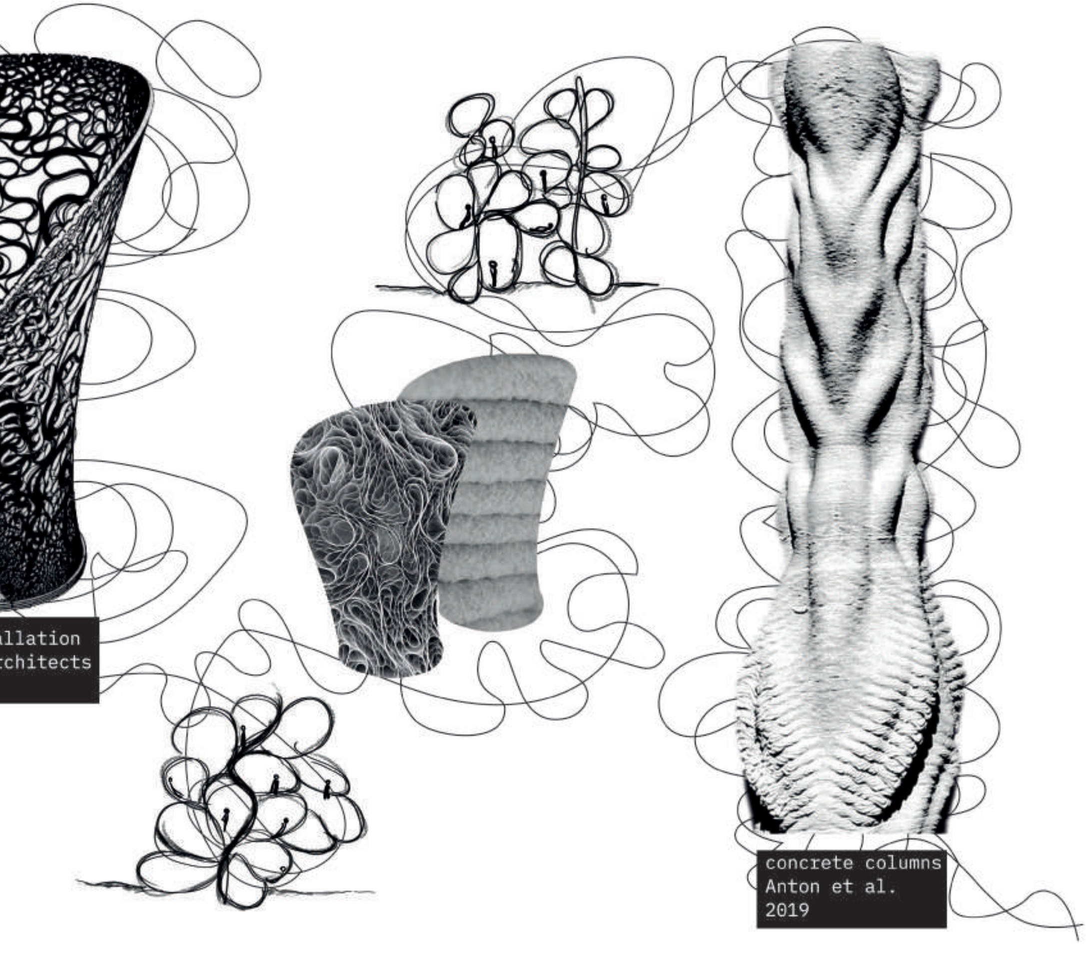


Figure 17: The shape of robotic arms' creations



llation
rchitects

concrete columns
Anton et al.
2019

shape our architectural mind will desire. As a result, the design possibilities are endless.

There are many buildings opportunities the future holds—this project attempt to examine just a pinch of them. The curved line promises some alternative designs, with advantages we could not achieve before.

Methodology

This project aims to answer the question defined earlier, 'Given additive manufacturing by a robotic arm, what climatic and aesthetics opportunities could be suggested to the building's façade design?'.

Design is a wicked problem (Rittel and Webber 1973) because many solutions would provide an answer for it. There are many possibilities for the design of the future's building, especially considering advanced technologies. The methodology I chose to answer this question is Research through Design (RtD) (Frayling 1993).

This section explains what Research through Design is, why It is suitable for this question, how data was collected and analyzed, and the tools and software. The section concludes with the limitations of this methodology and ways to overcome them.

Research through design

Research through design is a methodology that begins with assumptions and follows with a process of ideas to demonstrate them. The ideas are illustrated by iterations and replications, which can be shown as a list of alternatives. There is a study process in each alternative – one leads to the next, while the results are reported and analyzed each time. This process is usually presented in a sketchbook, describing the steps along the way. The result of this kind of research method is a specific application or action that demonstrates understanding and new knowledge (Frayling 1993). Sometimes particular rules or principles are defined at the beginning or along the process, and the solutions attempt to follow them (Rittel and Webber 1973).

To address the research question, one ought to understand that there are many possibilities for a building's façade, built according to robotic manufacturing methods. Advanced technology provides many opportunities to design building elements we could not create before. As a result, research through design methods can be suitable for this mission.

Collecting and analyzing the data

In this ocean of possibilities, the research method examines some of them until choosing one to describe. The chosen one reflects the shape of the robotic design, and it follows environmental parameters. In the beginning, some planning principles have been defined, such as adaptation to the program's functions, climatical efficiency, and unique aesthetics. Each time a building design, which attempts to answer some of the principles, has been proposed. This alternative was analyzed and reviewed by the instructors and me until it led to conclusions for creating the next one. A dictionary of possibilities demonstrate this process and the iterations along the way (figure 18). This building's façade could have many more iterations aiming to receive a better shape. Many opportunities that did not reach exhaustion are still available to examine, such as other shapes and patterns, other human-building interactions, and other climate-based designs. Eventually, one iteration has been

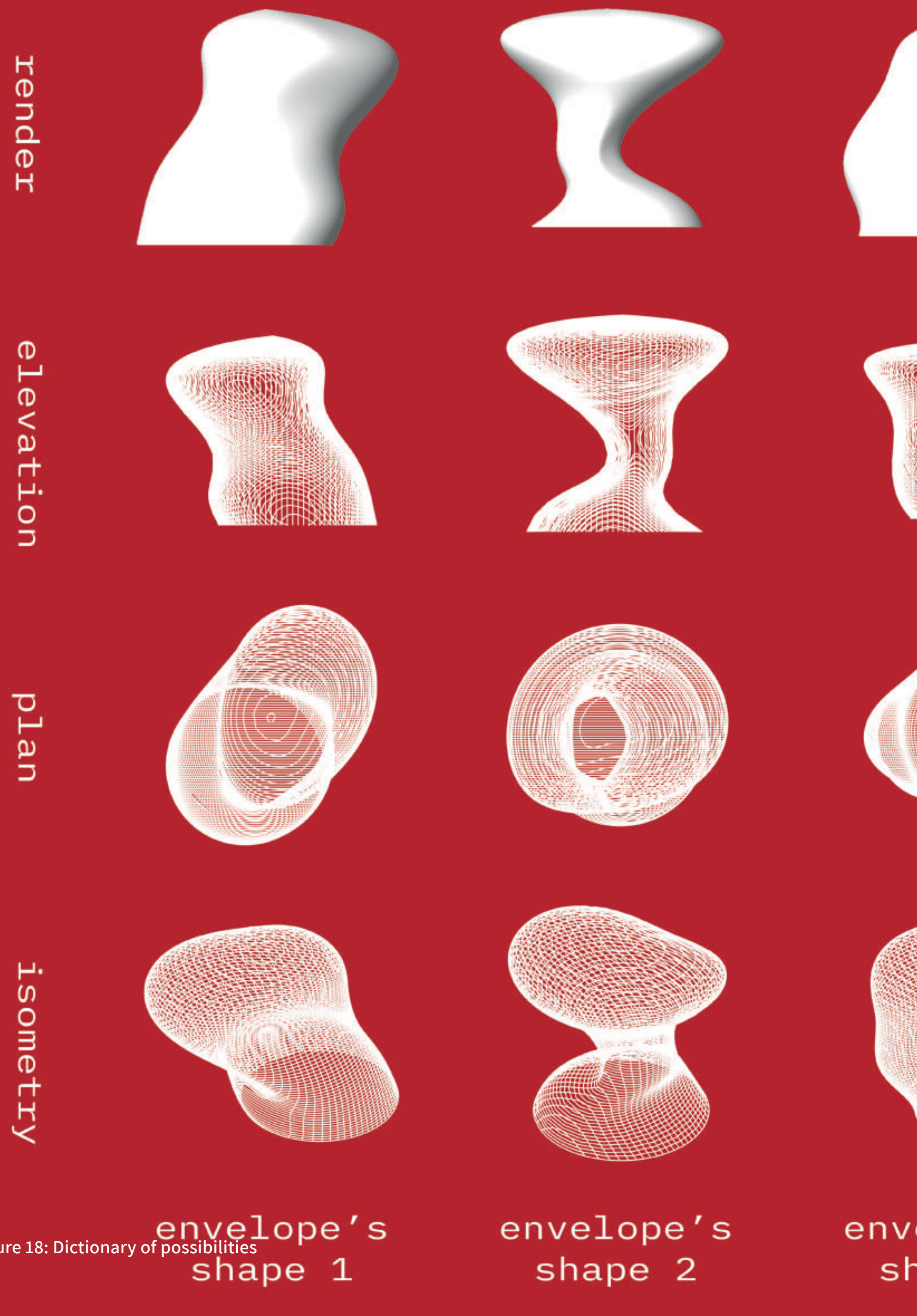
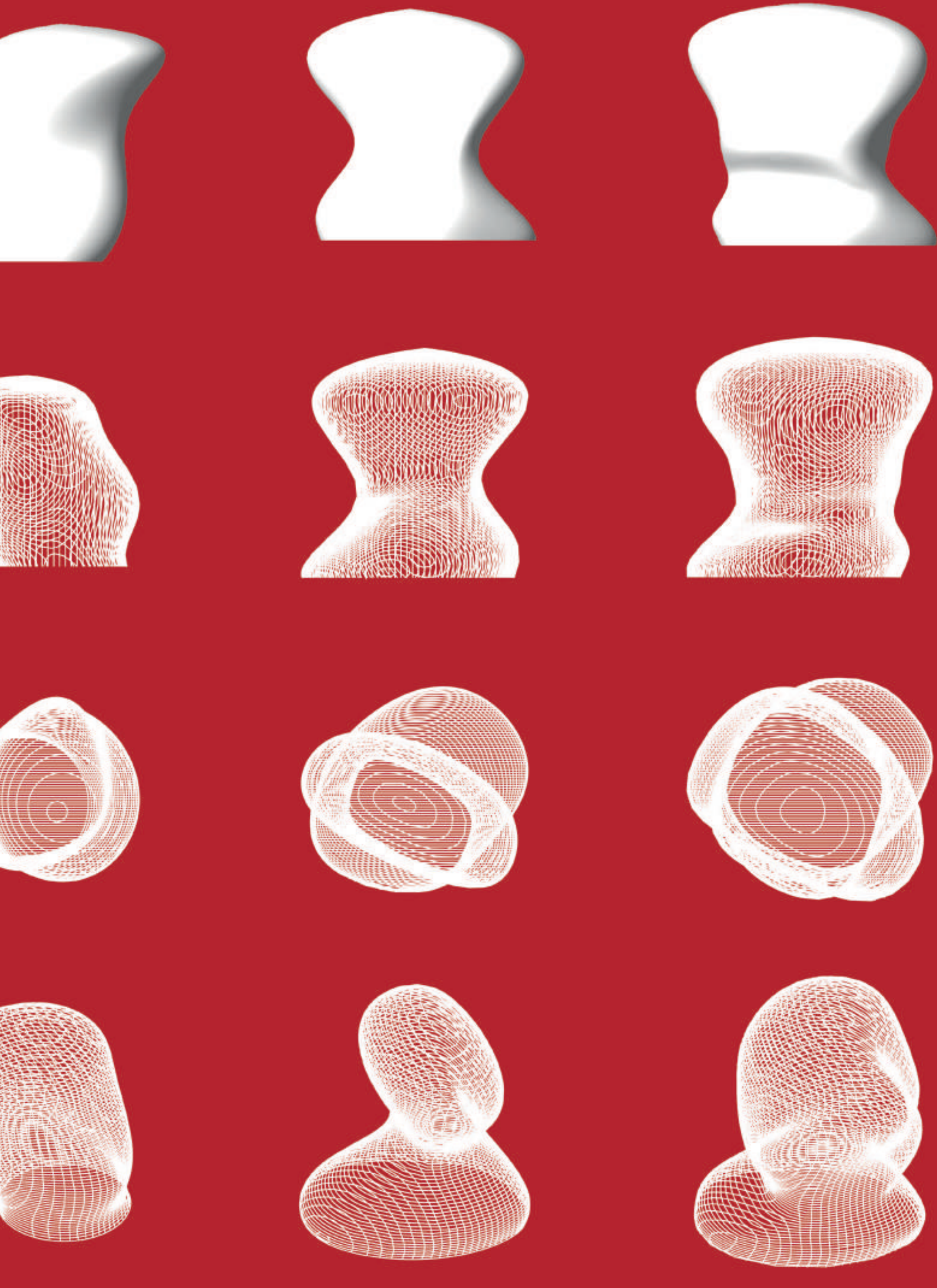


Figure 18: Dictionary of possibilities



elope's hape 3

envelope's shape 4

envelope's shape 5

chosen, and this is the one that is described in the results chapter.

Tools and Software

Each iteration began with a list of old and new principles accompanied by hand sketches inside a sketchbook. The possibilities were created by Rhino and Grasshopper's parametric design. The review was written inside the sketchbook to begin designing the next alternative. Some iterations combined an architectural model, crated by hand, laser-cutting machine, 3D printer, and a robotic arm.

Limitations

This research method is challenging because of the reasons that make design a challenging task. Design could be a never-ending process of answering a wicked question when there can always be another alternative to create. In addition, the evaluation system of the solution, which can change from one reviewer to another. Moreover, the beginning of each iteration is complicated and different from the rest (Rittel and Webber 1973).

Results: climatic and aesthetics building's façade

To answer the research question, 'Given additive manufacturing by a robotic arm, what climatic and aesthetics opportunities could be suggested to the building's façade design?', This project result is a design of a building's façade, which is based on climatic and aesthetics guides. The building's façade consists of two layers: the first is curtain walls located in all directions of the building, and the second is a parametric design print. This second skin's design is affected by principles of environmental consideration, such as solar radiation and wind power. In addition, it affects different spaces in the building.

Different façade for every building use

The program of the building is a mixed-use one in order to demonstrate different possibilities (figure 19). It contains residence apartments, offices, restaurants, shops, a kindergarten, events hall, gym, spa, pool, and lobby. The mixed-use program has been chosen because this project aims to explore the behavior of a computational designed and robotic additive manufactured building's façade in different program's functions.

This chosen program aims to examine many possibilities of the façade for different functions and various activities; therefore, the program includes some kinds of areas that require different treatment by the façade's planning (figure 20). The space requirements of offices are different from a residence, a commercial floor, a restaurant, and a ballroom. The façade also changes depending on the urban program of the place where it is located. It is affected by a city's park differently than a commercial street. Moreover, this kind of façade impacts the space around it differently. Some rooms receive privacy, while others have an extensive panoramic view. The feeling of freedom and being secured may be affected by the shape of the building's façade.

The shape of the building's façade was developed in two different scales: the scale of the building and the scale of a human. The planning by the building scale was used to alter the program function's shape, size, and locations (figure 21). For example, the events hall is placed on the top of the building in order to receive the best view and unique experience of an open sky between the façade's lines (figure 22). Another example is the kindergarten, located close enough to the ground for parents picking up their children, with a large balcony as a playground, not on the ground floor to avoid perverts and pedophiles without building a fence blocking the children's view of the landscape.

The façade was designed on a human scale to support planning decisions, such as the view amount to each function and the amount of privacy each activity requires. The façade shape created a difference between the feelings in various spaces by changing the place's height and the closeness to the façade itself. It is not feasible to touch the façade in some areas, whereas the façade is used as a security fence in others. Those changes of the façade's shape occur according to the human needs, the activity, and the function of each particular space (figure 23).

Figure 19: Mixed-use program

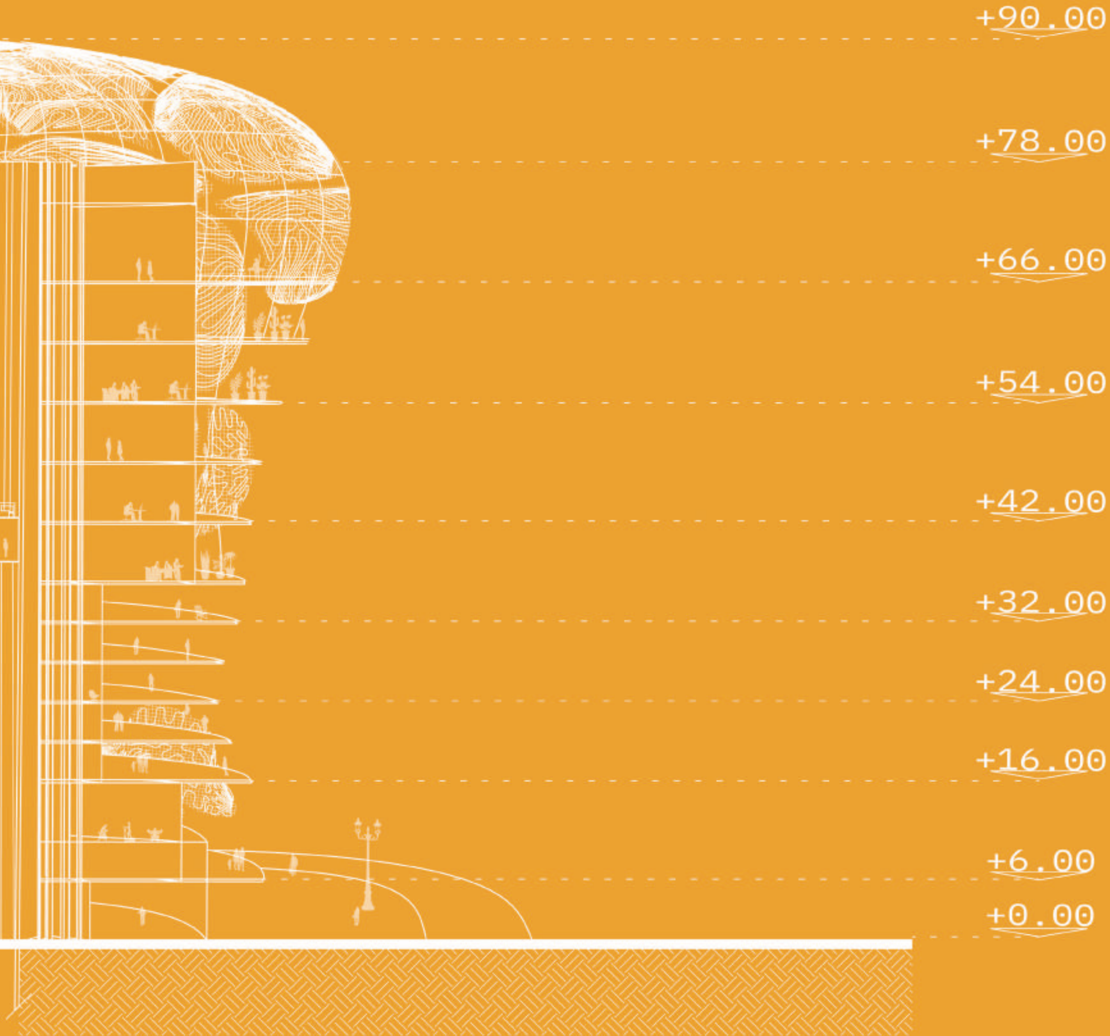
Programmatic


Events halls
Apartments
Kindergarten
Shops
Apartments Lobby

Scheme

Figure 20: Different treatment by the façade's planning

Secti



.on AA

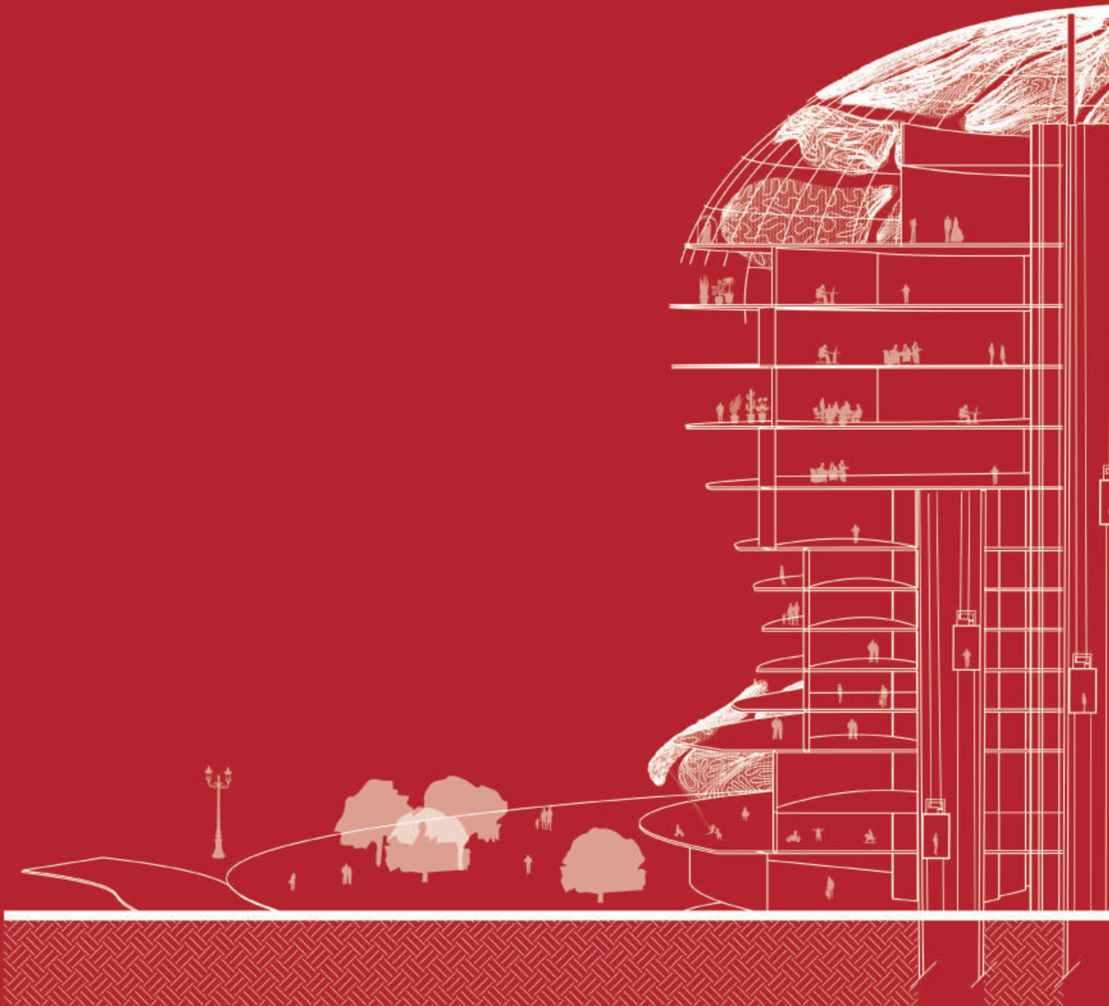
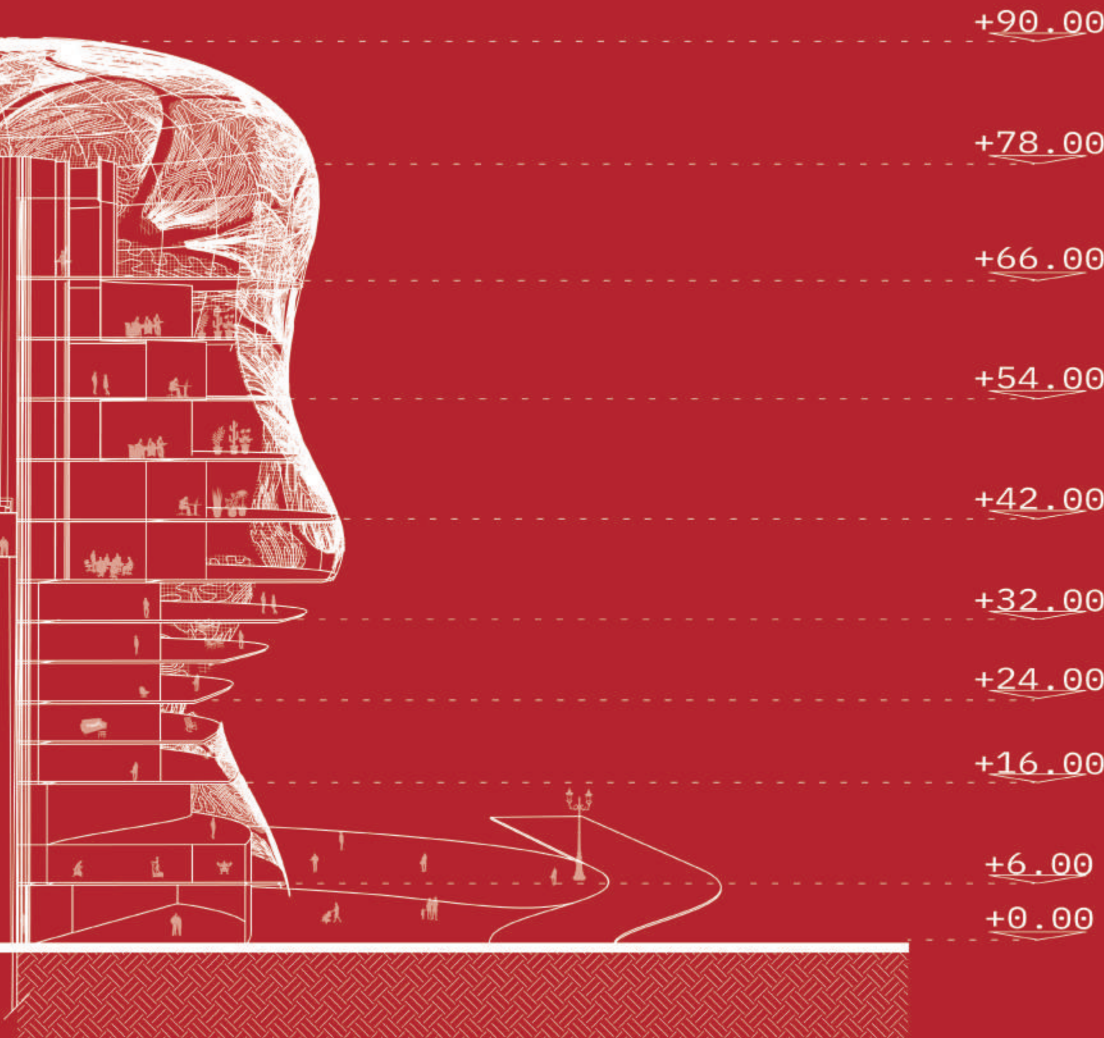


Figure 21: The planning by the building scale was used to alter the program function's shape, size, and locations

Secti



on BB

Figure 22: The events hall is placed on the top of the building

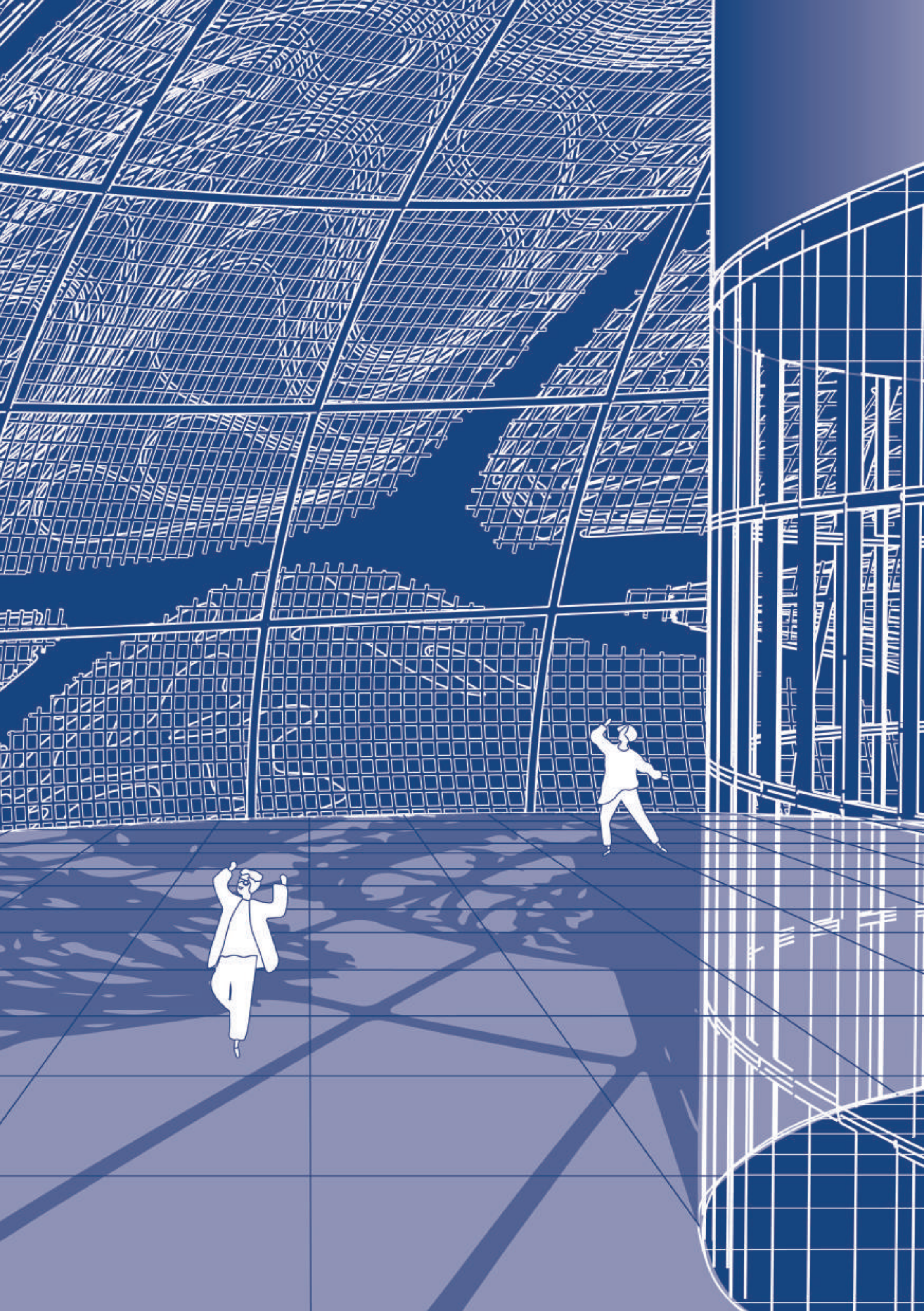
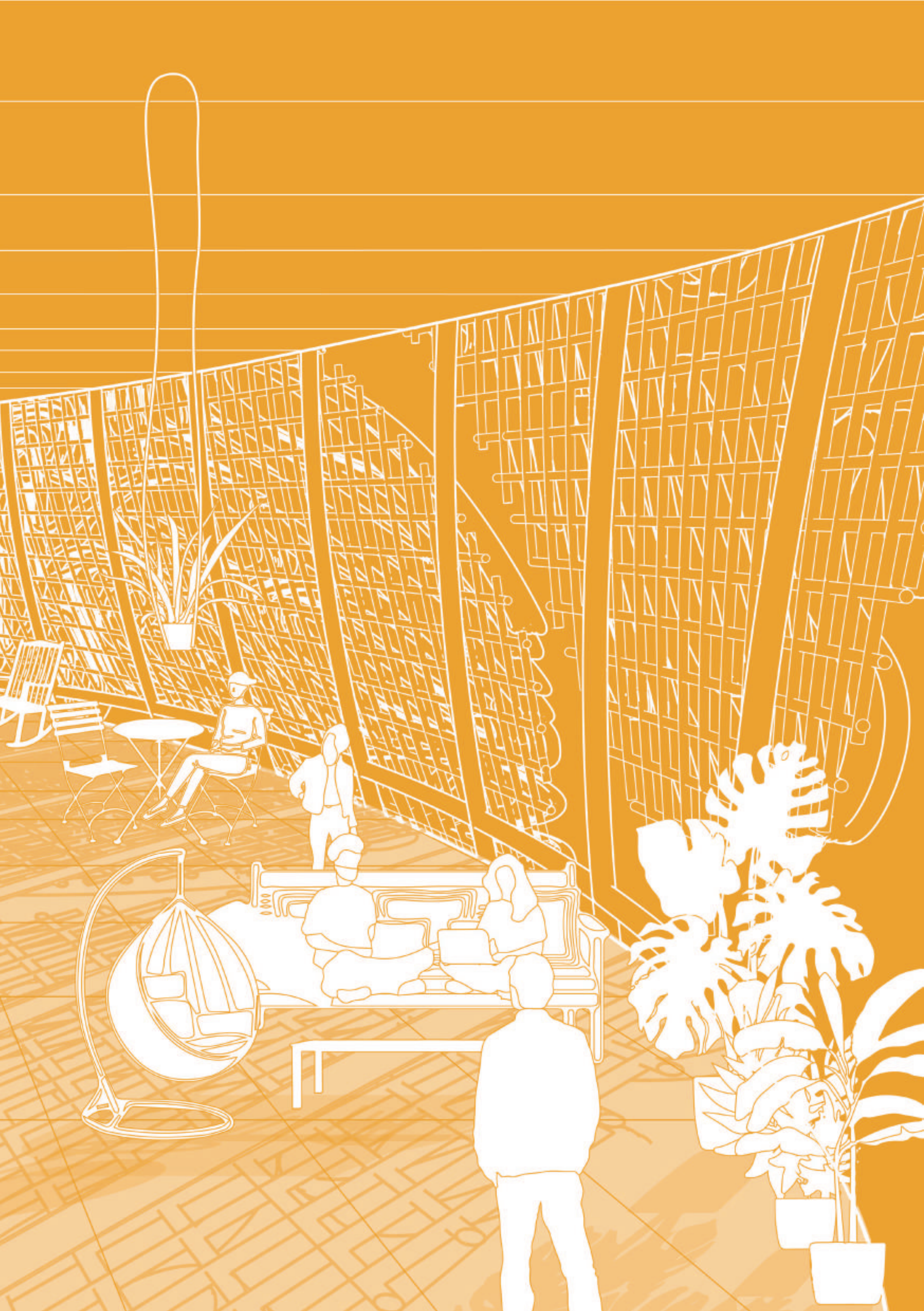


Figure 23: An floor



Climatical efficiency

For the building to reduce the negative impact on its environment and supply the best climate comfort to its users, the façade ought to follow some principles. The radiation and wind's power settings influence the design of the façade.

The radiation level on each façade area determines the patterns that allow various natural lights to enter the space (figure 24). When the radiation is too low, the façade allows a better light's entrance while filtering the light in areas with high radiation levels. The robotic arm enables the creation of various prints with different densities of material. The print's dense and spaced areas are determined according to the radiation levels of the building's façade: The red color relates to a high level of radiation. Therefore, the print is very dense. The blue color relates to a low radiation level; thus, the pattern is a low-density one. The yellow color is a level between the two of the above.

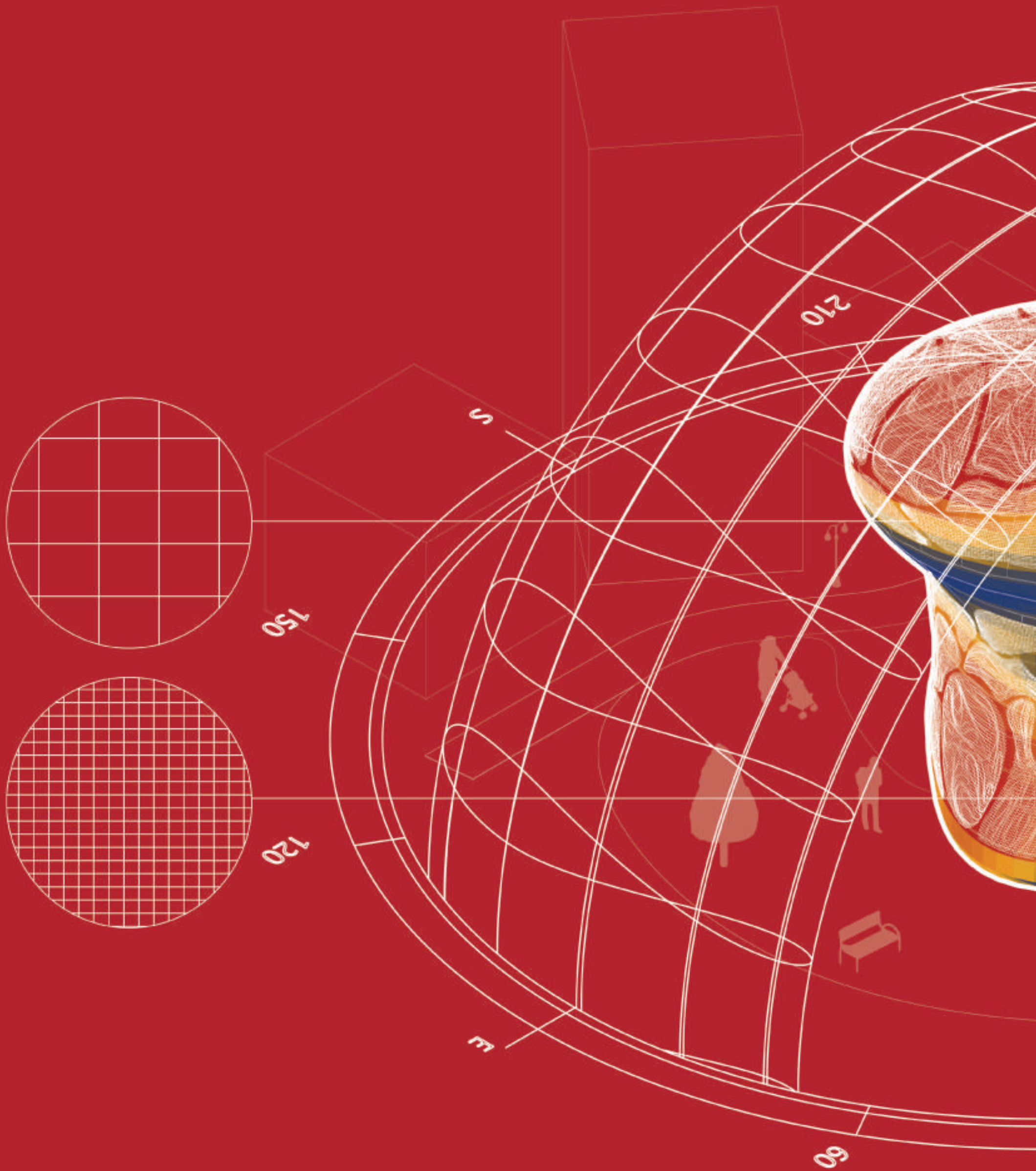
In addition to controlling natural light, the façade's density can be used to collect solar energy (figure 25). In areas with a large amount of solar radiation, the façade is denser; as a result, it is sensible to add micro solar cells to the façade. Cossu et al. (2016) have developed a semi-transparent photovoltaic module for a greenhouse. They had embedded micro solar cells in this module and proved that they could provide energy to the greenhouse (Cossu et al. 2016). The same micro cells can be combined in the additive manufactured material. The building's façade is composed of long printed lines, holding millions of these cells and providing renewable energy to the building.

Wind also influences the building's design (figure 26). There are methods to assess pedestrian level wind comfort and wind danger (Moonen et al. 2012), such as a wind rose calculation for a specific site of the location of the building. Different architectural shapes affect the wind's flow. For example, the aerodynamic shape will promise its fluency (Kormaníková et al. 2018). As a result, the shape of the building has been designed according to rounded, aerodynamic shapes.

Another solution to avoid uncomfortable wind and maintain natural ventilation is the use of louvers (Franco 2018). Louvers are usually a system of horizontal panels on the façade that prevent unwanted wind and radiation entrance due to the louvers' angle (figure 27). The robotic manufacture of the façade can create as many layers of material as the architect desires. In this case, more layers have been piled up in the direction of the uncomfortable winds and high solar radiation, according to a wind's power and solar radiation analysis code.

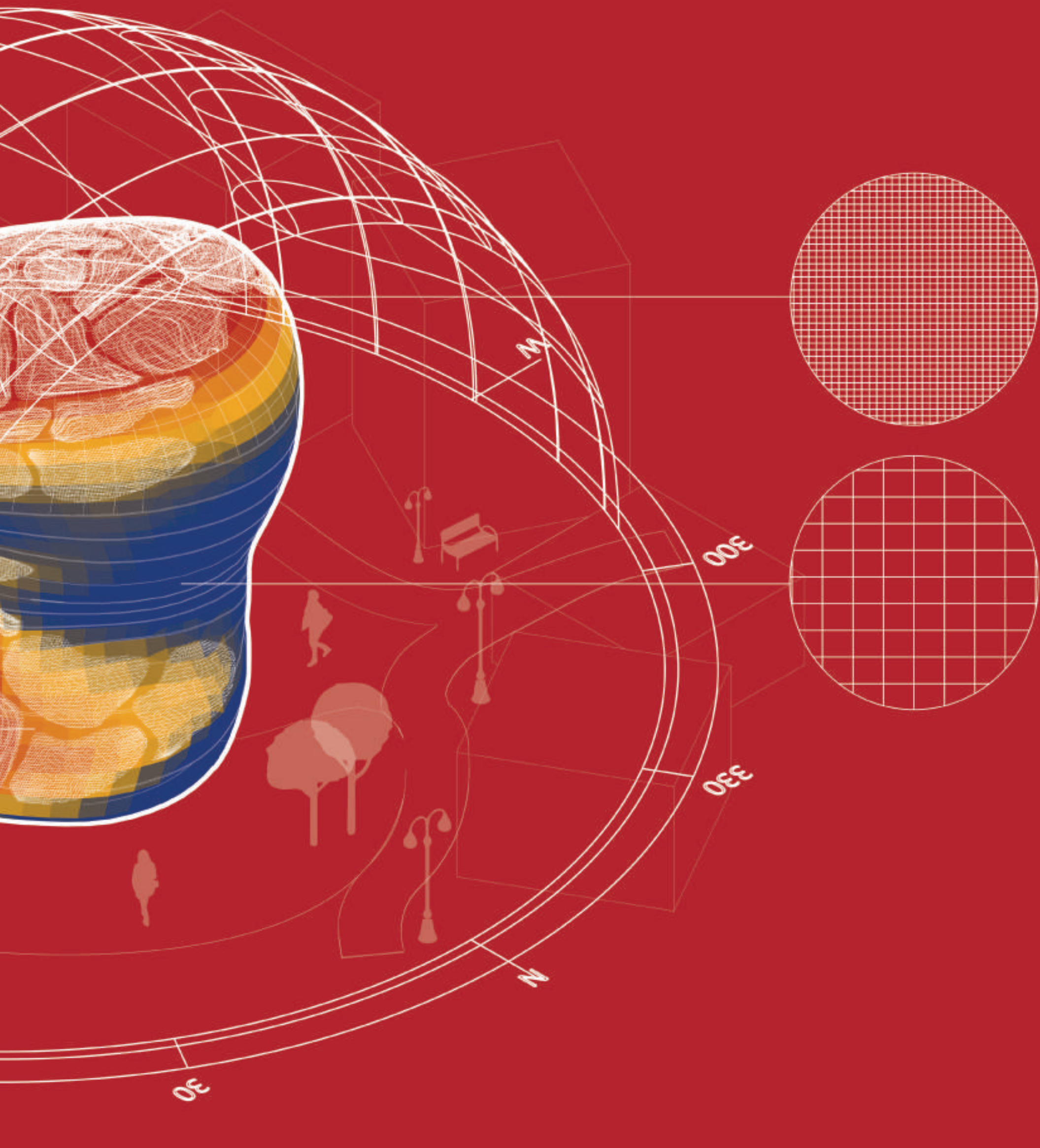
Creating more outdoor spaces

This climatic façade provides the balconies of the building a climatic comfort - outdoor places to enjoy the breeze without feeling the uncomfortable winds and solar radiation. Therefore, the terraces are extensive – creating recreational and workspaces at the office's floor, private



Solar radiat

Figure 24: The radiation level on each façade area determines the patterns that allow various natural lights to enter the space



ion analysis

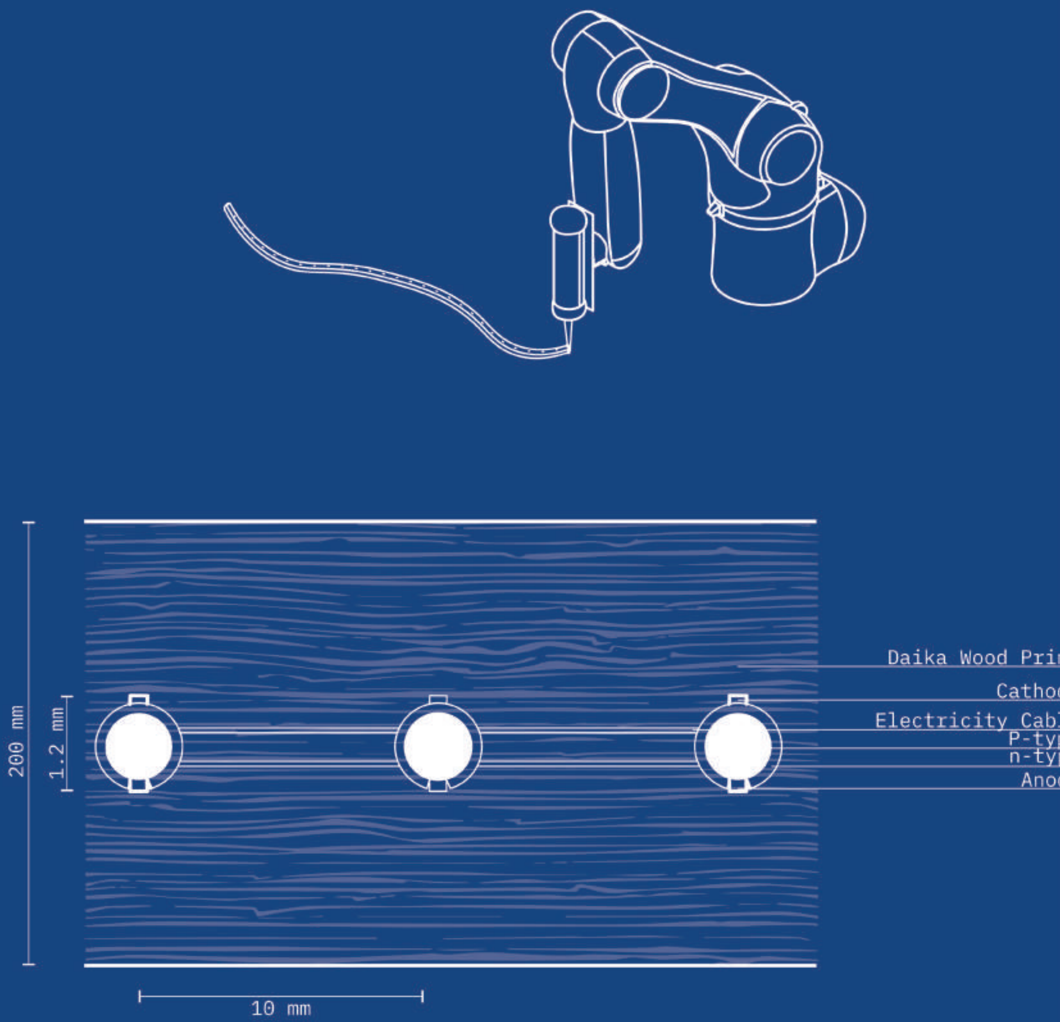
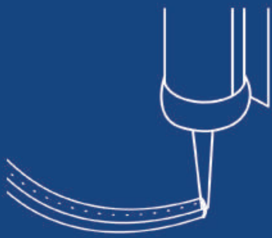
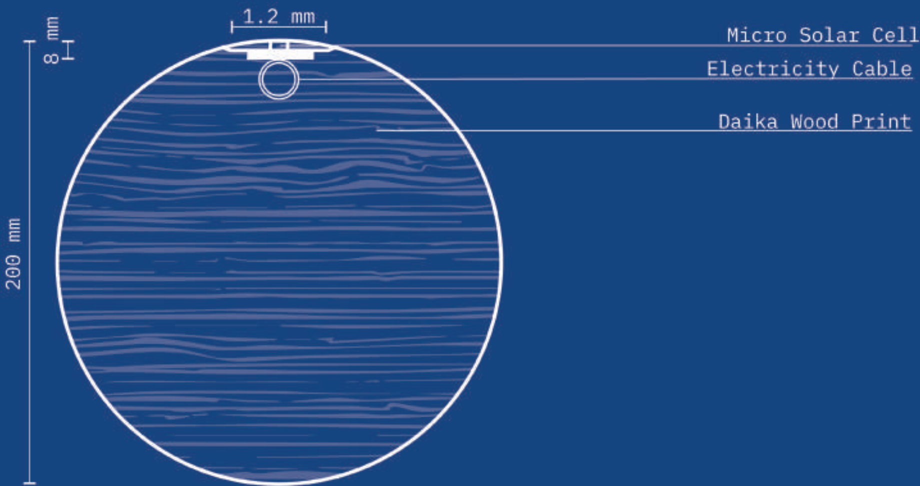


Figure 25: The façade's density can be used to collect solar energy

Micro Sol





nt
de
le
pe
pe
de

lar Cells

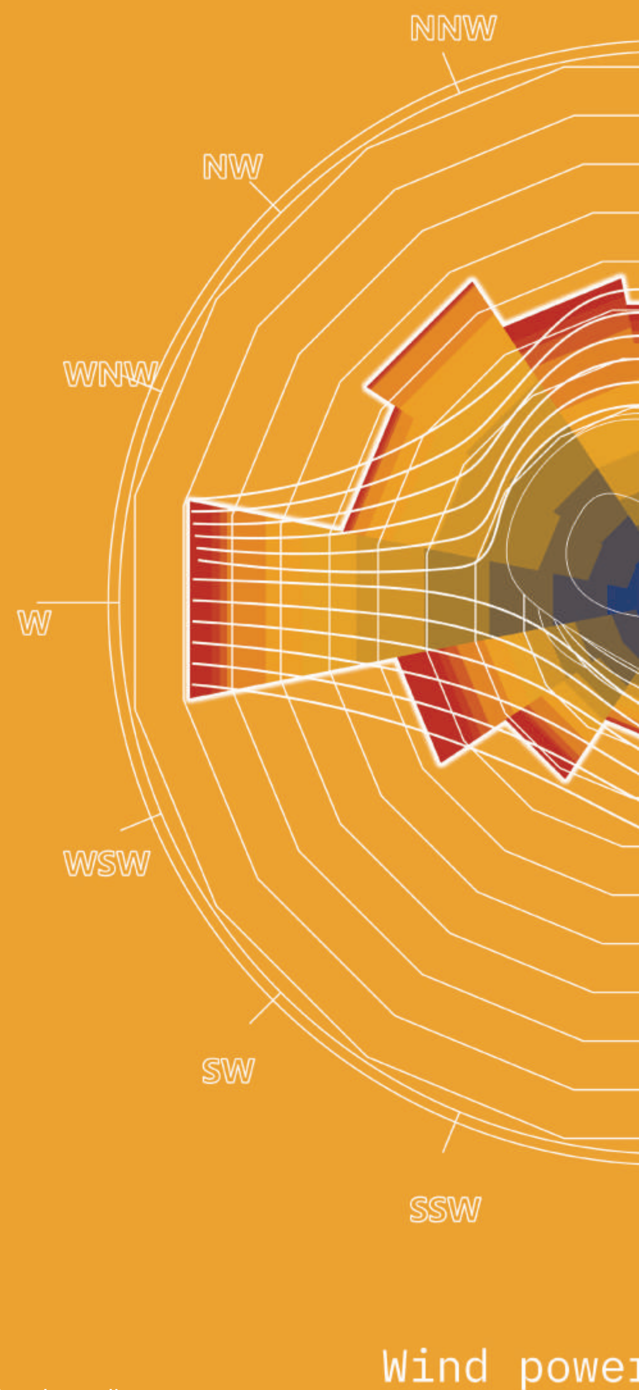
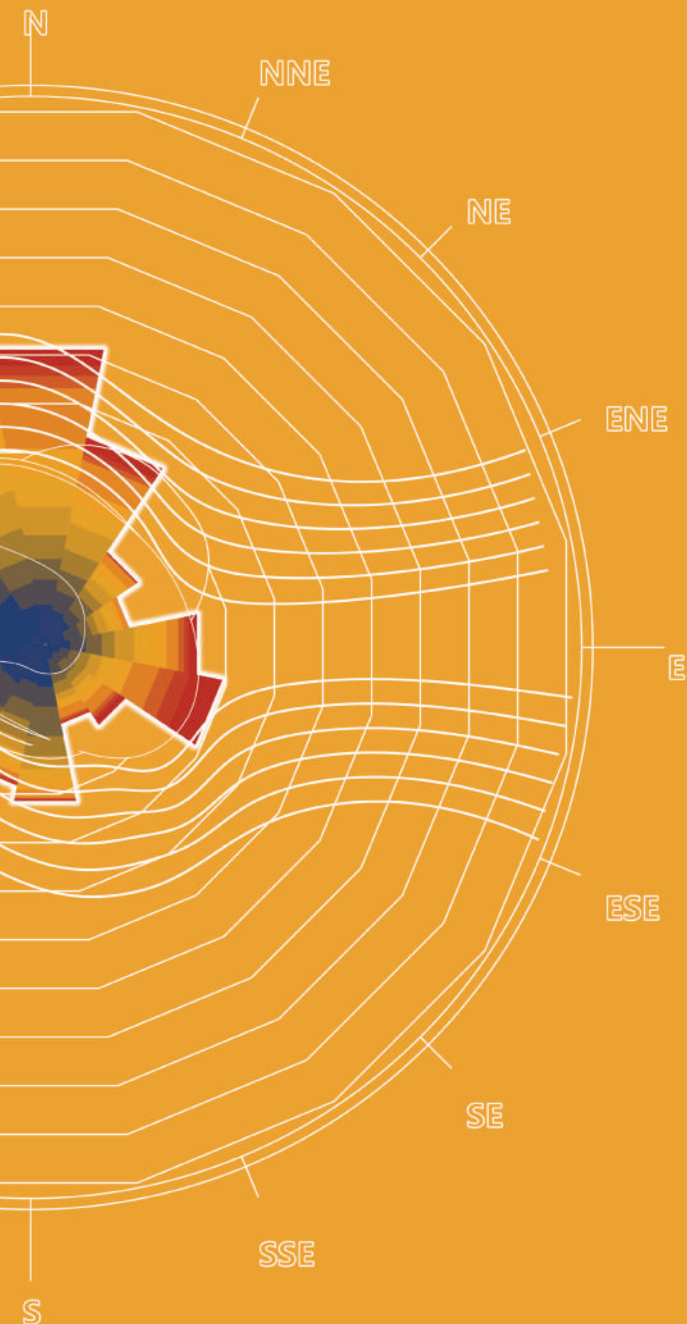
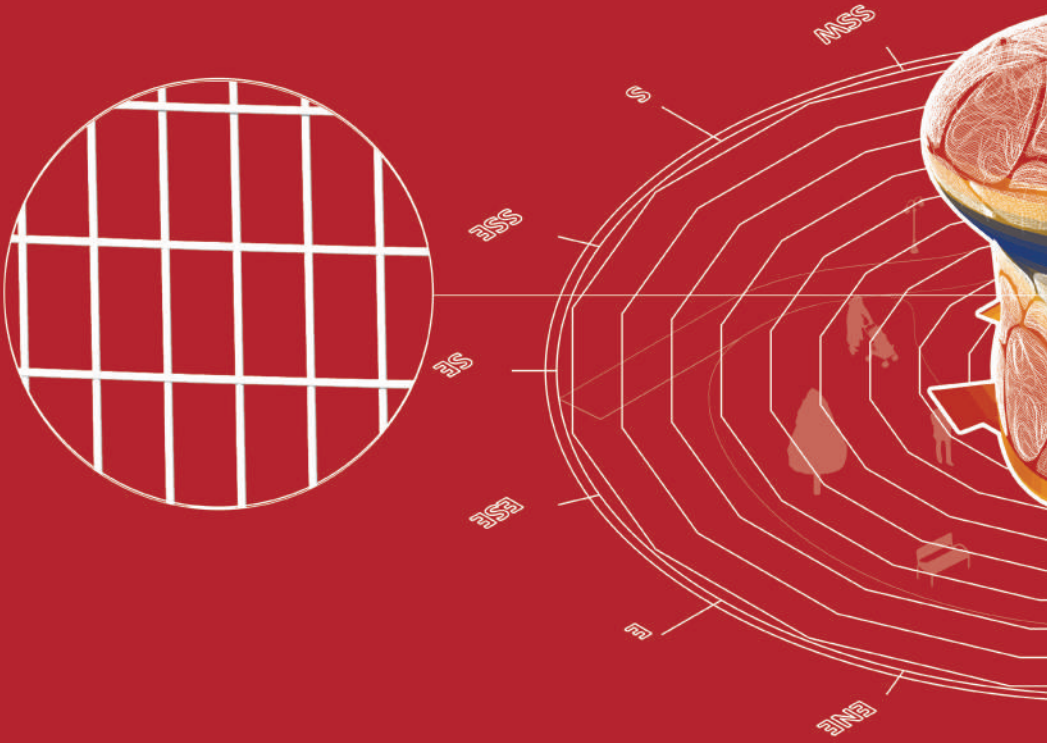


Figure 26: The shape of the building has been designed according to rounded, aerodynamic shapes

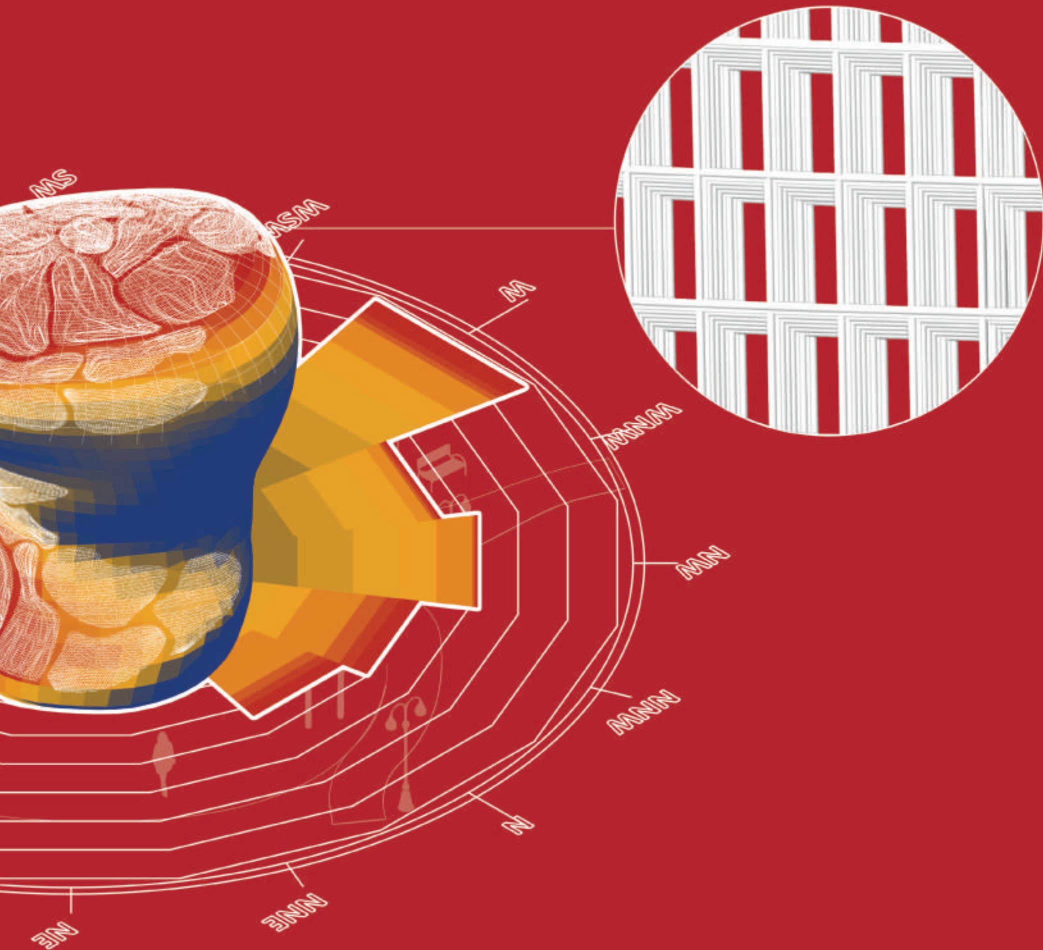


r analysis



Patterns layering

Figure 27: More layers have been piled up in the direction of the uncomfortable winds and high solar radiation



g and indentation

and public outdoor spaces for the accommodation levels, and a large space for the children in the kindergarten to enjoy the clear air (figure 28). The advantage of this façade is those exciting places between the two layers of the façade, inside and outside.

Uniqueness aesthetics

New technologies can create new ways of design thinking; as a result, different products and outcomes are willing to appear. Because this façade was designed by specific technology-oriented thinking, which is additive manufacture with a robotic arm, its aesthetics is different from the generic building (figure 29). Moreover, because the design of the façade was based on climatic parameters, which are different at each side of the building, the building looks different from any point of view and in any direction (figure 30). The robotic arm's additive manufacture technique created a unique aesthetic.

The aesthetics of the façade is composed of amorphic parts (figure 31). Those parts are located where there is a large amount of solar radiation on the façade. According to the amorphic shape of the difference between the radiation analysis parts, they are parted because of a changing radiation level. They are distanced from each other because of the planning decisions of the human-building interaction. Sometimes, although radiation is high, a human being would like to see the sky. The radiation analysis parameters determined each part's density based on a code that created the pattern accordingly (figure 32).

There are many alternatives to the pattern of the façade. All options are created by parametric design code, which considers the climate – the density and the amount of layer change according to the solar radiation and the wind's power at each façade area. All variations of patterns can be sort on a range between random to linear (figure 33). There are grid patterns with distortion of the intersection points where there is less amount of radiation. There are biomimicry patterns of corals' growth and the human gastrointestinal tract. Many more patterns can be created to follow these planning principles in the future.

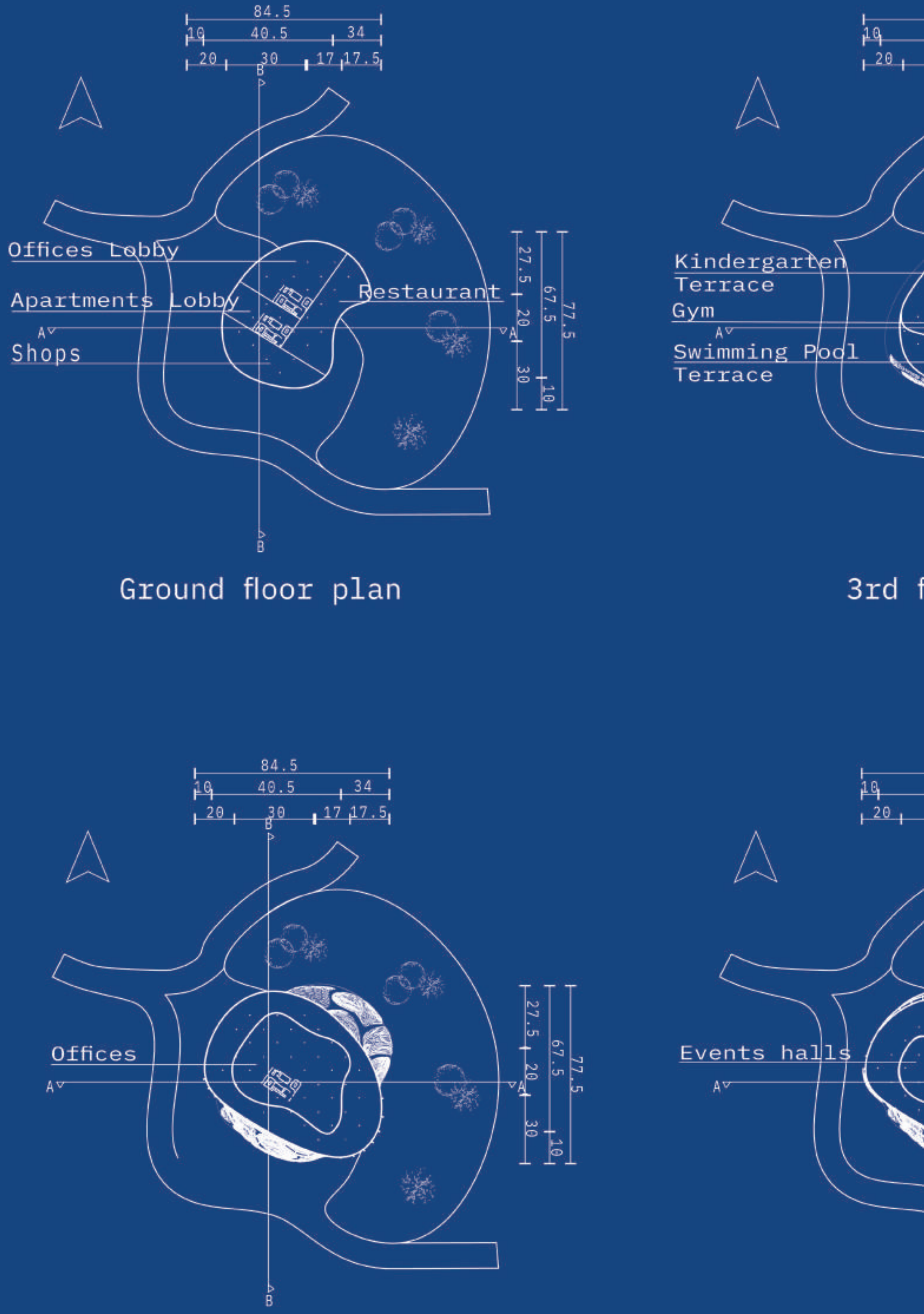
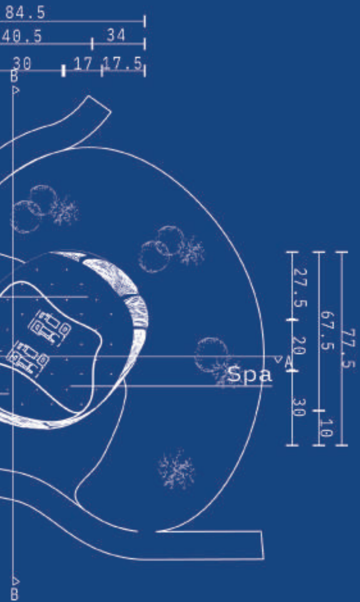
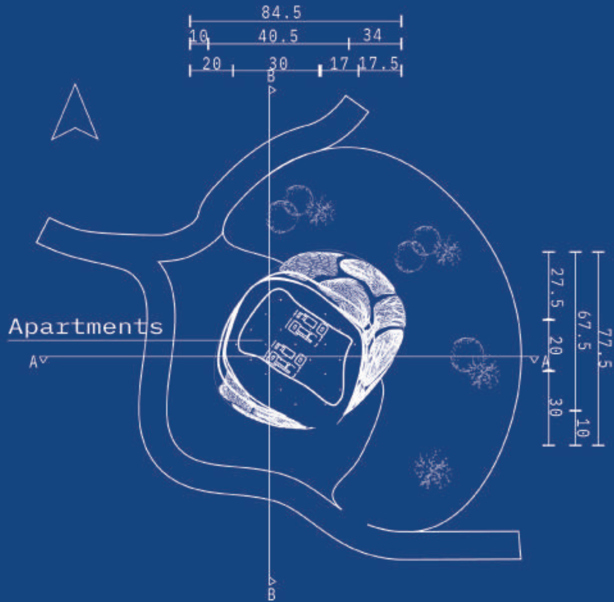


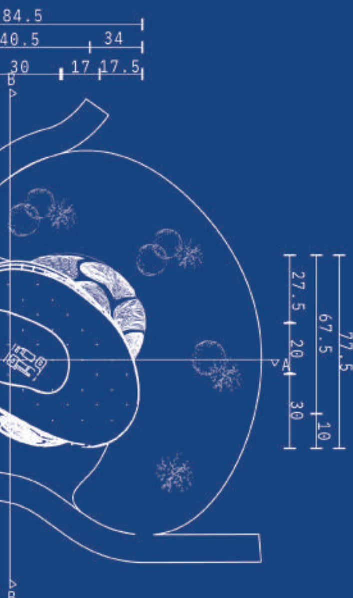
Figure 28: The advantage of this façade is those exciting places between the two layers of the façade, inside and outside



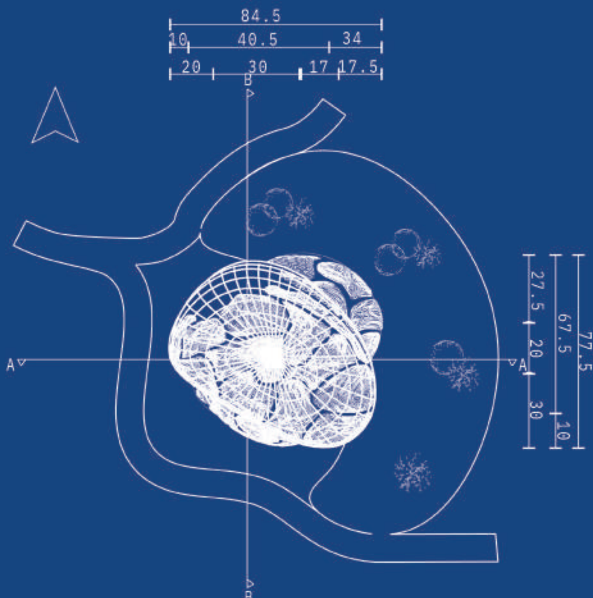
floor plan



7th floor plan

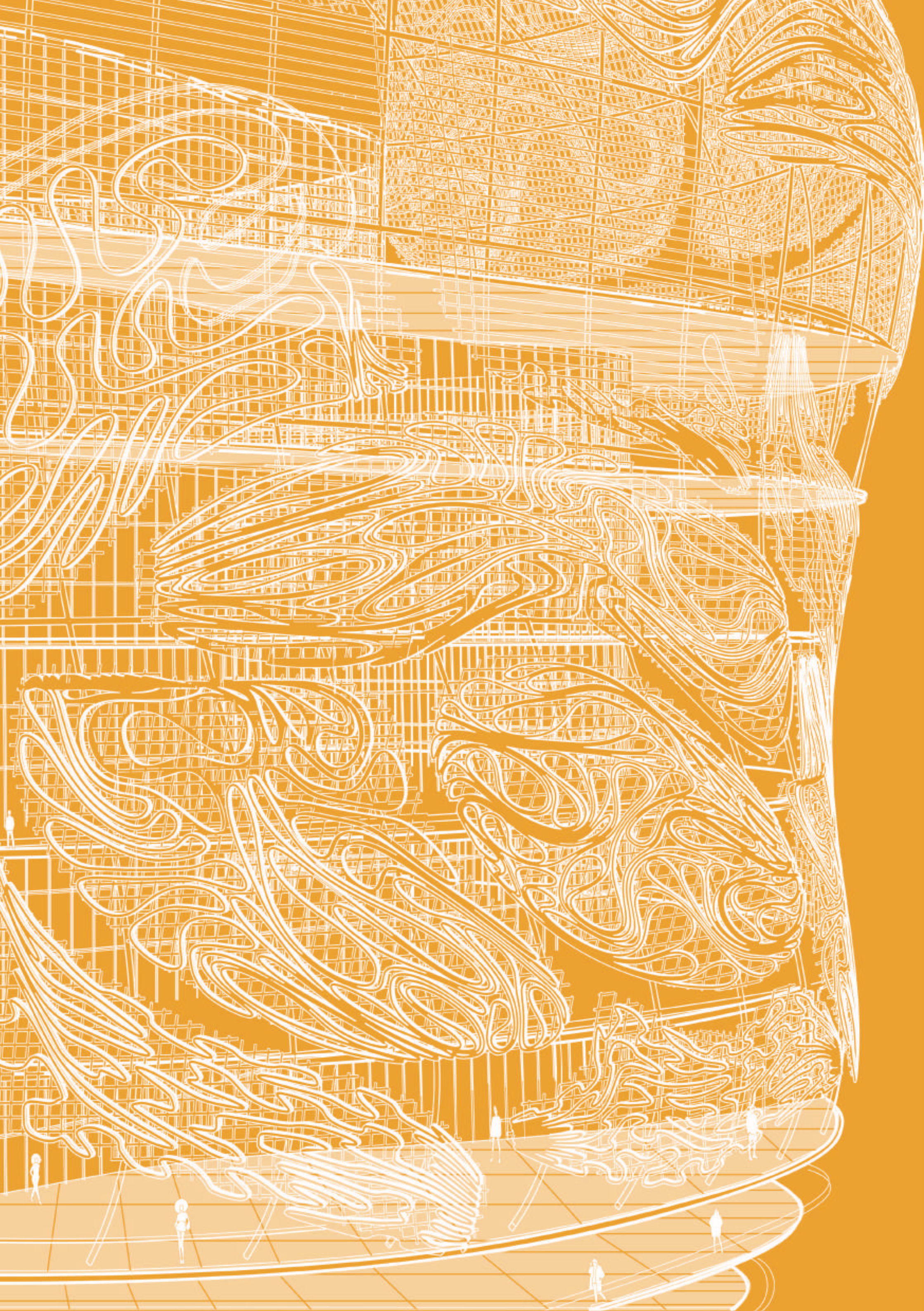


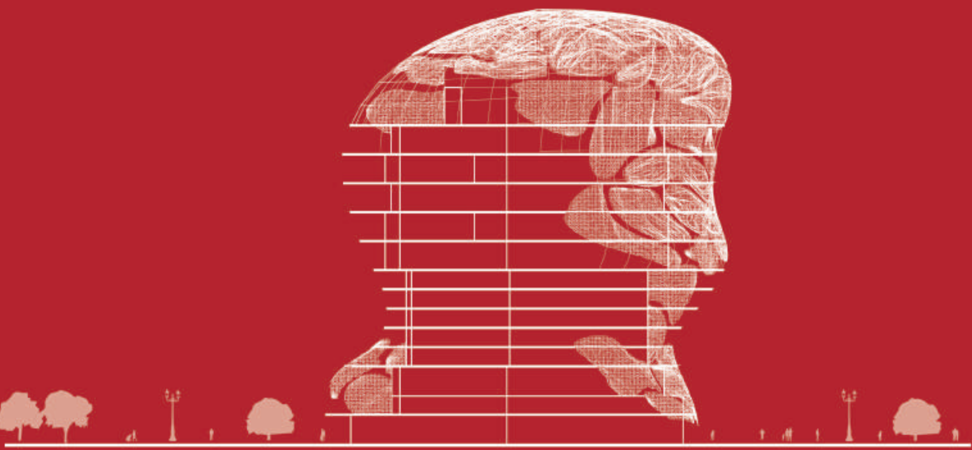
floor plan



Roof plan

Figure 29: The aesthetics is different from the generic building



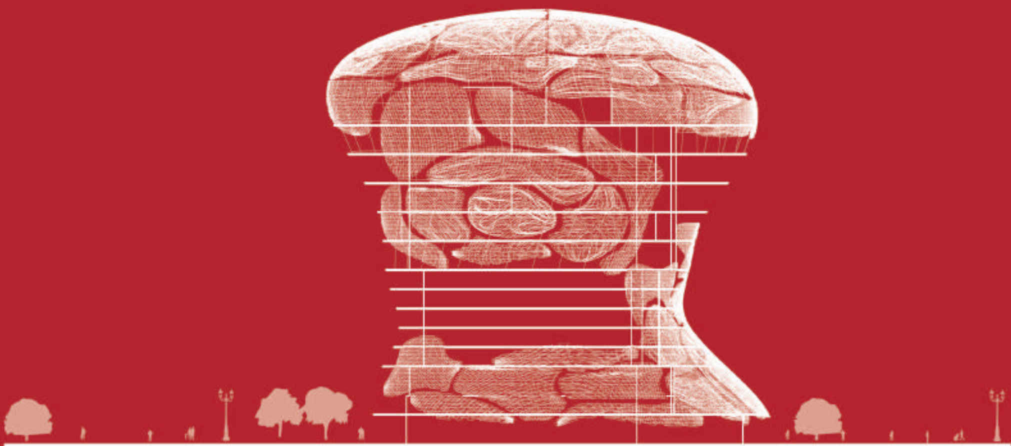


West elevation

North elevation

Figure 30: The building looks different from any point of view
and in any direction

East elevation



South elevation

North-west isometry

Figure 31: The aesthetics of the façade is composed of amorphic parts

South-east isometry

North-east isometry

South-west isometry

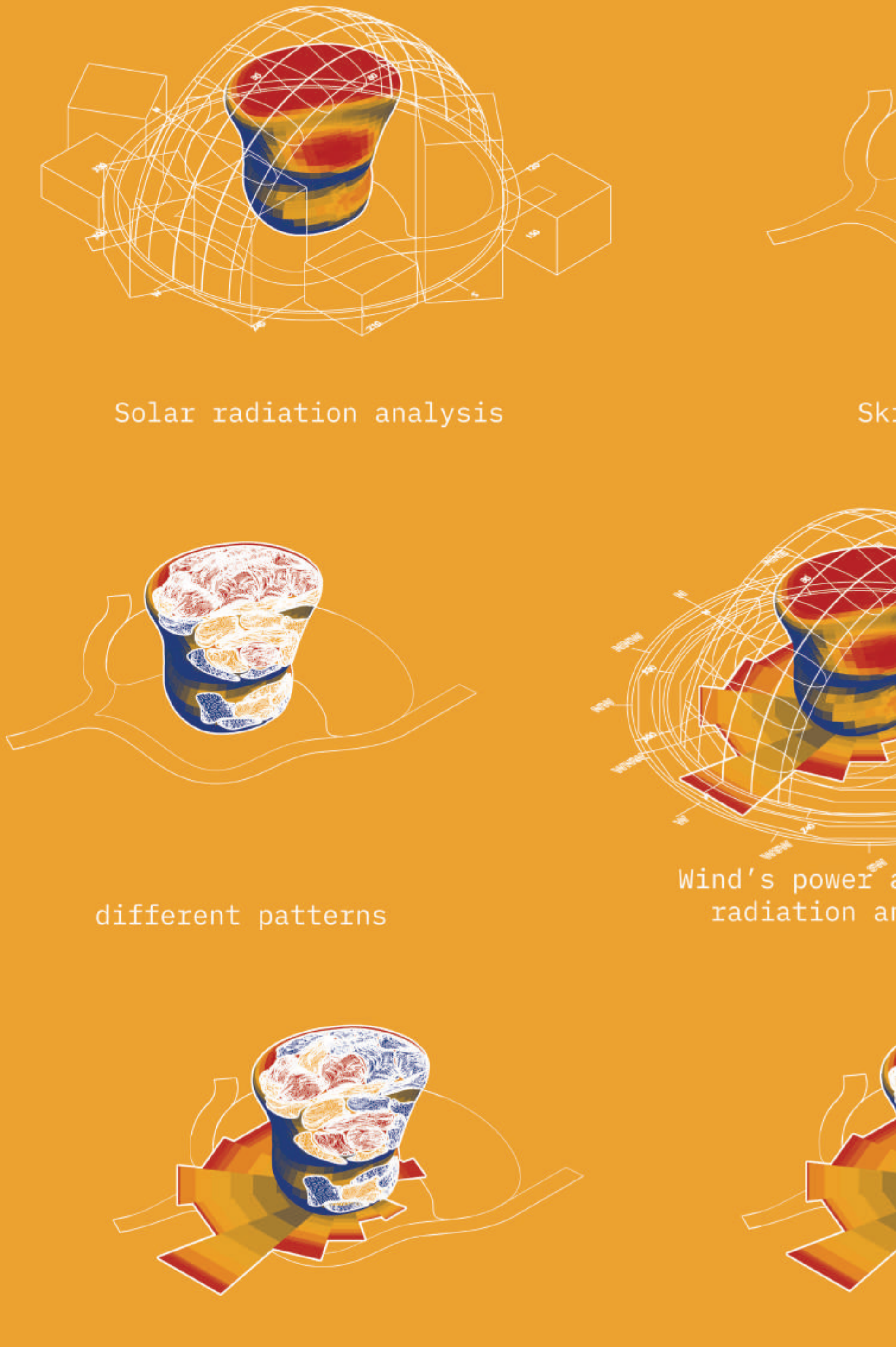
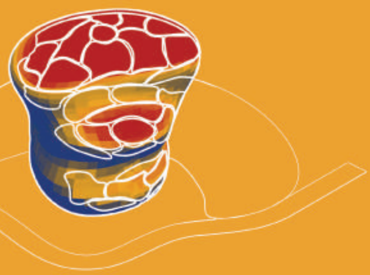
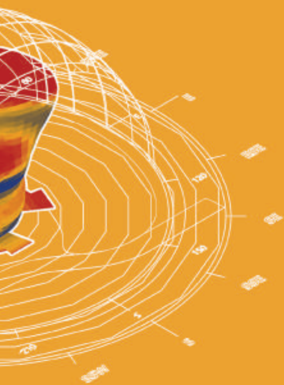


Figure 32: The radiation analysis parameters determined each part's density



in division

Skin division coloring



and solar
nalysis

Skin division coloring

ing and indentation

Isometry

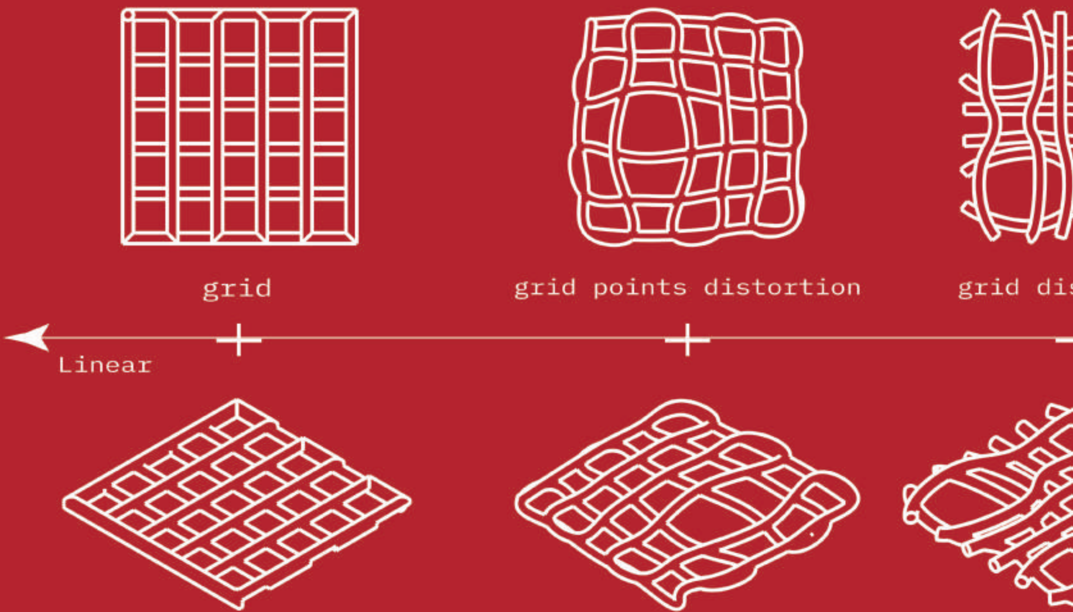
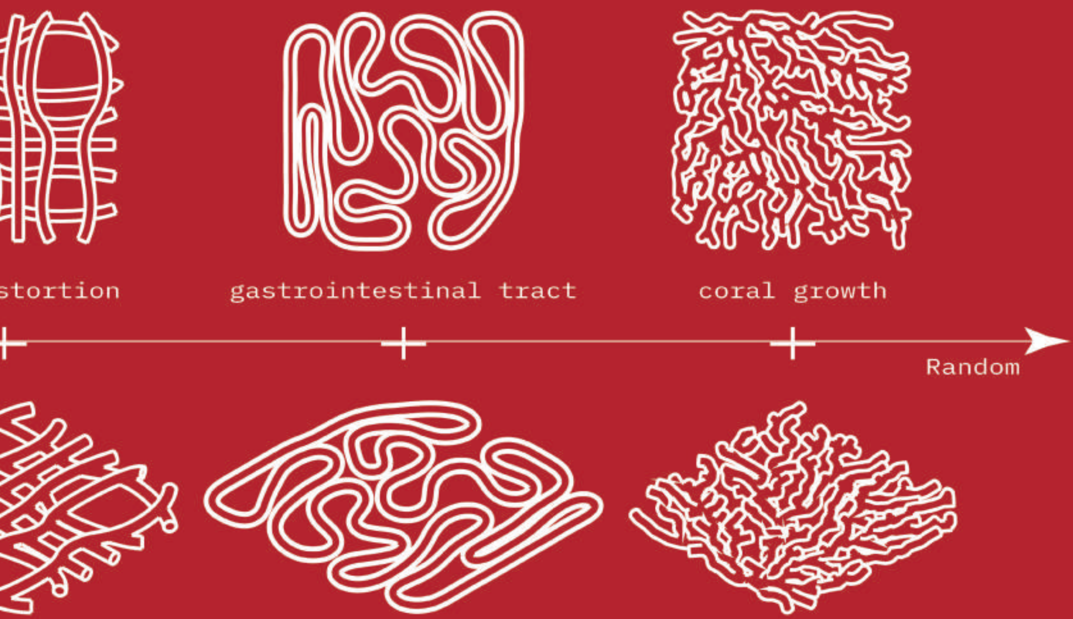


Figure 33: All variations of patterns can be sort on a range between random to linear


stortion
gastrointestinal tract
coral growth
Random

Manufacturing

The generic building process begins with excavating and leveling the ground, building the floors, core, and constructive walls, floor after floor until it reaches the top (figure 34). The following steps are the finishes which include the windows and the interior walls. A project based on a particular construction technology ought to suggest a solution to the manufacturing process because new technologies raise questions about their construction feasibility, manufacturing process, and the materials they are built from. The façade is composed of layers connected to the balconies' floors, the outside layer is additively manufactured on the building site with dedicated technology, and there are various options for the façade material.

Connection to the building

The building's façade is composed of three layers, creating its construction feasibility and suggesting a way to connect it to the building (figure 35). The building, like many generic ones, is built from concrete floors. To the edge of those floors, a grid system of round tubes is connected. This system can be made in a steel factory that rounds the tubes according to the plan. The next layer is connected to the rounded tubes by an adjustable façade fixing component. This layer is a thin steel mesh that also arrives from the factory the specific shape it planned to be. The third layer is the additive manufacture one which is connected to the second layer. The additive manufacturing layer has different layering in various areas of the façade, considering the radiation amount and the level of wind power.

Building site

After everything else is done at the building site, the first and second layers of the grid tubes system and the thin steel meshes are placed and connected to the floors (figure 36). The next stage is connecting light scaffoldings to the floors outside the balconies beyond the thin steel meshes. Rails are placed on those scaffoldings, and robotic arms surf on them, making them capable of printing all over the thin steel meshes. The robotic arms are located precisely on the spot they have in the manufacturing code to create the same print planned. In addition, a responsive sensor is connected to the edge of the robotic arm in order to add material only when it feels the mesh to avoid any minor inaccuracies. After the robots finish the additive manufacture, the scaffoldings are dismantled.

Materials for production

Eight materials have been examined to find a possible material for additive manufacturing of this building's façade. The analyzed materials are concrete, ABS plastic, copper, steel, glass, polycarbonate, carbon, and Daika wood. Precedents of architectural projects that used those materials were reviewed beside precedent of 3D printing and additive manufacturing. This examination focused on the robotic head tool suitable for each material, the printed results, and the raw material available to purchase.

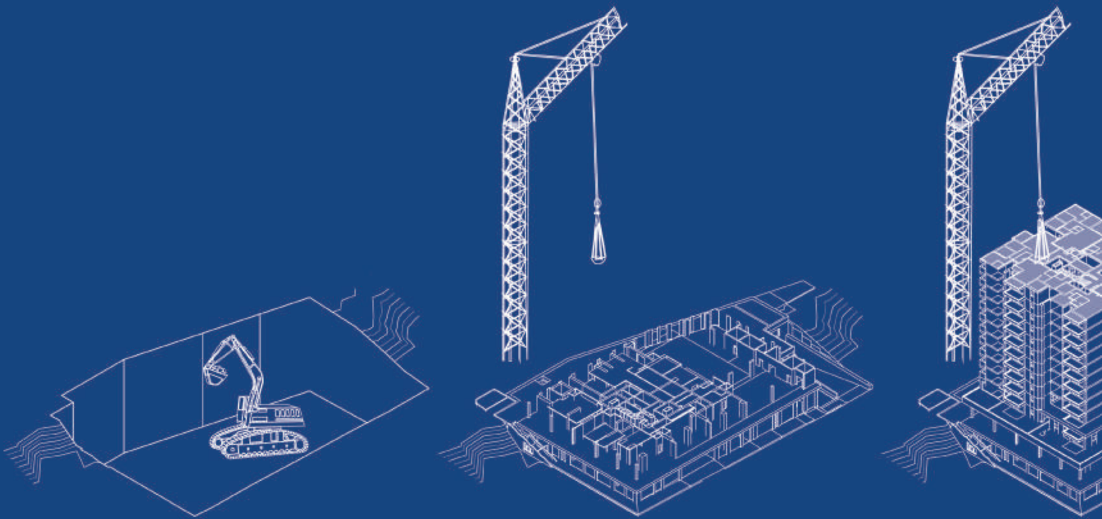
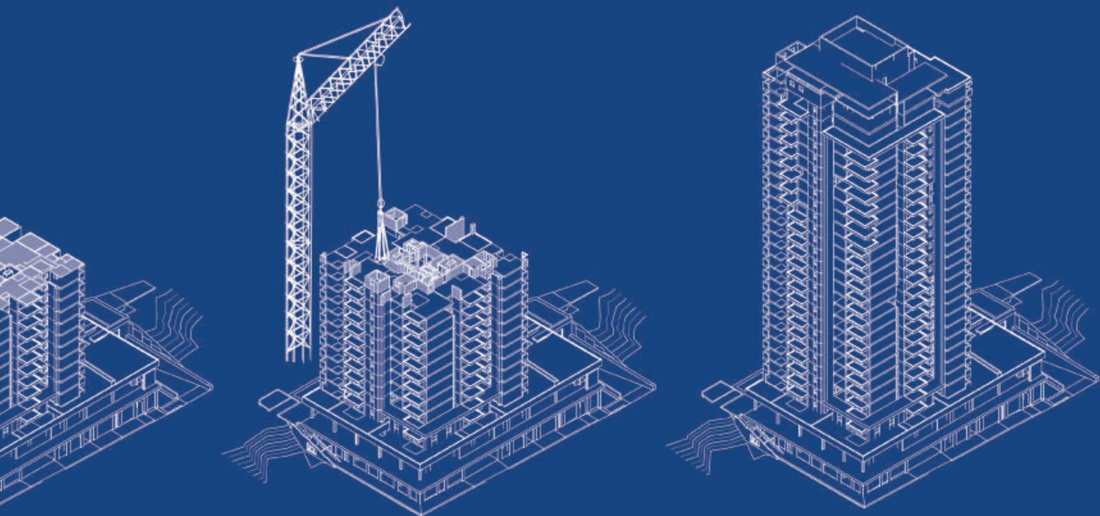
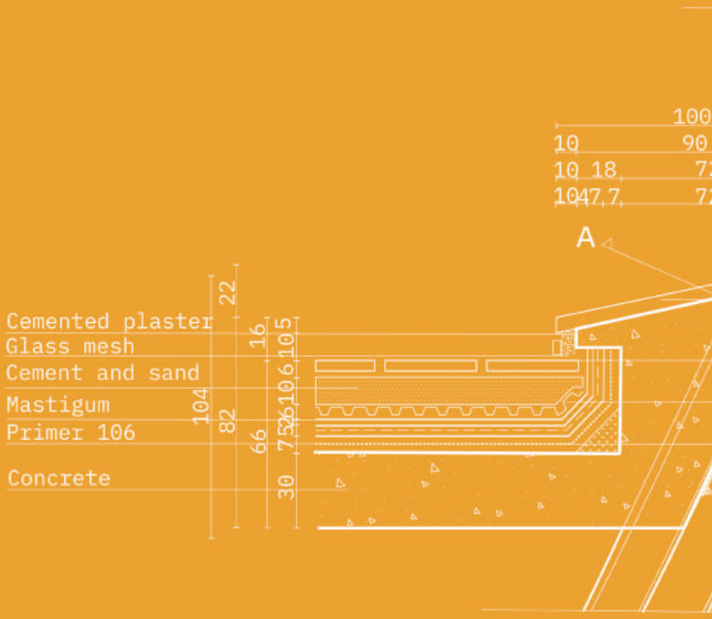


Figure 34: The generic building process





Detai

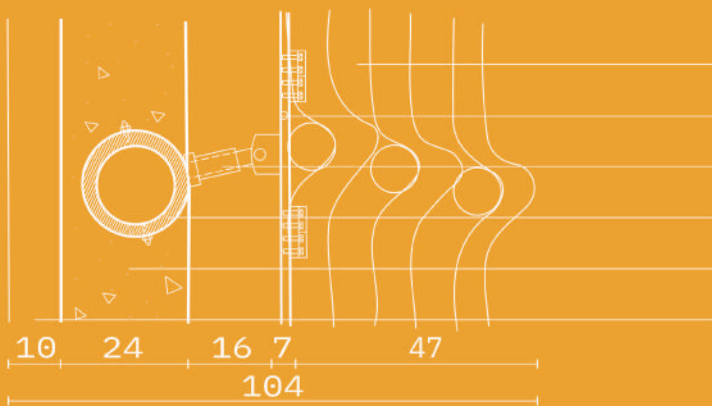
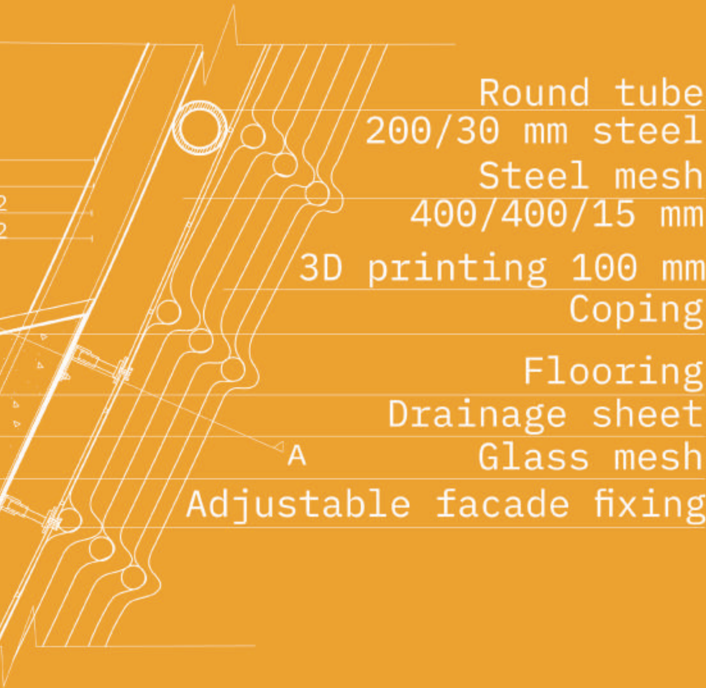


Figure 35: The building’s façade is composed of three layers

Section



1

3D printing 100 mm

Steel mesh 400/400/15 mm

Adjustable facade fixing

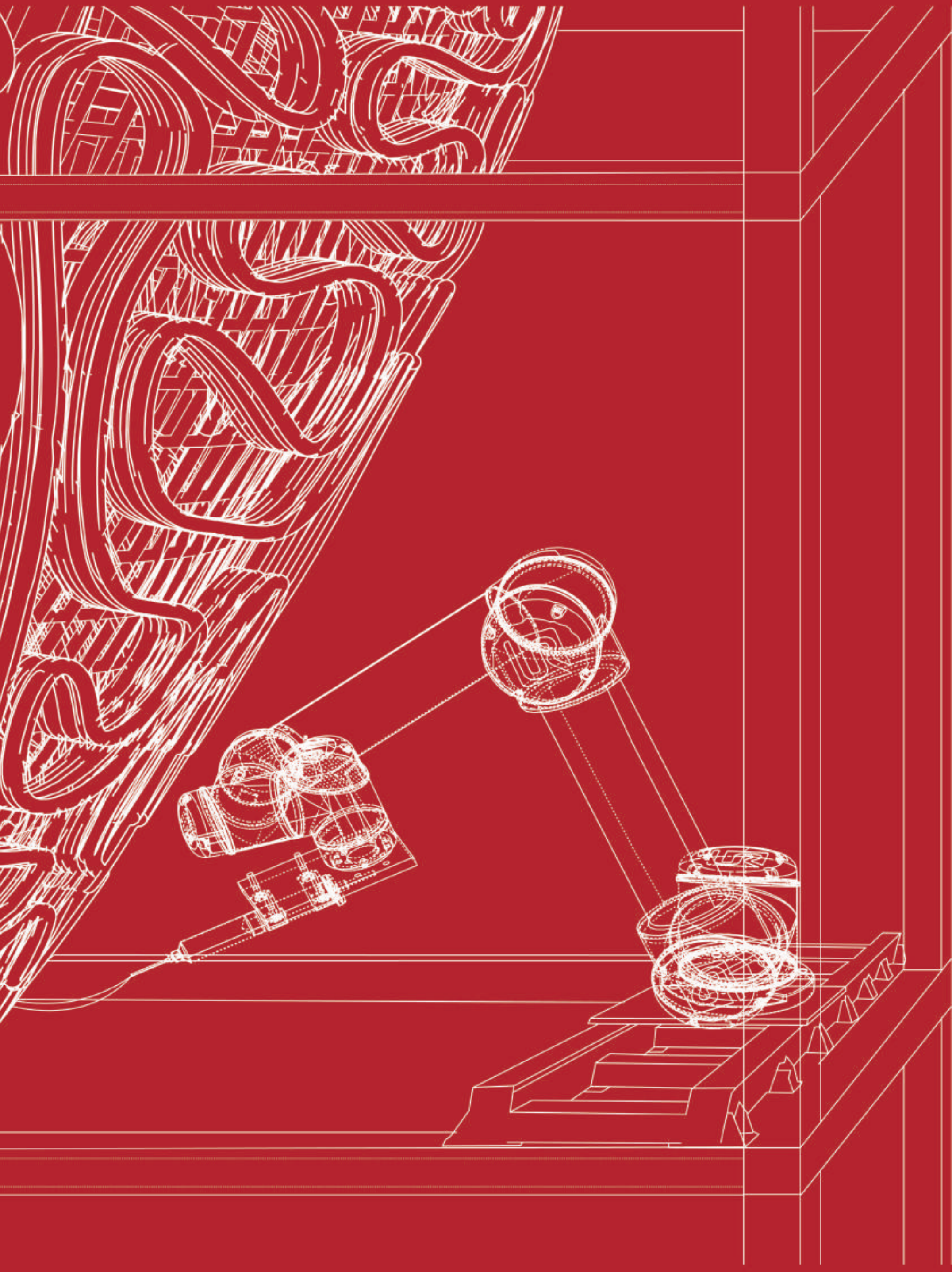
Round tube 200/30 mm steel

Concrete

Coping

AA

Figure 36: The first and second layers of the grid tubes system and the thin steel meshes are placed and connected to the floors



Eventually, each material analysis led to a company that supplies the material. The purpose was to find the suitable material for manufacturing the building's façade and find the right one for the additive manufacturing of a small-scale model of it (figure 37).

Concrete is a well-known construction material used for 3D printed buildings (PERI 2021; Apis Cor 2020), but it is too liquid and heavy to use or additive manufacturing on a vertical surface.

Steel is possible to use as a building's façade, and it is feasible to use as an additive manufacture material (MX3D 2019), but it is too complicated for a short-term project such as this one to build its robotic head tool (Novikov and Jokic 2013).

Copper is 3D printed by companies such as Systematics (Systematics 2021) and Impact labs (Impact Labs 2021). It is the proper material for an elevation of a building (OVO Grabczewscy Architekci 2015; LCR architectes 2014). However, it was not additive manufactured yet.

ABS plastic is a prevalent 3D printing material, and it can be made from leftovers of plastics and recycled plastic bottles. It was additive manufactured by a robotic arm for a store interior design (Krause Architects 2018), and it has been used to create terrazzo interior design (van Middelkoop and Dingemans 2020). In addition, it was used as an exterior (PTW Architects 2008; Playze 2011) but not as a 3D-printed façade.

Polycarbonate is feasible for 3D printing and additive manufacture, likewise ABS plastic, and it is used as an exterior material for an architectural project (SARL Architects 2011).

Glass could also be 3D printed (Oxman 2015), and it is a well-known exterior material (Herzog and de Meuron 2017). However, it could have been very complicated to produce a robotic head tool to additive manufacture glass with.

Carbon fibers have been used for several pavilions (Menges and Knippers 2015; Menges et al. 2017) and as an exterior material in Dubai Expo (Khan 2020). In addition, an exhibition at Venice Biennale was made from carbon and glass fibers (Menges and Knippers 2021). It has not been used as an architectural long-lasting exterior material and not as an additive manufacturing material, although it was used by robotic arms, which enwrapped and weaved the fibers on dedicated construction elements.

Daika wood is "a wood waste product which is "glued" with extracted wood products, to be a substitute for pristine wood. The final products are exhibit visual, textural, and physical properties of natural timber" (Kam et al. 2019). Its raw material is perfect for additive manufacture because it is wet and soft for a simple robotic head tool (Layani 2020). As a natural timbre material, it would not be appropriate for a building's façade on its outer side. However, it can be an interesting material for the small-scale architecture model.

There is enormous potential in additive manufacture, not

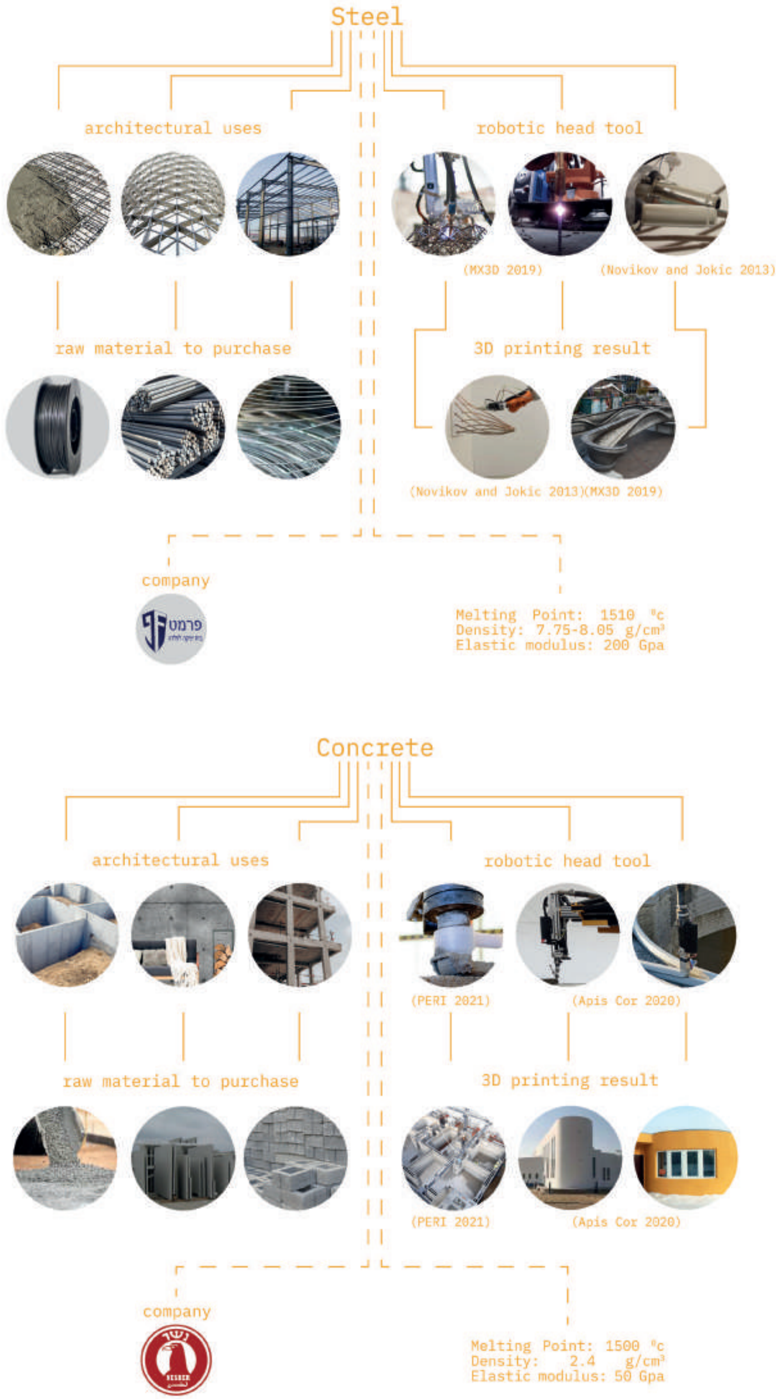
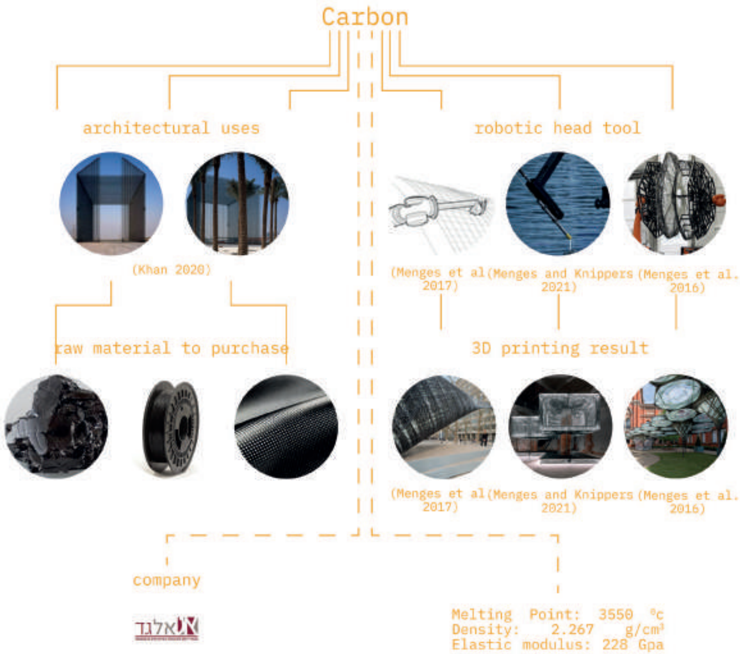
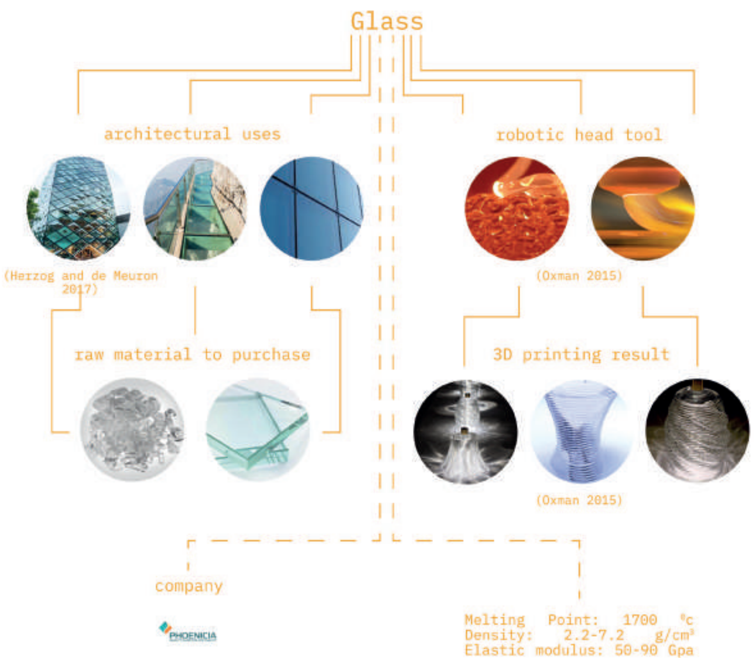


Figure 37: Eight materials have been examined to find a possible material for additive manufacturing of this building’s façade


Carbon
architectural uses
robotic head tool
(Khan 2020)
(Menges et al 2017)
(Menges and Knippers 2021)
(Menges et al. 2016)
raw material to purchase
3D printing result
(Menges et al 2017)
(Menges and Knippers 2021)
(Menges et al. 2016)
company
Melting Point: 3550 °c
Density: 2.267 g/cm³
Elastic modulus: 228 Gpa


Glass
architectural uses
robotic head tool
(Herzog and de Meuron 2017)
(Oxman 2015)
raw material to purchase
3D printing result
(Oxman 2015)
company
PHOENICIA
Melting Point: 1700 °c
Density: 2.2-7.2 g/cm³
Elastic modulus: 50-90 Gpa

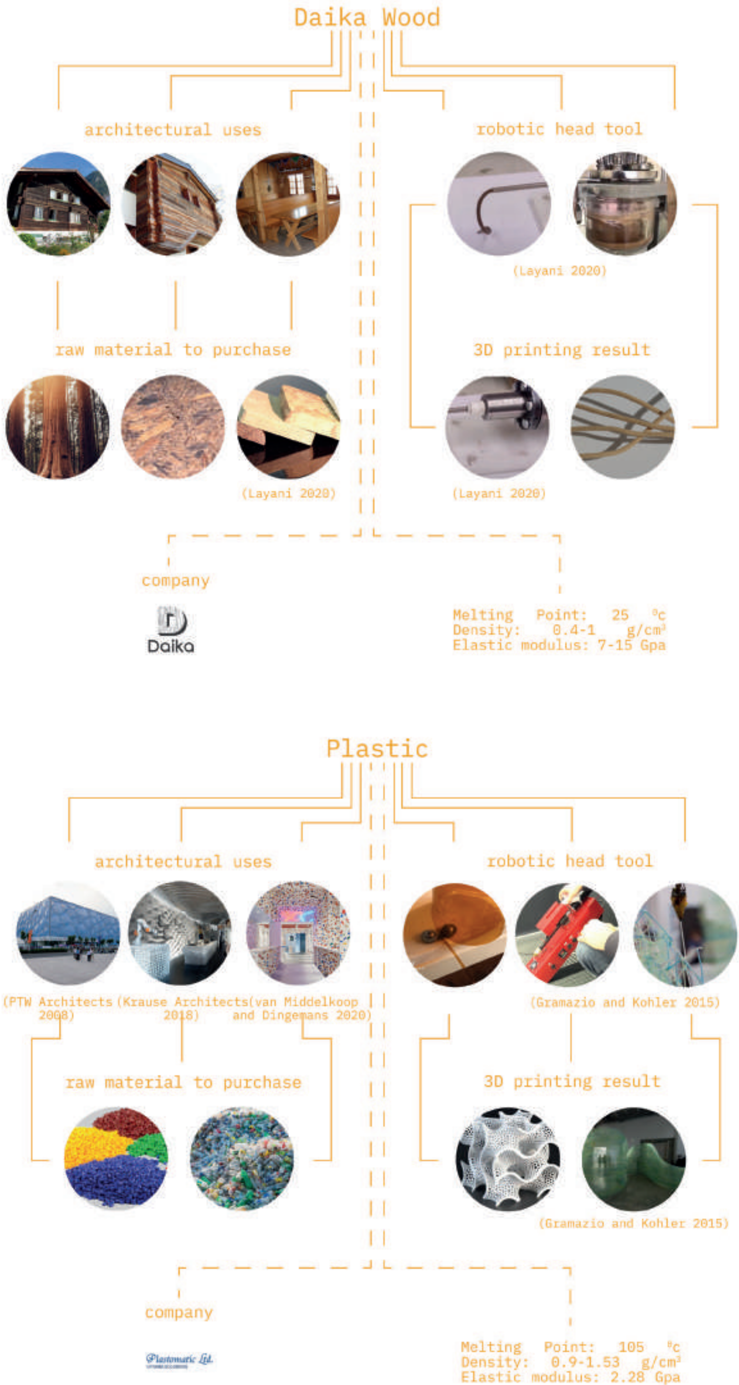


Figure 37: Eight materials have been examined to find a possible material for additive manufacturing of this building's façade

Polycarbonate

architectural uses

(Walker 2010) (SARL Architects 2011)

robotic head tool

raw material to purchase

3D printing result

company

Melting Point: 150 °c
Density: 1.2-1.22 g/cm³
Elastic modulus: 2-2.4 Gpa

Copper

architectural uses

(OVO Grabczewscy Architekci 2015) (LCR architectes 2014)

robotic head tool

raw material to purchase

3D printing result

company

Melting Point: 1084.62 °c
Density: 8.69 g/cm³
Elastic modulus: 117 Gpa

only a technological potential, but it can also open the gate to a whole new world of materiality, such as ecological and environmental materials. Soft material can be printed easily with an appropriate robotic head tool. Many new companies and researchers worldwide invent and investigate new materials, such as bioplastics, natural wood, and natural clay.

The Daika wood was chosen for the laboratory part of this project because of its sustainability and softness. The properties of this material were examined by hand and home devices until it was sure to be the proper material for additive manufacture technique.

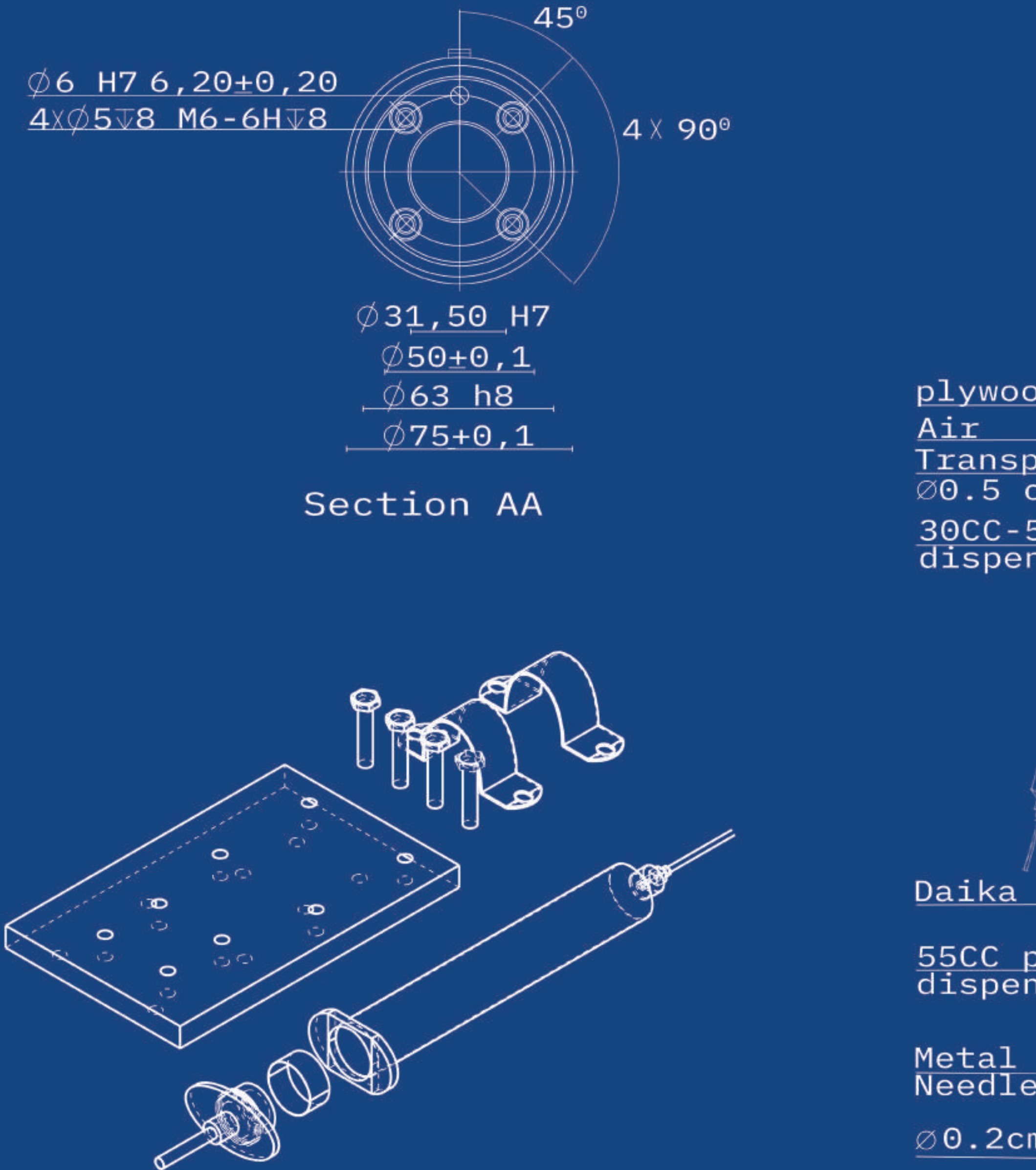
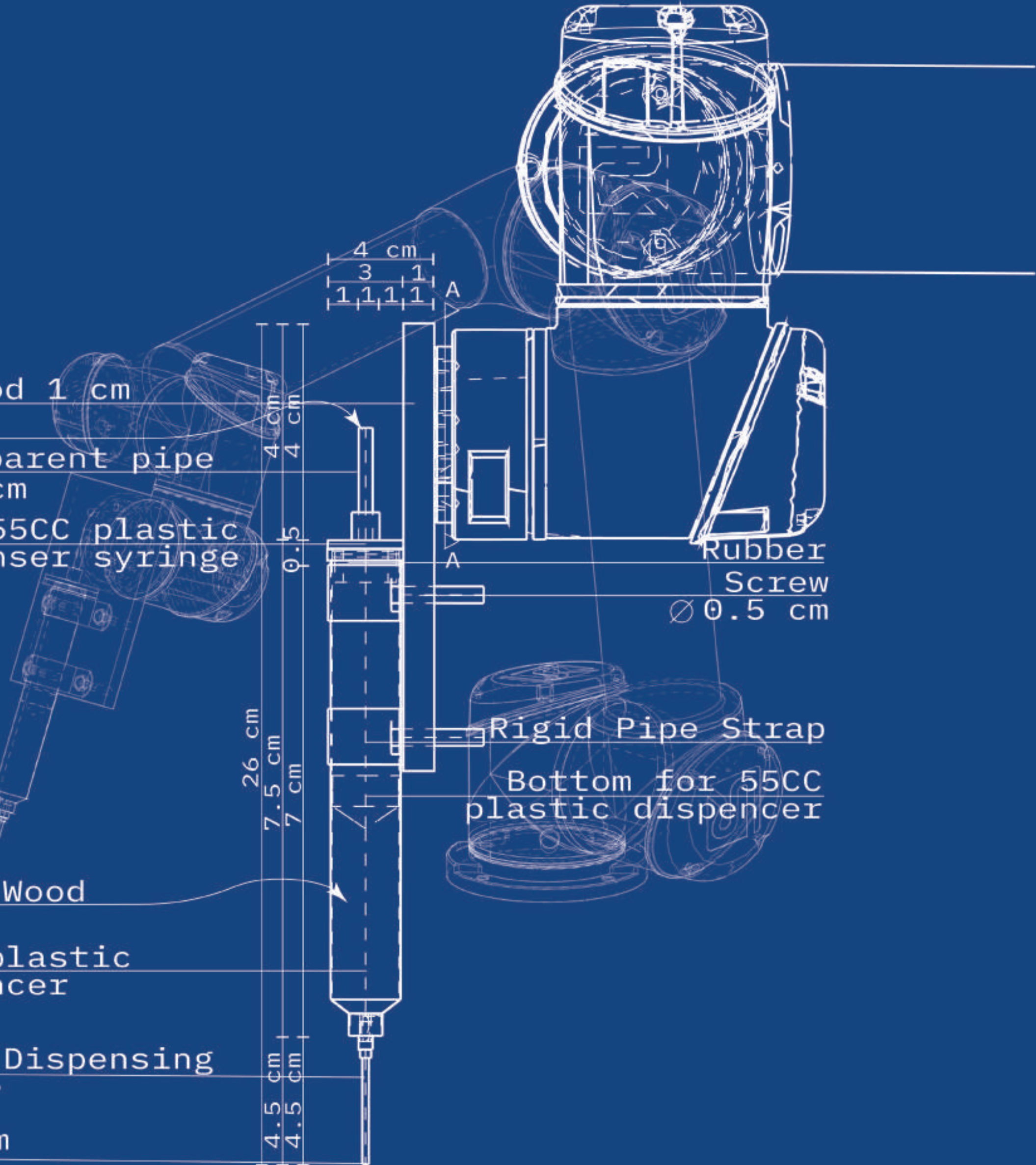


Figure 38: The robotic head tool is the edge part connected to the robotic arm



od 1 cm
parent pipe
cm
55CC plastic
nser syringe
Wood
plastic
ncer
Dispensing
m
4 cm
3
1
1 1 1 1
A
4 cm
4 cm
0.5
26 cm
7.5 cm
7 cm
4.5 cm
4.5 cm
Rubber
Screw
∅0.5 cm
Rigid Pipe Strap
Bottom for 55CC
plastic dispencer

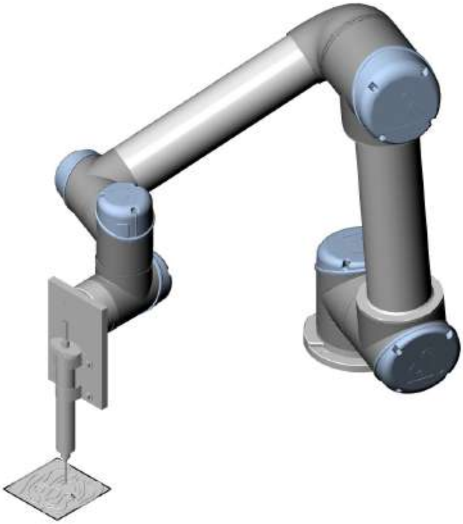


Figure 39: Horizontal additive manufacturing on a flat surface simulation

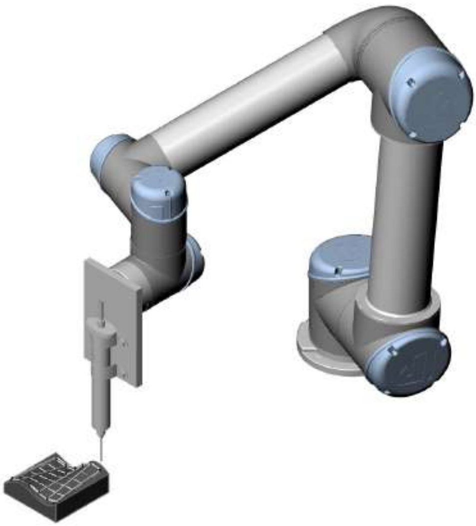


Figure 40: Horizontal additive manufacturing on a curved surface simulation

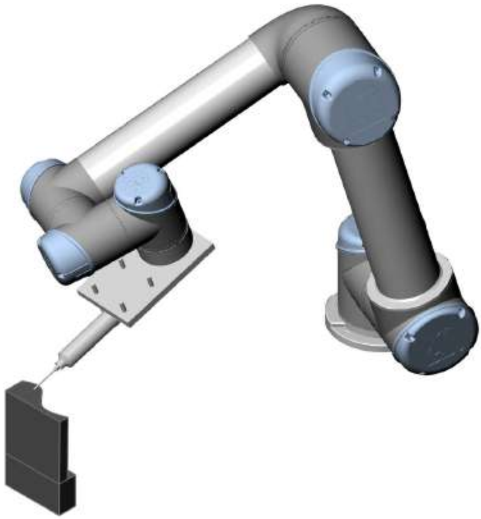


Figure 41: Vertical additive manufacturing on a curved surface simulation

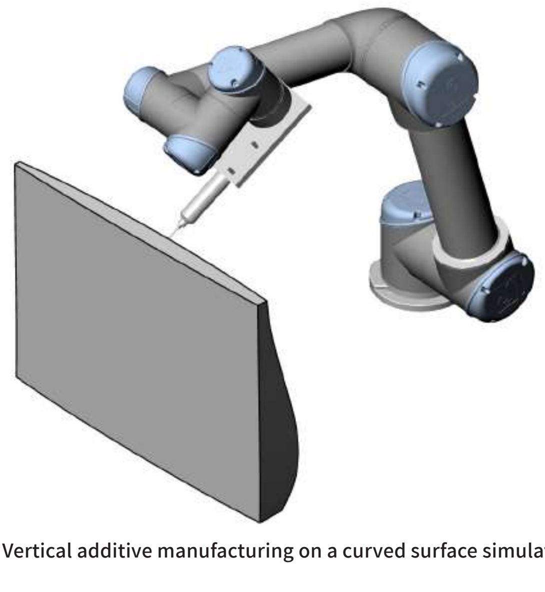


Figure 42: Vertical additive manufacturing on a curved surface simulation

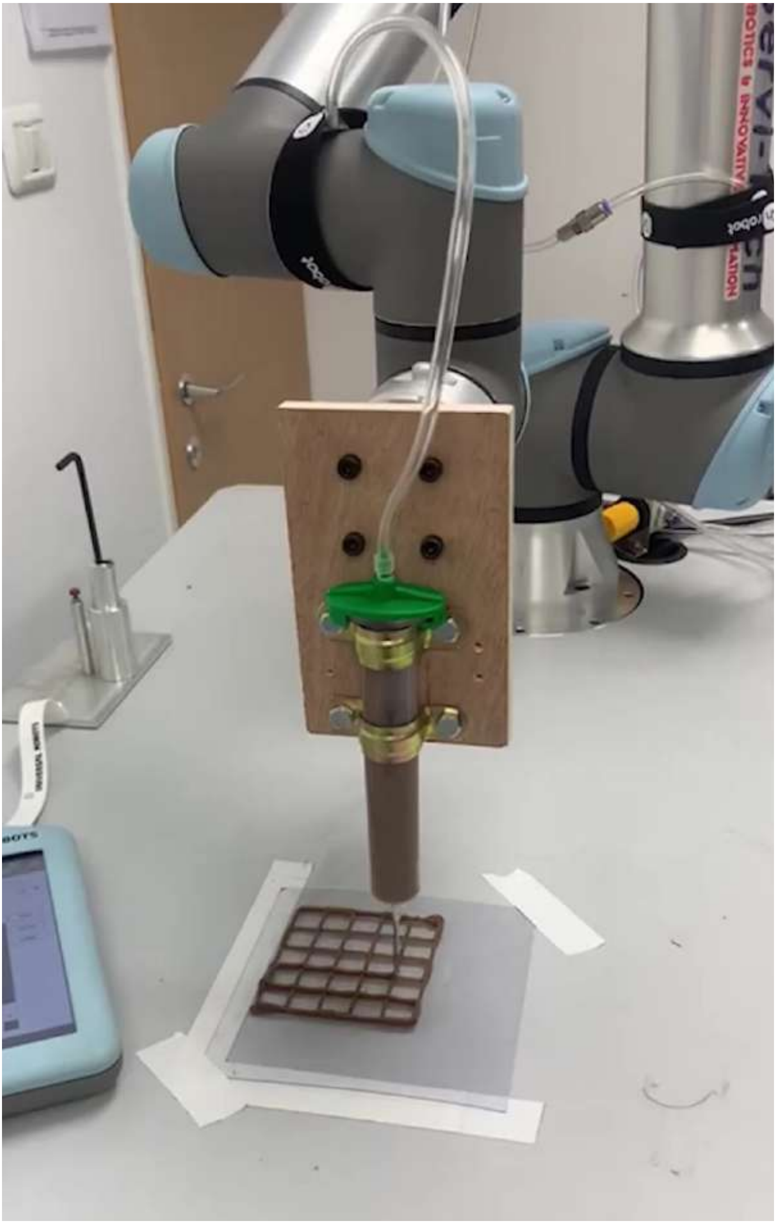


Figure 43: Horizontal additive manufacturing on a flat surface, by a robotic arm, with Daika wood

Figure 44: Horizontal additive manufacturing on a curved surface, by a robotic arm, with Daika wood

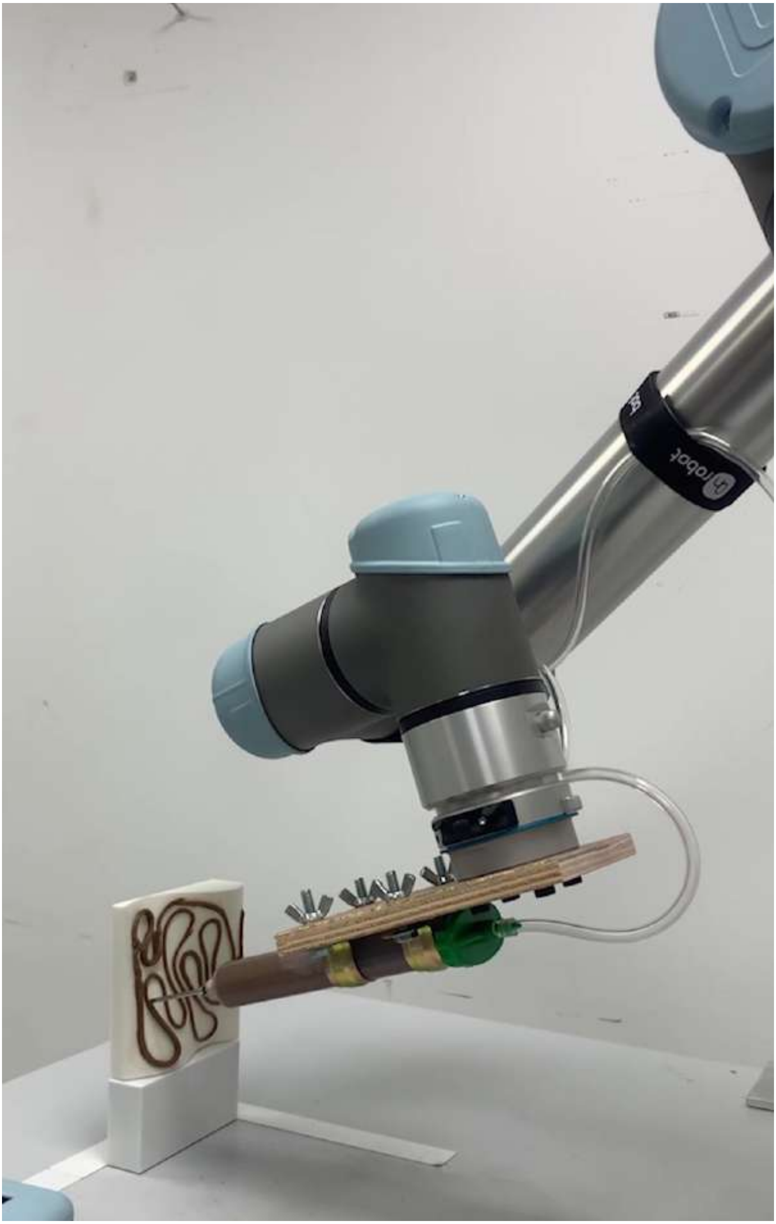


Figure 45: Vertical additive manufacturing on a curved surface, by a robotic arm, with Daika wood

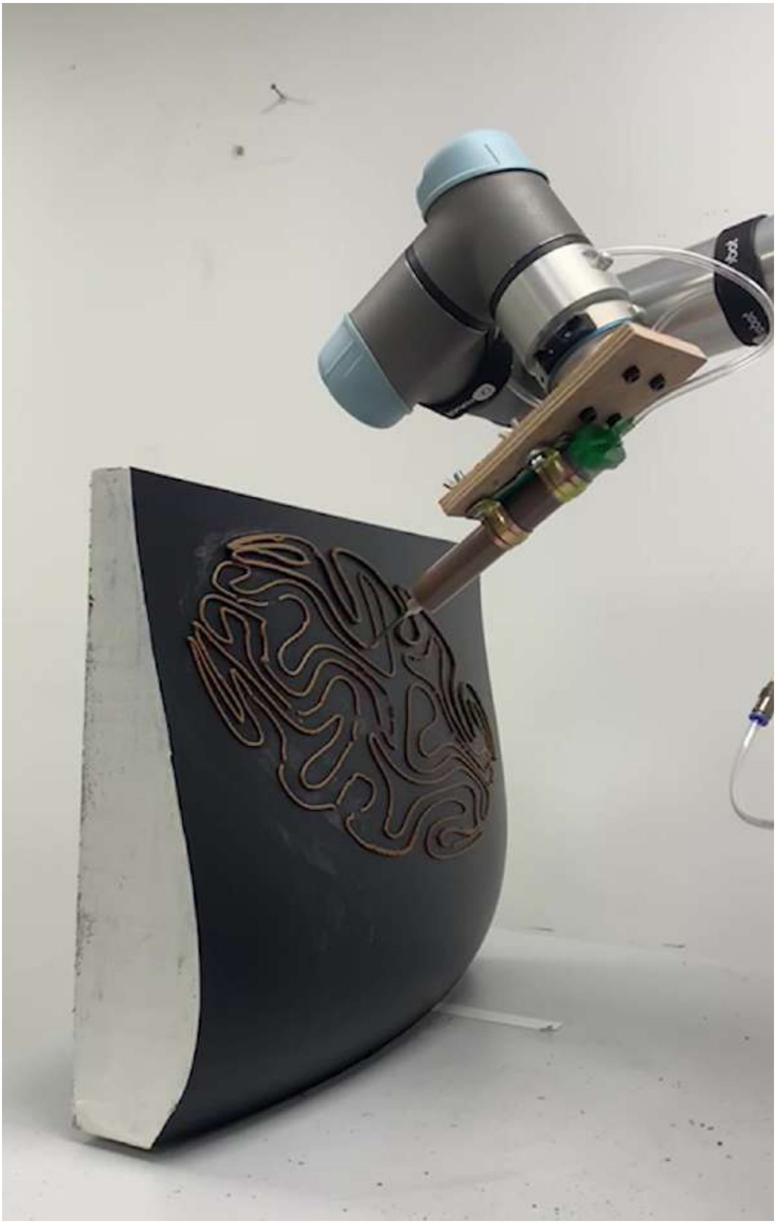


Figure 46: Vertical additive manufacturing on a curved surface, by a robotic arm, with Daika wood

Horizontal additive manufacturing on a flat surface of a grid pattern

Horizontal additive manufacturing on a flat surface of a grid pattern layers

Horizontal additive manufacturing on a flat surface of a gastrointestinal pattern

Horizontal additive manufacturing on a curved surface of a grid pattern

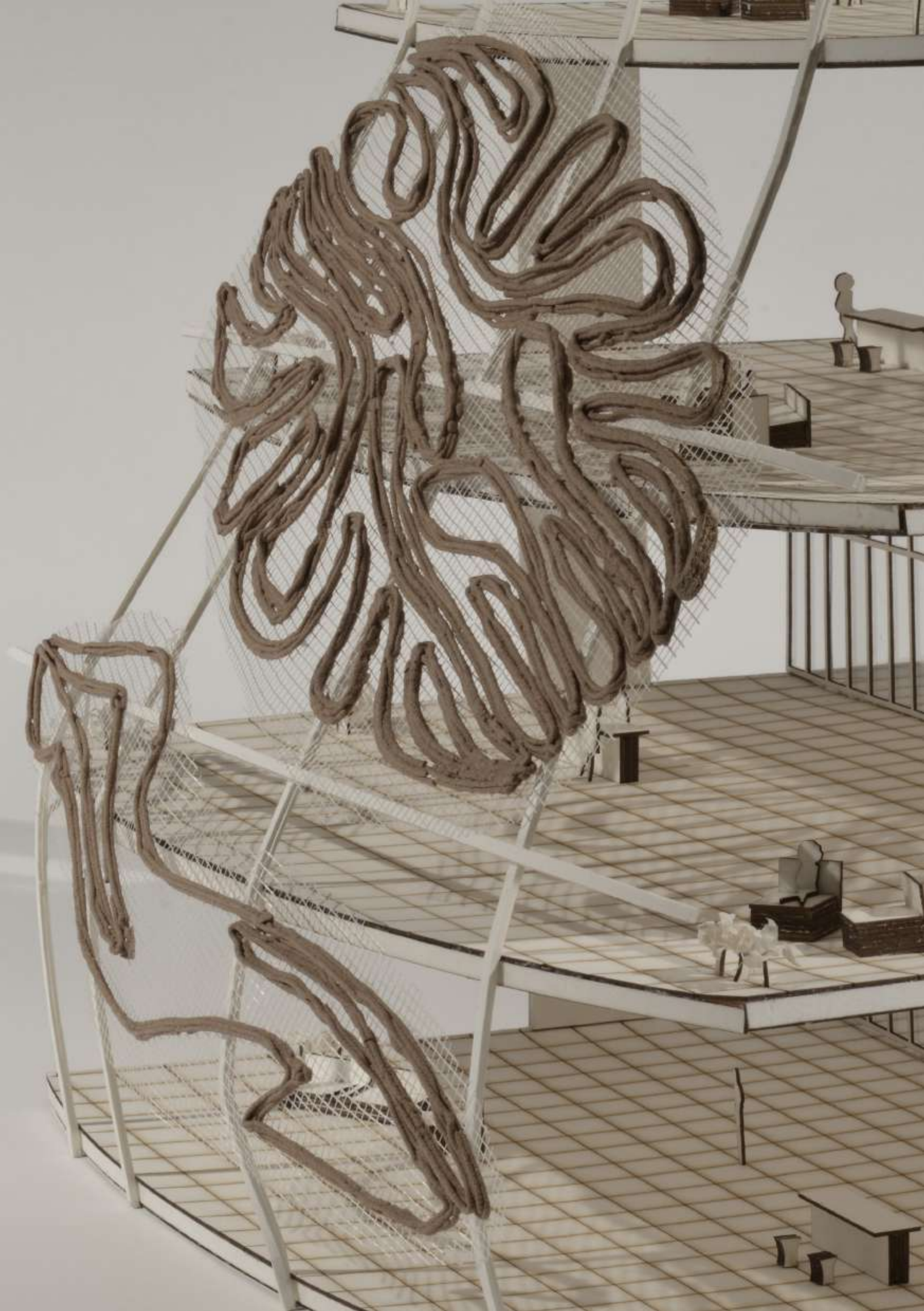
Figure 47: The experiments results

Horizontal additive manufacturing on a flat surface of a grid points distortion pattern

Horizontal additive manufacturing on a flat surface of a gastrointestinal pattern

Vertical additive manufacturing on a curved surface of a gastrointestinal pattern

Vertical additive manufacturing on a curved surface of a grid pattern



Conclusion and Discussion

New technologies hold the promise to create architectural elements we have not seen before. Those architectural elements suggest many new opportunities for future buildings (figure 48). As architects, we should use those technologies to diverse our cities, give humans a comfortable place to live in, and reduce environmental damage. If we embrace those technologies, the design and plan of the following buildings will change accordingly.

Additive manufacture with a robotic arm is only one technology that could help diverse architectural planning - there are many more. This project leans on this particular technology to demonstrate its advantages and the opportunities it could supply. By proving the ability to create such architectural elements, this project implies many more new technologies that will be used in architecture.

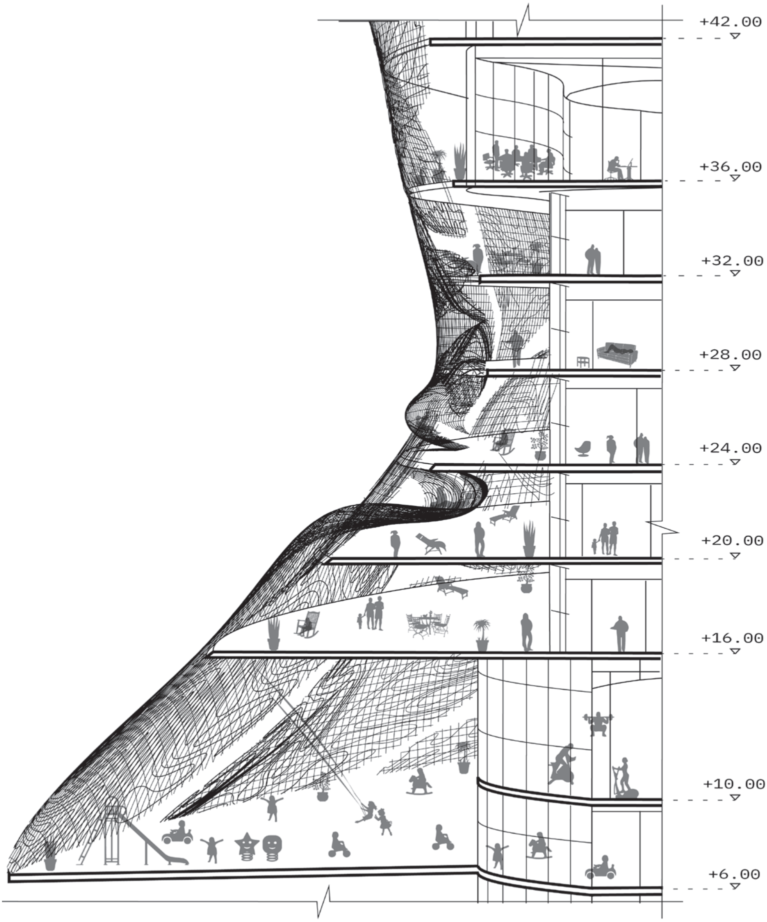
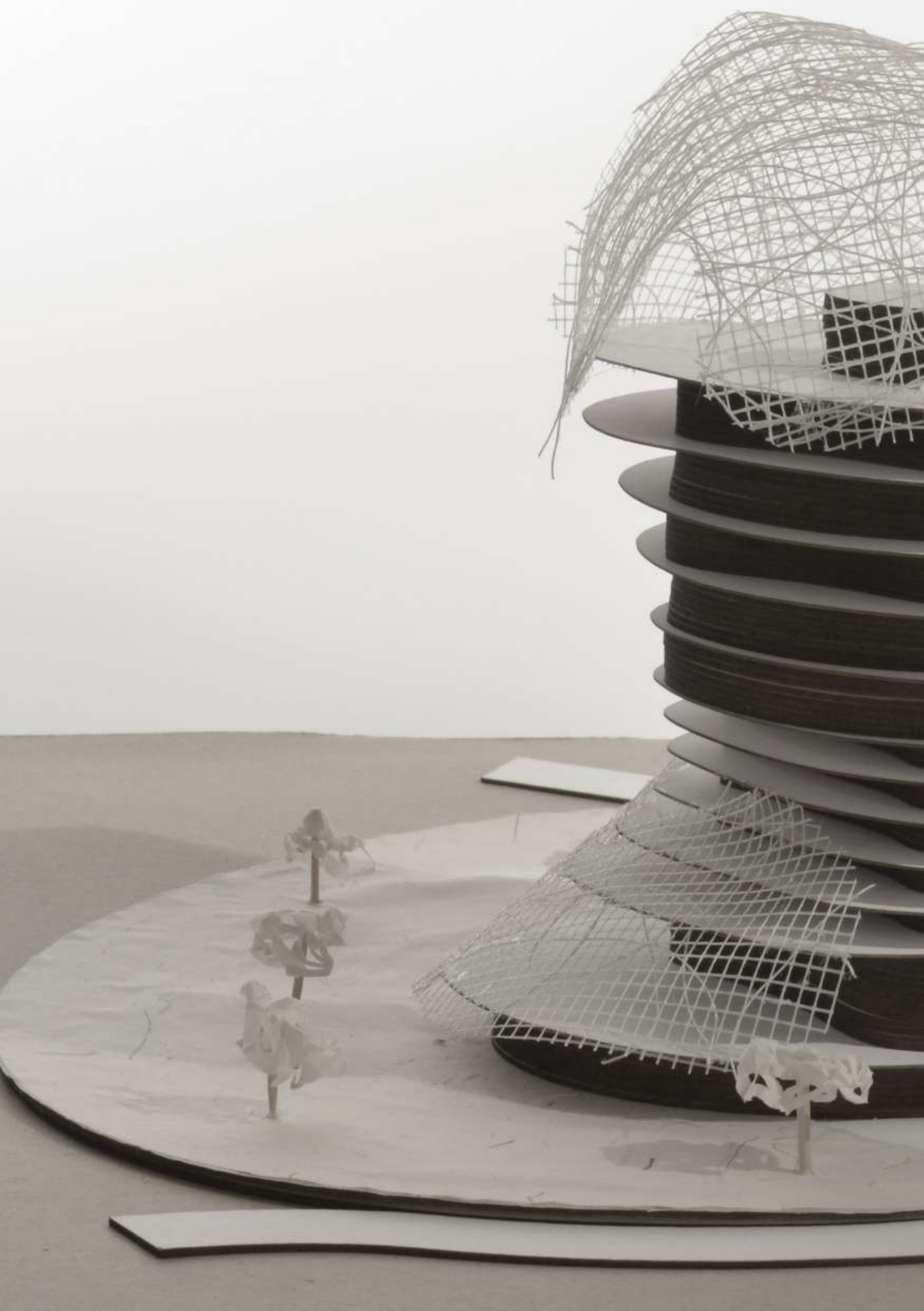
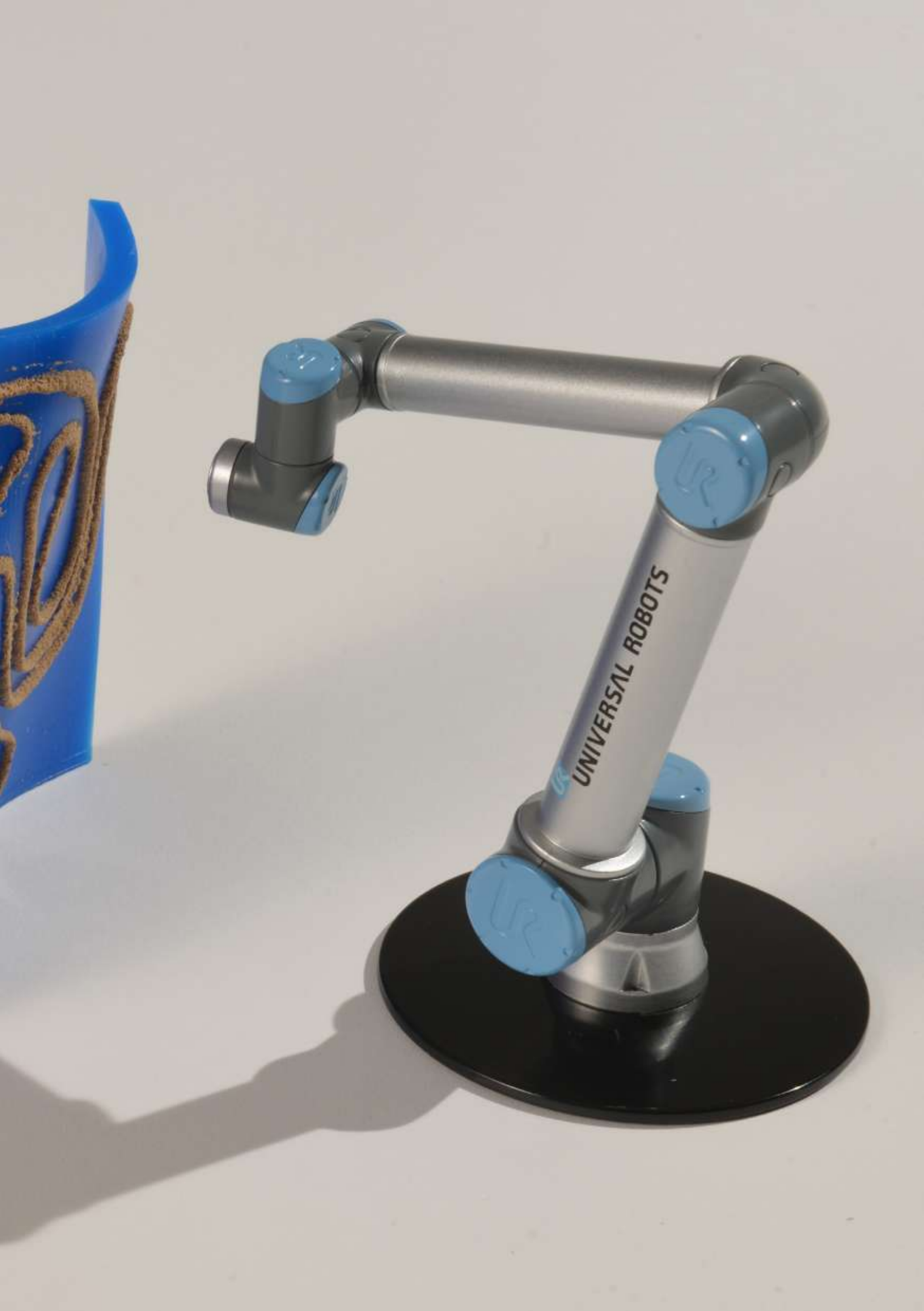


Figure 48: A section of a potential curving façade




UNIVERSAL ROBOTS

Bibliography

Ai Build. 2020. “Blossom.” Ai Build. 2020. https://ai-build.com/store-blossom.html.

Alaghmandan, Matin, Mahjoub Elnimeiri, Robert J. Krawczyk, and Peter von Buelow. 2016. “Modifying Tall Building Form To Reduce the Along-Wind Effect.” CTBUH 2: 34–39. https://www.jstor.org/stable/90006202?read-now=1&refreqid=excelsior%3A1fe27995911b808aef09c814873d3378&seq=1#page_scan_tab_contents.

Anton, Ana, Patrick Bedarf, Angela Yoo, and Timothy Wangler. 2019. “Robots 3D-Print Nine Different Concrete Columns without Any Formwork.” Designboom. 2019. https://www.designboom.com/architecture/3d-printed-concrete-columns-switzerland-eth-zurich-07-15-2019/.

Apis Cor. 2020. “We Print Buildings.” Apis Cor. 2020. https://www.apis-cor.com/.

Battaglia, Christopher A., Martin Fields Miller, and Sasa Zivkovic. 2019. Sub-Additive 3D Printing of Optimized Double Curved Concrete Lattice Structures. Robotic Fabrication in Architecture, Art and Design 2018. https://doi.org/10.1007/978-3-319-92294-2_19.

Beyond3D. 2020. “Inspiring Innovation.” Beyond3D. 2020. https://beyon3d.com/.

Cossu, Marco, Akira Yano, Zhi Li, Mahiro Onoe, Hidetoshi Nakamura, Toshinori Matsumoto, and Josuke Nakata. 2016. “Advances on the Semi-Transparent Modules Based on Micro Solar Cells: First Integration in a Greenhouse System.” Applied Energy 162: 1042–51. https://doi.org/10.1016/j.apenergy.2015.11.002.

Costanzi, Chris Borg. 2016. “3D Printing Concrete Onto Flexible Surfaces - Delft University of Technology Faculty,” 108. file:///Users/yechanlim/Downloads/CHRIS BORG COSTANZI 4411439 2016.pdf.

Després, Nathaniel, Edward Cyr, Peyman Setoodeh, and Mohsen Mohammadi. 2020. “Deep Learning and Design for Additive Manufacturing: A Framework for Microlattice Architecture.” Jom 72 (6): 2408–18. https://doi.org/10.1007/s11837-020-04131-6.

Dickinson, Duo. 2018. “Architecture without Architects: The Cut-Paste Typology Taking Over America.” ArchDaily. https://www.archdaily.com/907476/architecture-without-architects-the-cut-paste-typology-taking-over-america.

Eigensatz, Michael, Martin Kilian, Alexander Schiftner, Niloy J. Mitra, Helmut Pottmann, and Mark Pauly. 2010. “PANELING ARCHITECTURAL FREEFORM SURFACES.” ACM Transactions on Graphics 29 (3). http://

graphics.stanford.edu/~niloy/research/paneling/paneling_sig_10.html.

Elkabany, Sara N., Ahmed M. Elkordy, and Hesham A. Sobh. 2020. “Optimization of the Panels Used in Free-Form Buildings and Its Impact on Building Cost.” IOP Conference Series: Materials Science and Engineering 974 (1). https://doi.org/10.1088/1757-899X/974/1/012010.

Foster + Partners. 2003. “The Gherkin: Foster’s Monumental Building In The Heart Of London.” Archute. 2003. https://www.archute.com/the-gherkin-a-monumental-building-in-the-middle-of-london-by-foster-partners/.

Franco, José Tomás. 2018. “6 Spanish Projects That Creatively Use Louvers and Shutters in Their Facades.” ArchDaily. 2018. https://www.archdaily.com/900756/6-spanish-projects-that-creatively-use-louvers-and-shutters-in-their-facades.

Frayling, Christopher. 1993. “Research in Art and Design.” Royal College of Art Research Papers.

Grosso, A. E. Del, and P. Basso. 2010. “Adaptive Building Skin Structures.” Smart Materials and Structures 19 (12). https://doi.org/10.1088/0964-1726/19/12/124011.

Herzog, Jacques, and Pierre de Meuron. 2017. “Prada Anoyama.” DIVISARE. 2017. https://divisare.com/projects/336109-herzog-de-meuron-johannes-marburg-prada-aoyama.

ICON. 2020. “Project Olympus.” ICON. 2020. https://www.iconbuild.com/?utm_medium=website&utm_source=archdaily.com.

Kam, Doron, Michael Layani, Sheer BarkaiMinerbi, Donna Orbaum, Shir Abrahami BenHarush, Oded Shoseyov, and Shlomo Magdassi. 2019. “Additive Manufacturing of 3D Structures Composed of Wood Materials.” Advanced Materials Technologies 4 (9): Doron Kam.

Kormaníková, Lenka, Henri Achten, Miloš Kopřiva, and Stanislav Kmeť. 2018. “Parametric Wind Design.” Frontiers of Architectural Research 7 (3): 383–94. https://doi.org/10.1016/j.foar.2018.06.005.

Krause Architects. 2018. “London Store Recycles 60,000 Plastic Bottles for 3D-Printed Interior.” InHabitat. 2018. https://inhabitat.com/london-store-recycles-60000-plastic-bottles-for-3d-printed-interior/.

LCR architectes. 2014. “Public Middle School in France out of Copper.” Designboom. 2014. https://www.designboom.com/architecture/lcr-architects-labarthe-sur-lez-public-school-france-08-28-2014/.

Lu, Ming, Wei Ran Zhu, and Philip F. Yuan. 2018. “Toward a Collaborative Robotic Platform: FUROBOT Ming.” In Architectural Intelligence, edited by Philip F. Yuan, Mike Xie, Neil Leach, Jiawei Yao, and Xiang Wang, CDRF 2019:87–101. Singapore: Springer. https://doi.org/10.13128/Techne-23561.

Maas, Winy, Felix Madrazo, Adrien Ravon, and Diana Ibáñez López. 2017. Copy Paste. Edited by The Why Factory. nai010. https://thewhyfactory.com/news/copy-paste-is-out/.

Menges, Achim, University of Stuttgart) (ICD – Institute for Computational Design, Jan Knippers, and University of Stuttgart) (ITKE – Institute of Building Structures and Structural Design. 2017. “ICD/ITKE Research Pavilion 2016-17.” University of Stuttgart. 2017. https://www.icd.uni-stuttgart.de/projects/icditke-research-pavilion-2016-17/.

Menges, Achim, and Jan Knippers. 2015. “ICD/ITKE Research Pavilion 2014-15.” University of Stuttgart. 2015. https://www.icd.uni-stuttgart.de/projects/icditke-research-pavilion-2014-15/.

Moonen, Peter, Thijs Defraeye, Viktor Dorer, Bert Blocken, and Jan Carmeliet. 2012. “Urban Physics: Effect of the Micro-Climate on Comfort, Health and Energy Demand.” Frontiers of Architectural Research 1 (3): 197–228. https://doi.org/10.1016/j.foar.2012.05.002.

Novikov, Sasa, and Petr Jokic. 2013. “Gravity-Nwutral 3D Printing.” Mataerial. 2013. http://www.mataerial.com/#4thPage.

Ockman, Joan. 2018. “New Politics of the Spectacle: ‘Bilbao’ and the Global Imagination.” Architecture and Tourism, 227–39. https://doi.org/10.5040/9781350057715.ch-012.

OVO Grabczewscy Architekci. 2015. “Museum of Fire in Żory.” ArchDaily. 2015. https://www.archdaily.com/592195/museum-of-fire-in-zory-ovo-grabczewscy-architekci.

Oxman, Neri. 2015. “Neri Oxman’s New Glass Printing Technique Could Lead to 3D-Printed Glass Building Facades.” Dezeen. 2015. https://www.dezeen.com/2015/08/26/neri-oxman-3d-printing-transparent-glass-sculptural-structures-mediated-matter-mit-media-lab/.

Paoletti, Ingrid. 2017. “Mass Customization with Additive Manufacturing: New Perspectives for Multi Performative Building Components in Architecture.” Procedia Engineering 180: 1150–59. https://doi.org/10.1016/j.proeng.2017.04.275.

PERI. 2021. “PERI 3D Printing Project.” PERI. 2021. https://www.peri.com/en/media/press-releases/peri-3d-printing-project-beckum-wins-german-innovation-award.html.

Playze. 2011. “Tony’s Farm.” ArchDaily. 2011. https://www.archdaily.com/311024/tonys-farm-playze.

Richter Dahl Rocha & Associés. 2014. “EPFL QUARTIER NORD SwissTech Convention Center Retail and Student Housing.” ArchDaily. 2014. https://www.archdaily.com/519434/epfl-quartier-nord-swisstech-convention-center-retail-and-student-housing-richter-dahl-rocha-and-associes.

Rittel, Horst W.J., and Melvin M. Webber. 1973. “Dilemmas in a General Theory of Planning Published by : Springer.” Policy Sciences 4 (2): 155–69.

SARL Architects. 2011. “PETITE SCÈNE DEVIENDRA GRANDE.” Trophee Archizinc, no. 89.

Schipper, Roel, Chris Borg Costanzi, Freek Bos, Zeeshan Ahmed, and Rob Wolfs. 2017. “Double Curved Concrete Printing: Printing on Non-Planar Surfaces.” Spool 4 (2): 17–21. https://doi.org/10.7480/spool.2013.1.624.

Systematics. 2021. “Systematics.” 2021. https://www.systematics.co.il/about/.

Weiguo, XU, GAO Yuan, ZHANG Zhiling, SUN Chenwei, WAN Zhi, LIN Zhipeng, and HAN Dong. 2018. “3D Printing Concrete on Curved Surfaces.” Rob Arch. 2018. https://vimeo.com/287684647.

Wit, Andrew John, and Mahesh Daas. 2018. “Robotic Production in Architecture.” In TOWARDS A ROBOTIC ARCHITECTURE, edited by Andrew John Wit and Mahesh Daas, 28–61. Novato CA USA: AR+D. https://www.researchgate.net/publication/319967494_Robotic_Production_in_Architecture.

Yeang, Ken. 1998. “Designing the Green Skyscraper.” Building Research and Information 26 (2): 122–141. https://doi.org/10.1016/0197-3975(91)90039-N.

Zaha Hadid Architects. 2017. “Thallus Installation.” Zaha Hadid Architects. 2017. https://www.zaha-hadid.com/design/thallus-installation/.

This project develops a unique building's façade planned by digital design according to environmental parameters. This façade is produced by additive manufacturing techniques using a robotic arm. It provides climatical efficiency, more outdoor spaces, and unique aesthetics. This façade is different for every building use, according to the program's function. The façade contains curved surfaces with changing thickness; therefore, other building techniques could not produce it. It is possible to create this façade by additive manufacturing with a robotic arm, proven by models developed in this project. Many other possibilities for building's elements will be possible to create in the future with digital design and advanced technologies such as this one. The project's research question is: Given additive manufacturing by a robotic arm, what climatic and aesthetics opportunities could be suggested to the building's façade design?