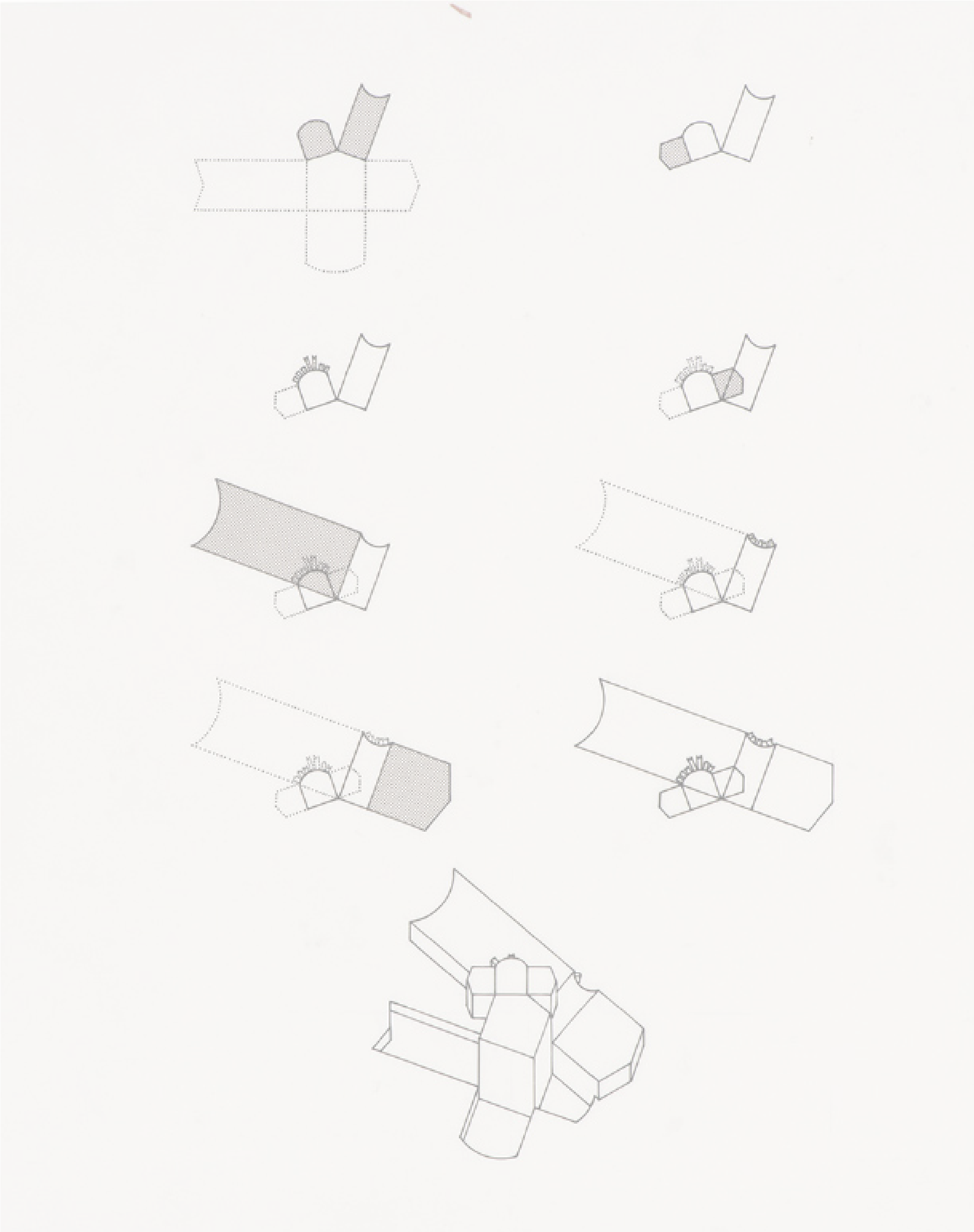
The Game Changer

The influence of computer on architectural design



Zofia Sosnierz
5352436

AR2A011 Architectural History Thesis
TU Delft 2020/2021

Table of Contents

Figrure X. Drawings itirations of the Biocenter project.

Introduction

The appearance of the computer in architectural design was a long-awaited moment. Designers had been long preparing for this invention. Since Renaissance the architectural profession has enormously developed and redefined itself in theory and practice. However, by the end of the XX century, the previous beliefs and architectural approaches started to be insufficient for the cultural needs and expectations. That is why at the end of the 1980s and throughout the 1990s the computer was welcomed with such enthusiasm. It was a machine that was enabling architects to move away from the old paradigms and limitations of the previous centuries. Not only it enabled the design and creation of new and complex forms of buildings but also became a critical instrument in the design process. It shifted the designs but also the approach to the whole architectural designing.

One of the first projects to use the computer in its design process was the Biocenter in Frankfurt by Peter Eisenman in 1987. The project was an extension of the Goethe University in Frankfurt am Main. In order to achieve its main objectives, it used biological concepts to obtain spatial structure and form of the complex. The team used coding devices inspired by the DNA structures as an abstract biological analogy of coding. It used parameters and variables to create heterogeneous spaces. The importance of this project in the history of the digitalisation in architecture is that it became an instrument to partially design the output of the project. In a way, its role was as critical as the design team's working on the project. It created a path for future architects to follow in the use of the computer.

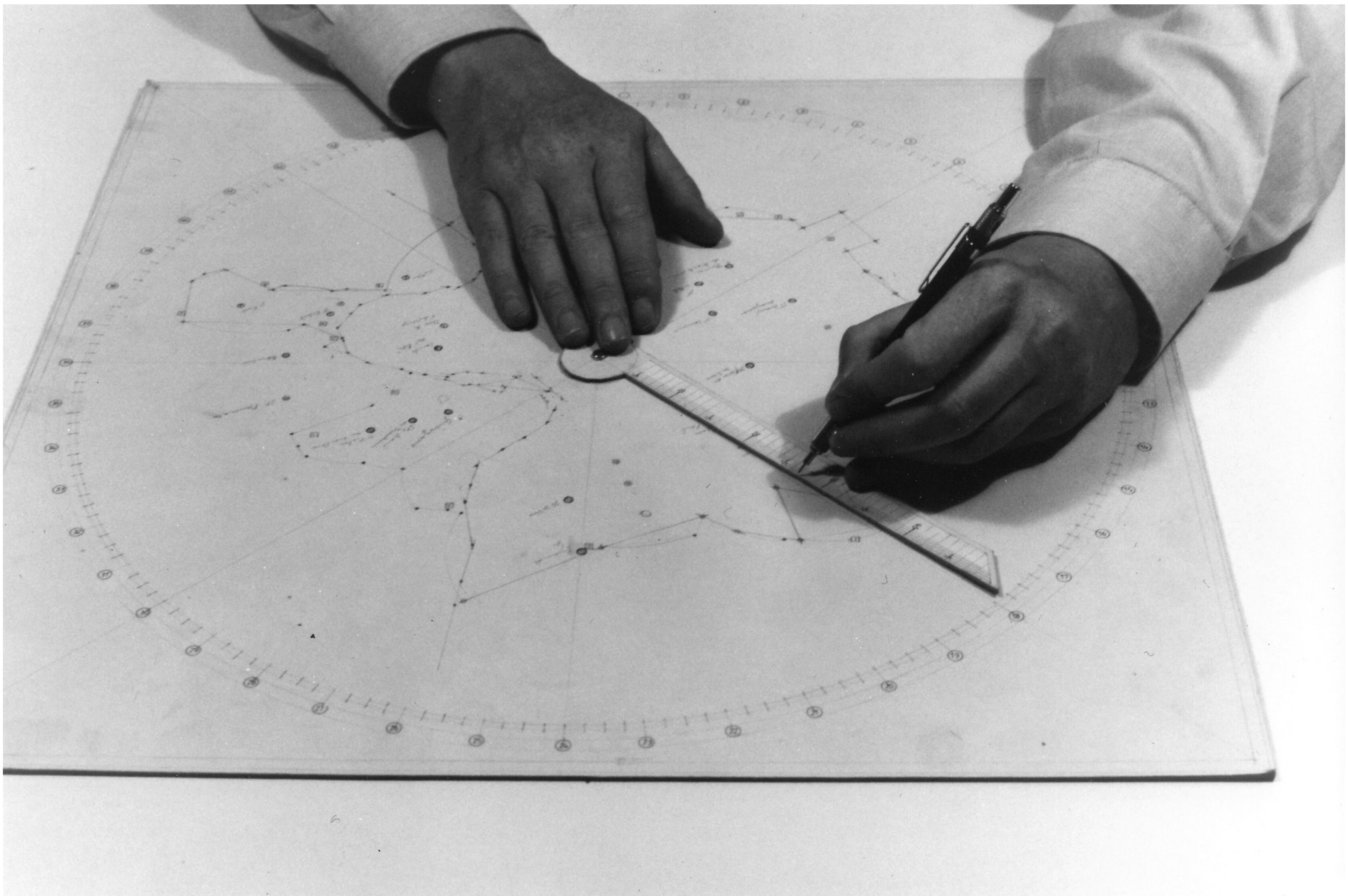
This thesis will investigate the relationship between the computer and the architect. It will begin with exploring the profession of an architect that was redefined in the XV century. By doing so, it will help the reader to understand the way the architects performed their profession throughout the centuries, until the digital revolution. Their methods and tools defined the way they approached the design, but also its final outcome and form. This will enable to fully grasp the changes the computer made by entering the architecture industry.

The project of Biocenter by Peter Eisenman will be used as a case study, to create a better understanding of how the computer started to be used by the architects. It represents a very conscious and inventive approach to the use of the digital. It underlines the main reasons why the computer should be used in the design and created a path for the next architects to follow. Next, other projects of the 1990s will be described to portray a better picture of different ways the computer was used by architects and engineers. By doing so, it will display the various parts of architecture that the computer had an influence on.

The structure of the thesis consists of three chapters. The first one explains the profession and development of the architectural practice. It explores the tools which architects used to perform their practice, as well as, cultural and economical developments that influenced the formation of architecture. The second chapter focuses on the project of Biocenter which is a case study for this thesis. It first explains the idea standing behind the project and the process of formation of its design. Secondly, it analyses how the computer was used in this project. Lastly, to help the reader understand better the way the computer performed in the design, it concludes by describing the difference between the performance of the computer and the human mind. The third chapter focuses on other projects formed in the 1990s with the use of computer and concludes in the analyses of changes made by the digital. Finally, the conclusion is made, which wraps up the whole thesis and answers the research question.

Throughout the thesis, the research question will be answered with the use of sub-questions:
What is the difference between the way the computer works and the human mind? What is it about the computer that has changed so much in architectural design? How the computer should be used in the process of designing?

To answer the thesis topic in the best way possible various sources have been used. Books, articles and lectures were analysed in order to gain knowledge about the historical, cultural, economical and social aspects of the profession of an architect and of the appearance of the computer in the field of architecture.



Figrure 1. Reconstruction of the map and drawing device following the methods and coordinates supplied in Alberti's Descriptio urbis Romae. Image by an courtesy of Bruno Queysanne and Patrick Thépot.

CHAPTER I: Pre- Biocenter approach to design

A. The profession of an Architect before Alberti

To fully understand the role of computers in architectural design it is important to first grasp the position of the architect himself in this process. In our present times, it seems obvious that an architect's job is to create the design of a building and to translate it into technical, parallel drawings to scale in form of plans, sections, and other. It is also known that after signing the drawings the designer becomes the author of the design. After that, the notations are passed on to the people responsible for building the object. Those are obliged to strictly follow the design when raising the structure. In the latter part of the process the architect does not take part physically, meaning he does not initiate the act of construction[1]. However, it hasn't always been this way. As all the professions in history at some point in time the architects' role had to be revaluated and understood in order for him or her to efficiently perform.

1. Pre- Renaissance

Until the XV century architects performed their profession in many different ways and played different roles in society. For instance, in ancient Egypt, the act of building monuments had a very high importance and only a limited number of people were allowed to become architects. In these circumstances, the position of the chief state architect was at the top of the social hierarchy[2]. Later, Vitruvius seemingly describes a word similar to the one we use to describe our craft. In his famous *treatise*(I, i) tries to grasp the meaning of the word "*architectus*" and talks about the importance of this role. However, the description of the man he is portraying, does not match the concept of an architect we have today. He depicts someone of a high social standing with many professions and talents. Moreover, the craftsmen of his times- who actually conceived the designs of the buildings- most probably were nothing like the person he is describing. And lastly, during the middle ages the pursuit of defining the profession of an architect lessened. Rarely craftsmen, who were the authors of the buildings were acknowledged as the designers of the building[3, 4].

2. Renaissance

This tendency to devalue the profession of the architect ended with the appearance of the Renaissance. The first to attempt to reconsider this role was Filippo Brunelleschi. In order to rationalize the space, he created a method to mathematize perspective. The mathematics of his work were based on plotting the image he saw on paper with the help of tools.[5] By doing so he improved the correctness of the architectural drawings and brought them closer to their aesthetic perfection. His work was of high importance to this profession.

Unfortunately, his methods and findings were mainly passed on orally and not put into any formula. And this is exactly where Leon Battista Alberti plays a big role. Even though the two individuals devoted themselves to similar fields of life and findings, they were very different in their background and the way they worked. Brunelleschi from the age of fifteen was a part of Arte sella Seta, which was a silk guild. There he learned to be a sculptor and a master goldsmith[6]. His creations were based on practical discoveries and findings. Alberti came from a different background. He studied at the University of Bologna and was a man of theory. Alberti created many treatises on diverse topics. In one of the first ones called *de Pictura* (on Painting), 1435, he codifies, simplifies, and writes down Brunelleschi's method of mathematical construction of perspective with a theoretical discussion on what it is to represent pictorial space. Finally, and most importantly for this paper, he wrote *de re aedificatoria*, which are 10 books on Architecture from 1452[7].

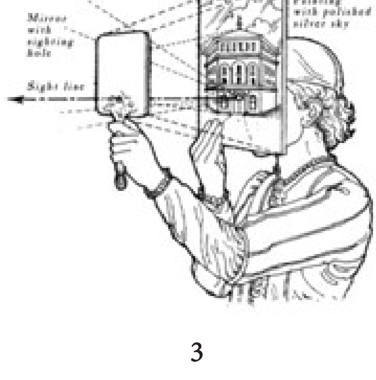


Figure 2. Brunelleschi's method of constructing perspective

B. Architect redefined by Alberti

The Renaissance period in Europe was a result of big changes in people's perception of reality. With this came the beginning of Western Humanism. As Peter Eisenman accurately pointed out in his text and lecture "Eisenman/Wigley X: The Problematic of Homogeneous Space" it was "a beginning of consciousness about what the relationship between the human- subject and architecture- the object, was about"[8]. This recognition grew into a need for discipline and its reassessment. This need was met with Alberti's *treatise*'s.

1. Redefining the profession

Leon Battista Alberti in his treatise *de re aedificatoria* (10 Books on Architecture) made a ground-breaking change in the understanding of the role and tasks of an architect. First of all, he is the author of the first interpretation of the elevations and plans in orthogonal and in proportion[9], which define the notation system used to this day. Secondly, he emphasized in the humanistic sense the role and importance of the architect as an author of the design. Meaning he brought to light the importance of authorship over the project. In combination, these two things became the two fundamental parts of the definition of the architect's profession. In Alberti's interpretation of the craft, the architect produces the design which he translates in form of the notations. These are later transformed into a building which becomes a copy of the architect's design[10].This is a revolution that has paved the way for generations of architects up until the rise of digital technologies.

2. Notations

As stated by Nelson Goodman we can divide arts into two types: autographic and allographic. The first type can be compared to a craft in which the craftsmen conceive and build the form by themselves. The second indicates a type of art in which the author of the design scripts it and others construct it. Goodman states that all arts first are autographic and later turn into allographic[11]. Looking back we can say this was also the case with architecture. Alberti, by creating the notational system, made this change. First of all, he highlights in his second book of De re aedificatoria that an architect should not use perspective drawings, but drawings consisting of "real measurements, drawn to scale", "true angles," and "consistent lines,". By doing so, Alberti additionally created a geometrical interpretation of the modern plans and elevations[12].Overall, in his books, he explains the difference between building and designing redefining the role of an architect to being a designer.

Figure 3. Medival Craftsmen working on a building site.

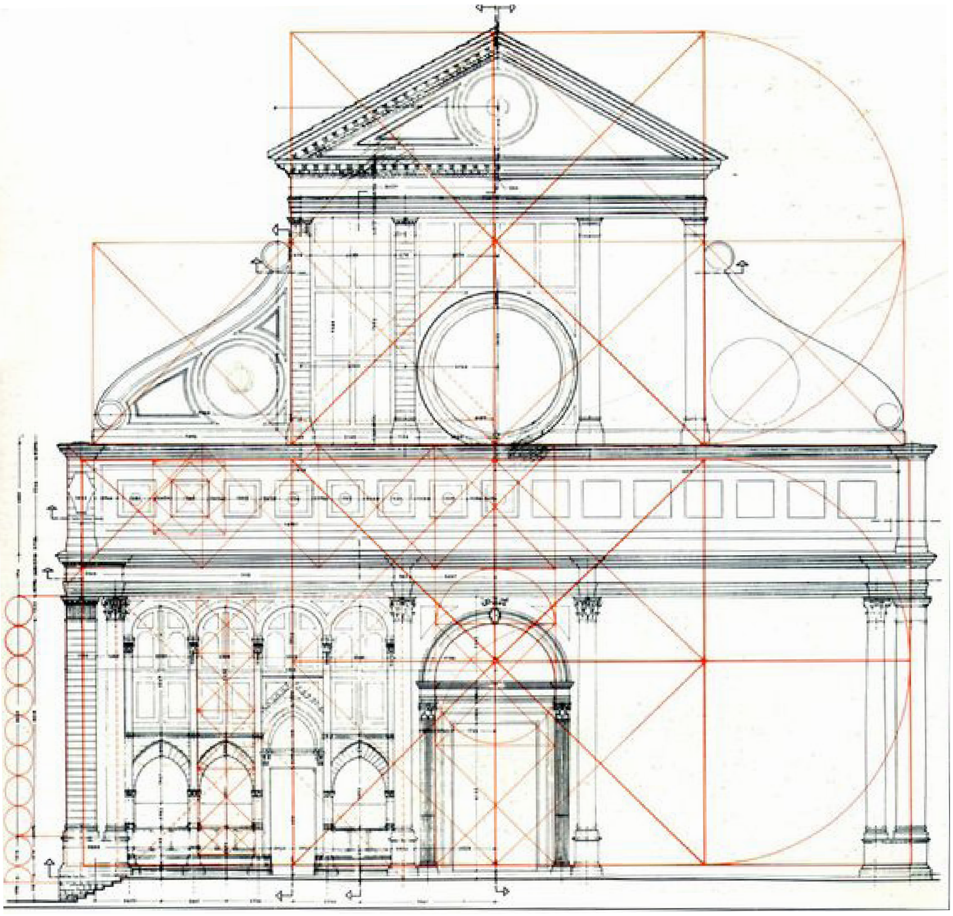


Figure 4. The geometrical proportions of the facade of the church of Santa Maria Novella by Leon Battista Alberti (mid 1400s) Florence.

3. Authorship

Any designer knows the struggle of maintaining the authorship of their design. On top of that, the battle to keep the initial design coherent and constant throughout the realization of the project. This was an obstacle (among others) Brunelleschi was facing during the construction of one of his projects: the dome of Santa Maria del Fiore. He was forced to always be present at the building site in order to not let the workers have access to his design and take over his authorship over the project[13].

Alberti found a solution to this. In his treatises, he emphasizes the importance of the drawing firstly as a tool ac companying the design process, and then as a tool of notation. He describes all the process of the design in which the designer is obliged to check his design various times. After that he should translate it into the final notation, which later is given to the builders. The workers are obligated to identically generate the design notated in the two-dimensional drawings into a three-dimensional object. In this way, the architect becomes the owner of the design and the craftsmen have no say in the latter and are not allowed to make any changes, which are inconsistent with the initial notation.[14]

Alberti in his treatises defined the profession and the job of the architect for many generations to come. Also, he depicted the concept of space and the notation system. It is important to understand that by doing so, he imposed a way of understanding space and therefore of designing in it. Additionally, he imposed a method of designing by notation, which enabled many new possibilities regarding the workflow and relationship between the architect and the design, but also created new limitations that did not exist before.

C. Identicality and its limitations

The designer and the design are always at the mercy of the tools used in the design process. These tools are usually a big help to the author of the project, but can also be a limitation. Back in the days the craftsmen were in charge of the design or in the instance of autographic art- the design was an outcome of the human hands, imagination and the possibilities of the material. If the craftsman was able to create the sculpture with his own hands and the clay was good enough for it, then the only limitation was the author's imagination, which is limitless. However, as was mentioned earlier in this chapter it all changed with the introduction of the notational system by Leon Battista Alberti in the XV century. For the first time the concept of identicality was introduced, which had an influence on architectural design for centuries to come. The instance of the identicality was later fixed by the invention of print, and after enhanced even more by the industrial revolution. Modernism embraced the latter and used design identicality to its limits. Identicality has created many new opportunities for the designers, but also has limited them. With the fall of modernism and the rise of postmodernism a new change was needed. That is exactly where the computer had its place and opened the doors to new ways of designing.

1. Alberti

Alberti's quest for identicality created the architectural profession and approach to design that is still known today. Only, the rise of the digital reevaluated it. Building by notation has become an indexical operation, where the final building is a 3-dimensional copy of the 2- dimensional drawing[15]. However, this system creates a situation in which the only projects that can be built are the ones that can be notated. The two- dimensional, parallel drawings are very difficult to use in complex geometries. The notations must consist of all necessary data, measurements and calculations that allow for the building to be built. In this way the built environment is the result of possibilities of what designers are capable of notating. This excludes all of the more complicated forms, that are hard to notate geometrically by a human and limits the designer to more simple forms.

2. Industrial Revolution

The second and maybe even stronger instance of identicality in the architectural modernity came with the rise of the industrial revolution.The industrial revolution has changed the world in an unrecognizable way and gave people a new range of possibilities. Modern industry is still largely based on mass production and economy of scale. Most of its tools use dyes, casts, moulds and other forms of mechanical matrixes. The creation of all the mentioned tools costs money. This is the reason why they have to be used as many times and ways as possible in order to compensate for their cost. The logic of the industrial revolution and standardization is as follows: the more identical copies are made, the cheaper they become.[16]This change had a big influence on architecture. A building is dependent on the materials it is created from. If the materials are produced identically, then the building that is made out of them will be also made up of identical elements. This in a way standardised the buildings being produced.

The industrial revolution gave a lot of new possibilities to architects, engineers and most importantly to architecture itself. New materials were used such as steel, iron and glass, which have changed architecture forever. It enabled the creation of better and stronger structures and added new aesthetic elements to designs. However, the identical logic that is inseparable from the industrial standardization is tied with new limitations in the architecture. Not only the project was still tied to the notational tool, but also was dependent on the dimensions and characteristics of the materials that were used. The mechanical tools used for creating architectural structures have limitations which enable them to create only certain sizes and forms of the elements. Although, architects in the XIX century famously rejected the logic and outcomes of the industrial revolution, in the XX century others put it in the center of architectural thinking[17].

Figrure 5. Ford assembly line in 1920s.

3. Modernism

The fascination with the identical copy carried on and blossomed in the XX century. Compared to other industries, the architects did not fully appreciate and use the products and logic of the industrial revolution until the twenties of the XX century. It was then that the pioneers of modern architecture claimed that an architect should design for industrial mass production. Groupius, Le Corbusier, Mies and Bauhaus called to standardise buildings or their parts in order to maximise the economy of scale, use of the industrial assembly lines and to make buildings cheaper. The modernity was led by standardisation- standard product, standard building, standard man[18]. It was a time of glorifying the automobile and the work of engineers.

4. Engineering before computer

This glorification of engineering brought many new architectural inventions, as well as highlighted its limitations. With the use of products created by the industrial revolution architects were now able to create structurally complex structures that were never possible before. Those forms were designed by structural engineers who used mathematical formulas to predict their structural resistance.[19] However, this emphasised a limitation that architects have always been struggling with- the limitation of the human mind. The structural calculations performed by humans were very limiting for the forms they were able to calculate and conceive. In the case of calculating structures there are many variables which have to be included in the equations. Engineers have found many ways the structures can work, but until the use of the computer their possibilities were heavily limited.

5. Postmodernism

Since the 70s postmodern philosophers and architects fought against the modernist standardisation and the spirit of the mechanical age. They argued for variation and differentiation. However, at that time there was no technological answer in architecture to their battle with mechanical mass production apart from regressing back to hand making and preindustrial craftsmanship. But the alternative to mass production in the industry finally appeared in the 90s, in the form of digital tools. Digitality is all about the variation. In a way the digital technologies became the answer to the cultural expectations and needs of postmodernity.[20] The digital variability confronted the postulates of identicality, which had been created in the previous centuries in Western culture[21].

Figure 6. Modernist Dream. La totale. Chapeau M'sieur Le Corbu ! Le Corbusier: Maison double à la Weinssenhofsiedlung, Stuttgart, 1927.

Figrure 7. A perspective view of the Biozentrum project. Image Courtesy of CCA, Montreal

Chapter II: The Computer in Biocenter

A. What is the Biocenter project?

The late 1980s and the 1990s were a period of extensive research and experimentation with the digital in the architectural industry. Before, when the 1970's and 1980's brought the recession and economic crisis, architects had to reevaluate their practice and observe the developments of other industries for insights.[22] Then, in the late 80s and 90s there was an overall pressure from the architectural research and development enterprises to architecturally advance, experiment with and use computer based tools. Following the other industries with implementing the digital into the process of design, the computer quickly guided the new architectural direction and became crucial in the interpretations of particular visions.

1. Peter Eisenman

The project of Biocentre by Peter Eisenman from 1987 will be a case study helping to illustrate and understand the appearance of the computer in architectural design. Also, it will help to investigate what influences the digital had on the process of design. Why this project? First of all, it is one of the first architectural projects in which the computer was used in the design process. Secondly, and more importantly it is a perfect example of the inventive involvement of the digital of the early years of digitalisation.[23]

2.The project

In order to present the project of Biocenter, it is important to understand first the man standing behind it- Peter Eisenman. He is one of the most significant architects of modernity. Not only is he an author of many notable buildings, but also of many architectural and philosophical texts and theories which developed overtime. One of the more important things about the figure of Eisenman is how his thinking and theories developed continuously changing and adjusting to the current and future cultural needs and movements.[24] This consciousness is always visible in his designs. No wonder Eisenman became one of the more important figures in the early years of digitalisation with his project of Biocentrum from 1987. He was one of the first architects to use the computer in the design process.[25]

The Biocenter is a project of an expansion of existing Goethe University in Frankfurt am Main, Germany. It was designed to host research laboratories for molecular biology, biochemistry and biotechnology and the supporting spaces. In the brief of the competition of this project we can read that the main objectives to be met were: "a maximum interaction between functional areas and between the people who use them (both within the departments of the university and between the university and the city), second, the accommodation of future institutional growth and change; and third, the maintenance of the site, as far as possible, as a green preserve."[26]A project like this needed an open approach, not constrained with the traditional approach to architectural design. A project that allows for the future growth. This was done by dissolving the lines between the disciplines. Eisenman in this project went deep into understanding the biological procedures, which helped him to create a building suitable for its future occupant- biology.

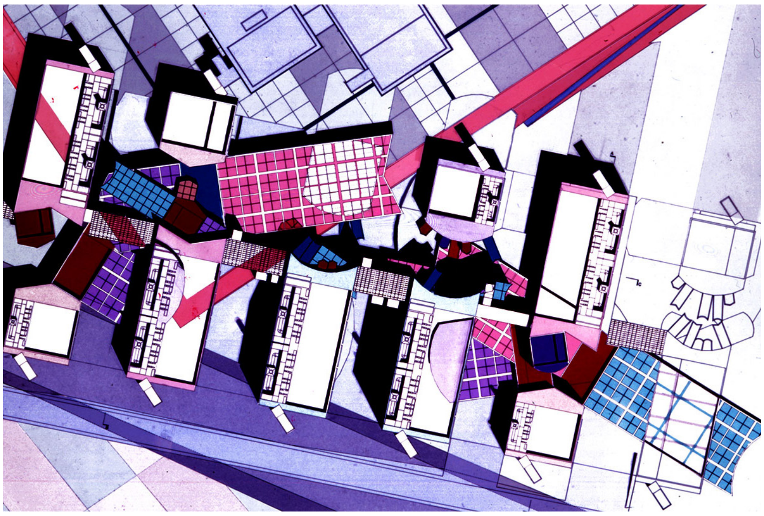


Figure 8. Drawing illustrating a view from the top of Biocentrum.

3. The DNA

In order to create the best location, dimensions, and form of the complex of the Biocenter Eisenman decided to use the biological procedures and concepts present in the DNA. In order to accomplish this, it was essential to have a deep understanding of that structure. DNA is made up of nucleotides, which all have a similar structure. Each of them consists of sugars connected with a phosphate group and one of the four organic N- bases: cytosine(C), thymine(T), adenine(A), or guanine(G). The DNA code is symbolized by four geometric figures which represent the construction of the nucleotides[27].Also, each of them is assigned a specific colour. Each figure, known as a base, has a corresponding pair to which it binds. After that, a double-stranded chain is formed, creating a scheme for proteins that are encoded in the long sequence of the figures. This chain was translated into an architectural form creating an analogy and connection to the discipline it hosts[28].

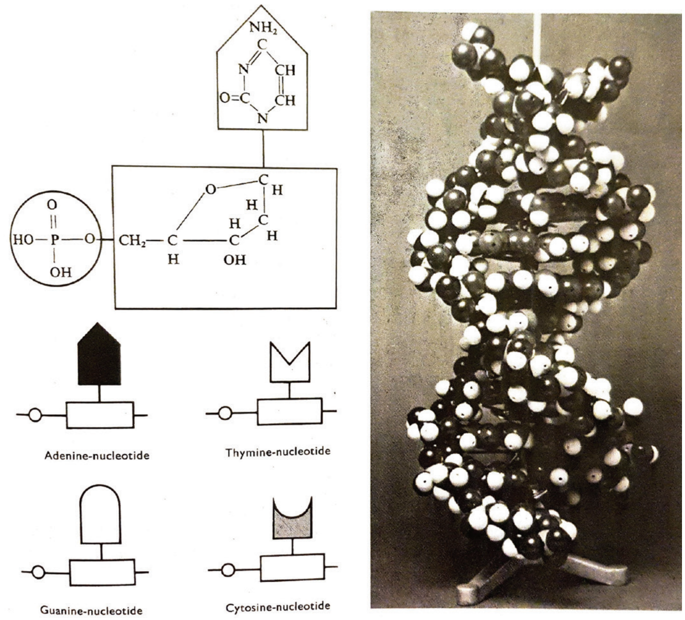


Figure 9. DNA Structure and geometry of nukleoids

4. The DNA and Biocenter

Eisenman in his design of Biocenter has successfully achieved an analogy between the biological and architectural processes. The fractal geometry navigating the design of the project was based on the iterations of DNA molecules. The analogy of the DNA chain coding for the protein collagen was created in the design by a zigzagging band, along which the biologist's figures are laid.These pairs of figures were individual laboratories located in 4 and 5- storey building blocks. As Greg Lynn notes "Using a fractal-like technique to duplicate these figures at varying scales and oblique orientations when aligned at shared faces, these shapes became cantilevered spaces for cafeteria, library and meeting functions, arranged along a central linear circulation spine."[4] By doing so the design articulates not only the physical configuration of DNA, but its three most basic processes: replication, transcription, and translation.[29] In this way, the architecture does not simply house the methods of biological research but is created by those processes.

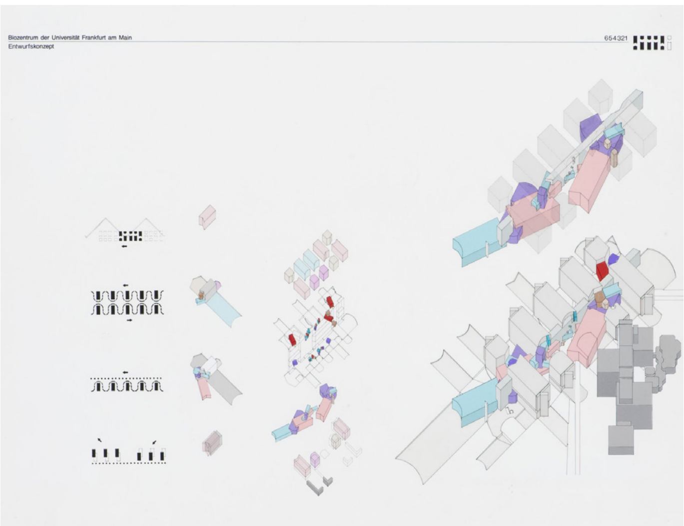


Figure 10. Eisenman/ Robertson Architects, "Design Concept, Biozentrum-Biology Center for th J.W. Geothe University, Franfurt am Main, Germany", 1987 Peter Eisenman Fonds: Canadian Center for Architecture, Montreal

B. The computer in Biocenter

At the time of the design process of the Biocenter project, the computers were new to the field of architecture. Other industry fields like aeronautical, automobile or shipbuilding were already using computer aided design softwares for some time to create more complex and smooth forms for their vehicles[30]. It slowly started to catch the attention also of architects who were limited in the notational system of two- dimensional drawings. Based on the tools worked out by their colleagues from other fields, architects started to create 3D, variable curves and forms. This had a big impact on the production of drawings and complexity of the forms. Nevertheless, the Biocenter project was the first to place the computer in the design process to generate the form.

1. Form Z

Eisenman used an earlier developed software called Form Z in order to use the computer to code design outputs for the project of Biocenter. It all started in the 1980's, when Peter Eisenman was working at the Ohio State University, where Chris Yessios directed the Graduate Program in Computer Aided Architectural Design since 1973. Eisenman didn't have a way to model three- dimensionally for his project - the building of the Wexner Center of Arts. That was the first time him and his team used computer modelling. Form Z was a computer aided design Software which allowed users to move easily from 2 dimensions to 3 dimensions. This software was later used to generate the complex of Biocentrum.[31]

2. Coding

In the project of the Biocenter the computer was used for coding based on the biological codes embedded in DNA structures in order to develop the ground plan and complex mass of the Biocentrum. Eisenman's aim in using a computer was to use it as a procedural modelling tool. Its purpose was to draft figures in different scales and positions in unending sequences, which came from the logical structure of the code. Greg Lynn who worked on the project of Biocenter in Peter Eisenman's office recalls about the process: "Eventually, eight figures, borrowed from the chemistry of biology used to represent genetic sequences, were arrayed in size and position based on the shared dimension of one line segment. Eisenman was looking for a digital counterpart to his vision for a rational linguistic tool capable of creating complex overlapping figures with intricate alignments, connections and scales scripted using logical statements that could be revised or repeated endlessly. The oscillation between written code and algorithms, between plotted arrays and plans drafted with adjustable triangles, and the ability to visualize the 'spine' space using layers of objects based on their iterative generation, was a hybrid between digital and analog design."[32] Overall, there was not much correlation between the sequence and the code. The purpose of the sequence was to obtain the spatial outcome. [33]

3. Pre- consciousness of computer

The way the computer was used in the project of Biocenter depended a lot on what the office wanted to achieve and the circumstances they were working in. As Peter Eisenman recalls- their work was pre- conscious of a computer.[34] The use of the digital wasn't the aim itself. It was an instrument that they knew could do the work they needed. They knew the computer was good at iterating, so they were creating instructions in the form of scripted sentences that would be reproduced by the tool. At that time Eisenman's office did not even own a computer. Thus, every day they would fax chains of symbols based on coded sequences to the computer lab at Ohio State University. There, the plots were created by the custom software. Every morning a FedEx package would arrive at the architect's New York office and would be marked up, revised and hand drawn over the plots.[35]

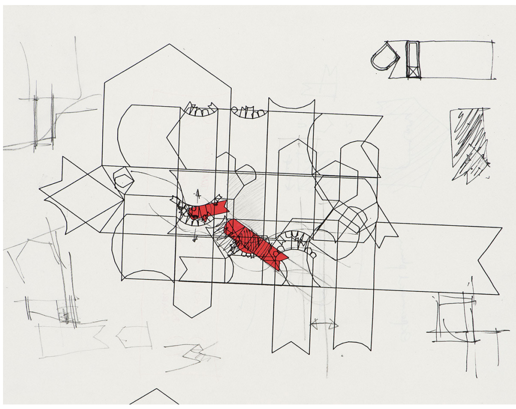


Figure 11. Biocenter Project-Sketch of plot during the design process.

4. Search for Solution

Eisenman was very interested in the diagrammatic processes and more precisely in a morphological diagram, which analysed the possible design results. He already created a Cannaregio diagram made out of architecture. [36] However, if the blocks in that project were twisted- there was no change of the reading, while Eisenman was looking for a diagram that depending on the position of the elements would shift its reading. And that is where and why he needed the computer. It was not just for the use of it, but to explore the idea he had created. However he was not able to materialise it. As Greg Lynn argues this way of thinking gave birth to the parametric approach.[37] The changing one parameter that influences the whole complex.

Overall, it comes as no surprise that it was Peter Eisenman, who was one of the first to use this instrument in the architectural design. Looking closer at Greg Lynn's hypothesis, it can be observed that by seeing the potential of the computer and by using it in a correct way, Eisenman created a path for his fellow architects and successors to follow in the use of the digital and the development of parametricism.

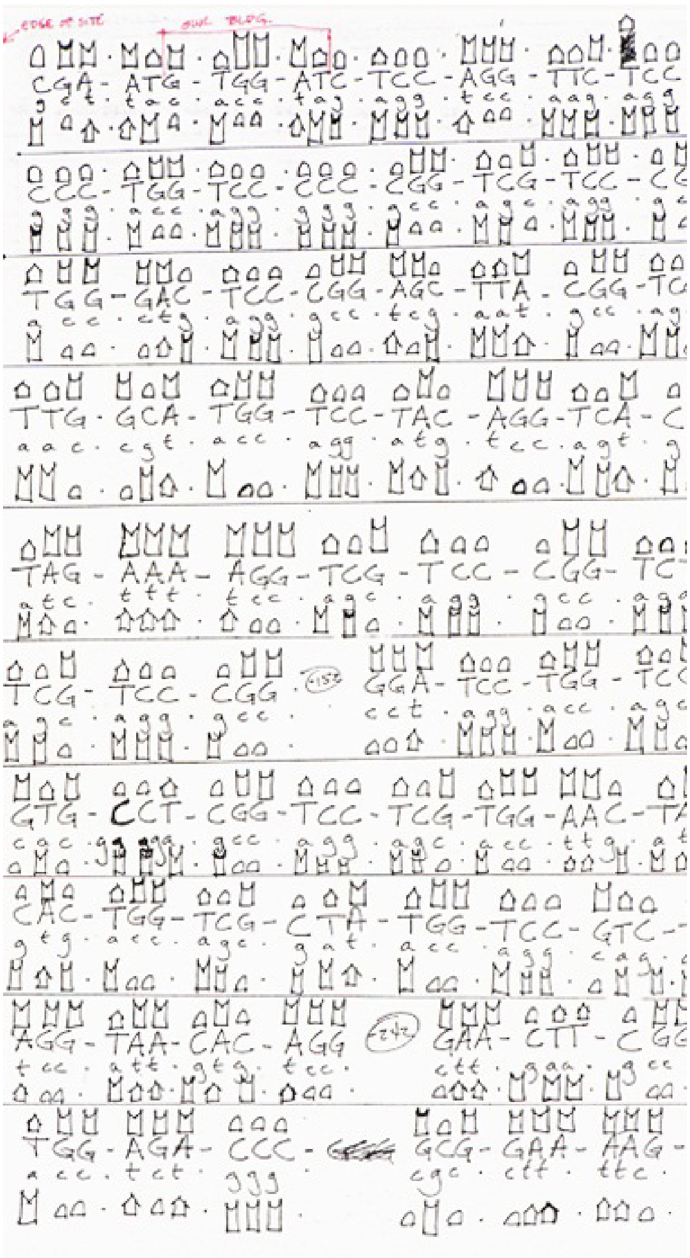


Figure 12. Variations of tructural code. Eisenman was mapping the structure of DNA to codify the spacial outcome of Biocenter.

C. Conclusion- so why the computer in Biocenter?

In the late 80s and early 90s, when the computer finally entered the architectural design industry, it started to be used more widely by architects who would try to experiment with this tool. Nevertheless at that time many architects still did not understand the potential the computer could give to the architectural design. For many it was more intuitive to use the computer in a traditional way, as another notational tool. So what was it about the use of the computer in the Biocenter project that was so revolutionary. What did the computer change in the design process?

1.The human mind-sorting

First of all, it is important to understand the difference in the way of processing information and problem solving of a computer and a human mind. All throughout the history of humankind people have been sorting the world around them. They do it for two main reasons. The first one is the pursuit of order. That is when people obtain peace and stability, and the world makes more sense to them and is more clear. The second reason is to know where things are, once they were placed somewhere. Sorting the world can go from big scales like organising the cities to very small scales like listing the words in alphabetical order in the dictionary. This is the way humans are able to understand and process the world around them. This also helps improve the efficiency of said processing.[38]

The same logic of sorting, humans have always used in mathematical functions, which are used to notate various geometric figuresand curves. In calculus by using two letters-x and y- and three coefficients or parameters- a, b, c- we notate an infinite number of points of a parabola. This mathematical formula compresses a huge amount of data, which helps us determine exact measurements of forms.[39] Overall, this is also the way the architects think and design. For centuries they were sorting elements and forms in pursuit of order. Moreover, they used calculus to notate forms and their structures. However, some of the structures would still be too complex to calculate for a human or even if possible, it would be just not efficient to do so it, as it would take too much time.

2. The computer- searching

So what is the difference in the way the computer works? While it was made by a human, and the logical deduction would be for it to follow the logic of a human mind, this is not the case. The computers create long lists of possible variations from which they look for the best answer. The computers do not sort, they search. [p29 SD] It is not important for them if the possible answers are in any kind of order. A list of possibilities that would take a human a long time to gather, put in order and scan, the computer does sometimes in a few minutes. The same goes for creating forms and curves by a computer. It is able to create a list of thousands of points in the blink of an eye.[40]

3. Biocenter

At the time of the design of Biocentrum the computer was a very new tool in the architectural industry. Nevertheless, Peter Eisenman made use of it in a very conscious way. In Biocentre the coding system that was used by the coding devices of the DNA structures played an important part in the design process. In order to find the best combination of the spatial arrangement, many variations had to be analysed. This is what the computer was doing, which is what a computer does best- iterating possible outcomes and searching. The interesting part about the use of it at that time was the fact that it was iterating at the speed the design team was drafting. Probably it was one of the last projects in which the computer had such a slow speed.

Nevertheless, the cooperation between Eisenman's architecture team and the digital was the way it should be. A way that was found to work best with the digital. The designer is the creative mind who gives an idea and creates a design query to solve. The computer is a machine that is good at searching. Once certain parameters of the design are put in place, it searches for the best outcome. Finally, the result is examined by the architect, depending on their preferences, in order to check whether that's the desirable effect. If not, the parameters are changed and the process repeats. This approach of Peter Eisenman to design, which was very novel for the late 80s has revolutionised the digital in architecture. It is a withdrawal from the traditional approach of design. Peter Eisenman highlights himself, that his actions were pre- conscious of the computer.[41] However, the outcome of those actions created a way for architects to follow and approach the new technology.

Figrure 13. Frank Gehry, "Guggenheim Bilbao", 2016

Chapter III: Digital in Architecture

A. Digital in the 90s

In the 90s the interest in digital in architecture rose, growing closer to the other design disciplines. In this subchapter, the work of two important figures of that time will be talked about in detail- Greg Lynn's and Frank Gehry's. They both had a significant influence on the development of the digital in architecture. To portray a better picture of the architectural movements of those times, the work of Chuck Hoberman, and Shoei Yoh will also be mentioned, due to their unique use of digital with structural design.

1. Frank Gehry

One of the most important aspects of Frank Gehry's work is how it brought the discussion about the digital in architecture to the public eye and the architectural forefront. His projects were a promise of something new to come. However, at the same time it is very important to understand that even though his works used the digital, they were a continuation of the architect's traditional quest for identicality. This means that the capabilities of the computer were not fully used.

When one sees Frank Gehry's early projects they might think that their language of design comes from the computer. Nevertheless, their design process began from handmade, sculptural maquettes. These non geometric, irregular 3-dimensional forms would be scanned, measured, notated, and later built. In the early nineties, already many tools were available to scan and digitize more complex forms. Gehry's office used them to scan a sufficient number of points of the models to obtain a digital version of the form. After that, work would be continued on the real and digital model. Finally, the process would conclude in drawings to scale of a designed building in the form of printouts of the digital model.

In the early 90s, Gehry's office implemented CAD/CAM technology, which was developed by the ship, aircraft, and car industry. Already from the 1960s, the car industry was first preparing for and then working on creating softwares that would create smooth and complex geometrical shapes. From their previous studies, they knew that it would take years for an engineer to obtain the measurements for those complex and spline forms. But with the use of a computer, it was possible.

In 1991, Frank Gehry's office started to use a software called CATIA in order to create a complicated form of the El Peix sculpture in Barcelona. It was earlier developed by the aircraft maker- Dassault. The programme enabled them to create free-form curves by using splines. It was finally possible to create forms that were not able to be notated before. The adaptation of CATIA software revolutionised the use of computers in architecture. All Gehry's projects like the famous Bilbao Museum or the Lewis Residence were based on this process and the use of the programme.[42]

Overall, even though Gehry's projects might seem very complex and computer-driven they are an extension of an allographic strategy, that Alberti would approve of. The digital was used in the instance of those projects as a kind of pantograph in three- dimensions[43]. Gehry's engineers, similarly to their predecessors, were translating project drawings into constructed buildings that were notational copies. Not using the digital to help in the search for a form, does not use its potential. Nevertheless, it brought a lot of new and interesting forms into the architectural world.

2. Greg Lynn

Greg Lynn's approach to the digital was very different from Frank Gehry's. Lynn is a former student of Peter Eisenman, who had worked in his office on the project of the Biocenter. His and Eisenman's approach to the digital was very similar- the digital should be used in the process of form generation through variation, irritation, and optimisation. They were one of the few architects that already in the early years of the computer, understood its potential. They opted for the digital design from the start of the design process by creating algorithms and digitally variable objects, instead of making three-dimensional copies of physical models.[44]

In 1993 Greg Lynn edited and prefaced Architectural Design's Folding in Architecture issue. Never before had a whole issue of the magazine been devoted to the topic of exploration of digital technologies reflected in architecture. [45][46]It was a time of discourse about digital variability. Greg Lynn together with Peter Eisenman focused on the "creative adaptation of the Deleuzian fold to American post- deconstructivist". The preface written by Lynn campaigns for cohesion in all categories: technical, visual, environmental, programmatic, symbolic, and others. [47]

Another important step in the exploration of the digital in architecture at that time was Greg Lynn's project of the Embryological House (1997_2001).). The main focus of this project is its process of form generation, which resulted in vector-based surfaces identified as "blobs". The design was not tied to two-dimensional notation. Instead, Lynn moved into form iteration developed by parameters lying in spline curves. Lynn's goal in this project was to create numerous types of houses, which all had the same amount and type of parts, with the same assembly. However, the elements would not be identical. By doing so, he created a design that could develop depending on the needs of the user, but its structural code would stay the same. [48]Lynn's goal was to manufacture the houses, expecting that in the future CNC manufacturing and computer-aided design would be more integrated in the architecture design.

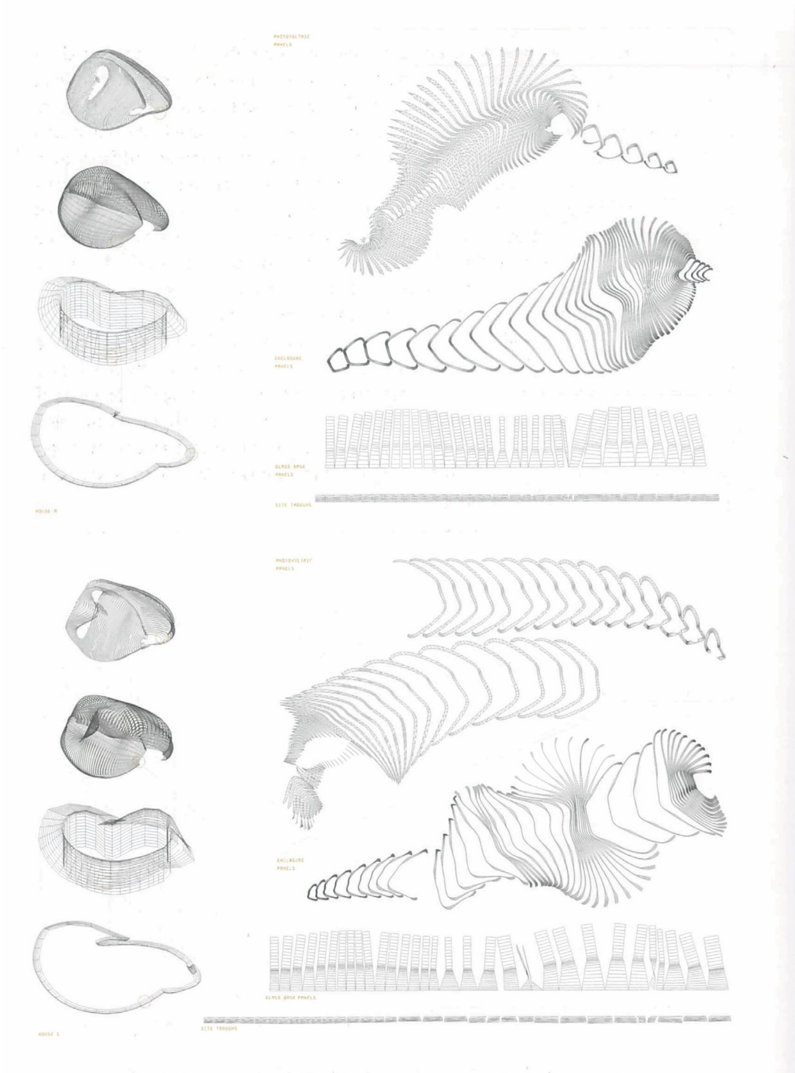


Figure 14. Greg Lynn FORM, "Embryological House", 1998

3. Shoei Yoh

Many other architects and engineers took part in the exploration of the digital in architecture in the 90s. Among them were Shoei Yoh and Chuck Hoberman whose work had a big contribution. Shoei Yoh is a Japanese architect, whose office in 1991 became a finalist in the competition in Odawara, Kanagawa Prefecture, Japan for a sports complex. The design demanded an adaptable to spatial use 3-storey roof structure. To meet the requirements he carried out computer simulations to establish the dimensions of every element in a 3- dimensional grid consisting of trusses. [49]Greg Lynn commented on this project by highlighting that it "includes a stunningly perceptive and precocious analysis of the new tectonic, formal, and economic potentials brought about by the merging of computerized design, construction, and fabrication.)" [50]

Figure 15. Shoei Yoh with his model of the roof of the Sport Center in Odawara.

4. Chuck Hoberman

Chuck Hoberman, internationally known for his transformable structures, seamlessly fuses the disciplines of art, architecture and engineering in his two projects Expanding Sphere and Iris Dome in the late 1980's and early 1990's.[51] The main aspect of his works is the ability of the structures and spaces to resize and change form, by specific movement of their elements. The development of these prototypes has been incorporated with engineering and design "hinged and folding mechanisms capable of expanding and contracting without colliding with neighbouring components."[52]

As seen, the digital allowed architects and engineers to create forms that were never possible before. It not only stopped the notational limitation but also allowed for a completely new way of designing. The architect was not the only one taking part in the design process, but so was the digital. The late 1990s and 2000s brought new opportunities to architects. The expanding economy brought a big amount of money into architecture and many concepts from the previous decade turned into real form realisations. Finally, the outcomes of the digital that had been explored prior to that time could be tested in a scale of real buildings.[53]

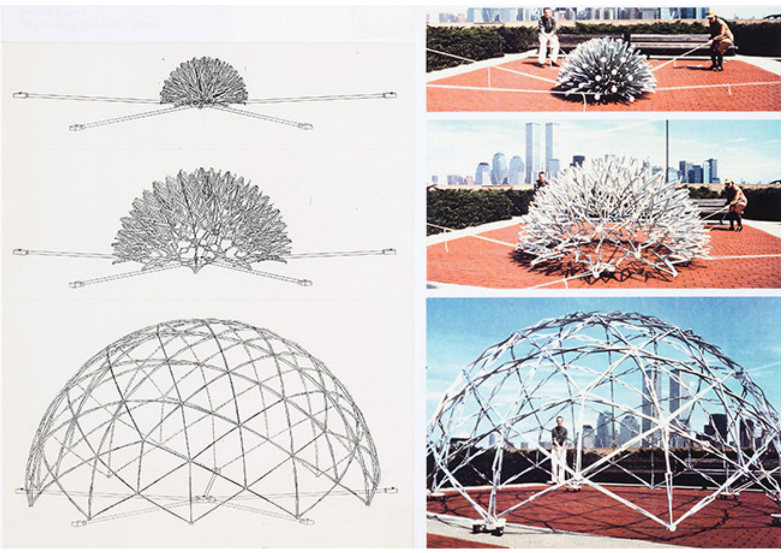


Figure 16. The movement of an expanding geodesic dome, designed by Chuck Hoberman in 1992. Image Courtesy of Hoberman Associates

B. The Changes

So what has the digital changed in the architectural design? The previous examples showed that the new possibilities of form formation emerged. However, it should also be visible that this was just an outcome of the new tool and not its main function. It is worth looking closely into how the digital has put an end to identicality initiated by Alberti; introduced a change in authorship, influenced all the limitations of the previous eras, and changed the process of design by becoming a part of it.
54

1. End of notational limitation

As was established in the previous chapters, the design process introduced by Alberti is based on a system of notations, in which all parts of the building must be notated down with measurements for the builders to later understand and reflect it in the built form. Thus, what couldn't be drawn, couldn't be built. However, the computer finally put an end to this limitation. From the early 90s, the computer softwares gave architects the possibilities to create a design on the computer screen which at the same time was automatically measured and built informationally, which meant it was geometrically defined, thus buildable. [55]This enabled almost any kind of form to be designed.

2. Variability

Everything about the digital is variable. Variability was the biggest change that was brought by the computer into the design world. First, Alberti's approach imposed identicality by of the notations. Later, the industrial revolution with its matrixes, casts, and molds brought mass production and standardisation. Finally, industrial modernity embraced, even more, the identicality in standard products, standard buildings, all for a standard man. The forms were designed to be reused to make them cheaper. However, the logic of identicality and standardisation does not make sense when it comes to the digital. The computer can create various variations of forms in a blink of an eye without creating any additional costs. No longer identicality is profitable. The exploration of variability in design was very visible in Greg Lynn's earlier described project of Embryological House (1997_2001), which explored unending iteration of form.

Figure 17. An architect in his office 1988.

3. Authorial approach

The next limitation put upon architects by Alberti was the authorial approach to the design. The validity of it started to be questioned with the emergence of the digital. If the computer creates variations of the design, can it still be said that the architect is the only author? How to grasp the designer's intellectual ownership of the finished project in regard to the digital? Parametric design and many structural engineering programmes consist of variable parameters. To achieve the desired outcome the software is instructed to generate variations based on the parameters put in place. The latter can be fixed and changed by the designer depending on the preferences and their vision. It is visible that in this instance the designer is "authorizing" the design by regulating the variables. However, the digital also becomes partially an author of the outcome, as the result was created by it. Furthermore, another instance has to be considered: Building Information Modelling (BIM), which has evolved with the digital. In this case, parts of the project can be changed by someone other than the "original" author. [56]In short, when using digital tools the authorship is no longer what it used to be. Parametricism is embedded in every digital tool. And parametricism implies an open form of authorship- meaning more people can interact with the same notation or the computer itself. The designer while using the computer has to allow for some kind of indeterminacy, which is out of his or her control. [57]As scary as it sounds, the unknown added by other parties can be beneficial to the outcome of the project.

4. Randomness and indeterminacy

As discussed, the lack of the author's complete control over the design introduces some level of randomness into the project. This was something that Alberti put an end to. All the elements of the design were created by the architect. All the parts of the building together with the structure were predicted and notated. If that wouldn't be the case the building would not be able to be built. However, the process search of the form or structure by the computer can not be fully controlled by the author. It searches in a different way than us. The project of Biocenter was probably one of the last ones where the computer was iterating at the speed of the human. A new way of designing was created- a design open to randomness and unexpectancy. In which the architect has certain requirements and parameters regarding the design from which the computer conceives a project. However, parts of the outcome can evolve unexpectedly. Peter Eisenman states that this is one of the interesting aspects of designing with the computer.[58]

5. Calculations

Lastly, if the computer is so good at searching for the best outcome, it very quickly started to be also used in the design of the structures and their elements. Structural calculations made by engineers are very limited to what can be calculated by them and therefore to what structures can be created. The traditional engineers would use a set of formulas that would calculate the resistance of the structure. By all means, history knows impressive complex projects and realisations calculated by human minds like Nervi's vaults or Eiffel's tower.[59] Nevertheless, there is still a big range of complex forms with too many different parts which until the rise of computer could not be calculated. Software's for computational finite element analysis started to be used to test structures in simulation. Through trial and error, the programmes create simulations in which they search for the best outcome. Certain parameters are set and through optimalisation the solution is reached. The projects of Chuck Hoberman and Shoei Yoh were a perfect example of welcoming the digital into the world of structural engineering.

Figrure 18. Early Computers and architecture world.

Conclusion

Without a doubt, the computer has revolutionised the architectural industry. It has influenced not only the final forms of the architectural designs but also their process of design. The digital not only became a new tool for notating the project, but also an instrument helping in search of the form and its elements. It gave a new understanding of authorship and moved architecture away from allographic art. It changed the way the designers approach the design by showing and enabling many variations of the design in a short amount of time. By doing so it enabled new possibilities of forms and structural engineering. It helped the architects come closer to craftsmen prior to Alberti, whose works and structures were based on the model of trial and error.

Humans were always dependent on the tools they were using in order to create structures and buildings. However, only since the time of Alberti these forms not only had to be built but also had to be notated in a clear way for the builders to later understand them. The new softwares finally opened the way for architects to create more complex forms, which are hard to notate in 2d, parallel drawings. Not only it enabled to create them in 3d on the screen, but also to measure and build informationally at the same time. By doing so it enabled the design to be later built and for its elements to be designed accordingly. This change has influenced the look of our cities, neighborhoods and even interiors of our homes.

The Biocenter project designed by Peter Eisenman and his office in 1987 was a good case study of how the computer had an influence on the design process and the thinking of an architect. Firstly, the office of Eisenman used the digital to list and search for the best variations for the outcome of the project. It was one of the first times in history when the human was cooperating and working aside of the technology to create an architectural design. It showed a conscious understanding of the search abilities of the machine, that humans are not capable of. This was a very big step and a change in the architectural world. No longer the architect had the best answers and solutions for the design. The architect had an idea, parameters, and a preference for the outcome. Nevertheless, it was the machine in its complexity searching through the combinations. It was a big change for the architects to give away partially the power and control over the process and the design. This created a change in their thinking and made them step back from the authorial approach that was created by Alberti. Also, they gained results that were created by a digital way of thinking which probably the human mind would not be able to create.

Furthermore, the computer bridged the gap between the design and structure of the building, which was created by Alberti and continued by industrialisation. Ever since the computer entered the design industry new structural possibilities appeared. It enabled the complex forms to be calculated. The way of working by the computer through search and iteration (that was used in Biocenter to find the best combination of special layout) started to be also used to find the best structural combinations. By using a computer the engineers and architects could now try out on screen through many sessions of trial and error the different structural combinations with no extra cost. Technology, unlike blueprints, is a responsive tool. It can be almost concluded that a new era has begun where the designers are working more as craftsmen and artisans prior to Alberti, than their predecessors of the previous centuries.[60] This method of creating and evaluating at the same time is close to the autographic art of the craftsmen working on a building and trying out different variations of the structure.[61]

Overall, the changes and influence that the computer brought into the architectural design can be found in every part of the architecture. The aspect that is responsible for most of those innovations is the variability embedded in the digital. From Alberti, throughout the industrial revolution and modernity identicality was reigning over every part of the design. As proven in the thesis identicality helped the world move forward, but also brought numerous limitations with it. With the appearance of postmodernism, the world was in a need of a big change. Variability has finally brought an end to identicality because nothing that is variable is the same. Variability showed new possibilities to all the industries. The computer is always in search of the best variable, so as the project of Biocentrum showed, if the architects use it in a correct way, they can find the best outcome possible.

References

1 Mario Carpo, *The Alphabet and the Algorithm* (Cambridge, Mass. : MIT Press, 2011), 22

2 Spiro Kostof ,*The architect : chapters in the history of the profession*, (Berkeley : University of California Press, 2000), 6

3 Nikolaus Pevsner, *The Term 'Architect' in the Middle Ages (*The University of Chicago Press, 1942), 549-551

4 Carpo, *The Alphabet and the Algorithm,* 16-17

5 "History of Arch Lecture 21 Alberti", Youtube video, 00:44:33, CosmoLearning, August 22, 2017, https://www.youtube.com/watch?v=b55rOrtawlE&t=653s&ab_channel=CosmoLearning

6 Giovanni Fanelli, *Brunelleschi* (Harper & Row, 1980), 3

7 "History of Arch Lecture 21 Alberti", Youtube video

8 "Eisenman/Wigley X: The Problematic of Homogeneous Space", Youtube video, 1:40:52, Columbia GSAPP, September 12, 2013, https://www.youtube.com/watch?v=0_b5COTxHuc&t=521s&ab_channel=ColumbiaGSAPP

9 Carpo, *The Alphabet and the Algorithm,* 19

10 Carpo, *The Alphabet and the Algorithm,* preface X

11 Nelson Goodman, *Languages of Art: An Approach to a Theory of Symbols* , 2nd edn. (Indianapolis: Bobbs-Merrill, 1976), 122, 218–221

12 Carpo, *The Alphabet and the Algorithm,* 19

13 Carpo, *The Alphabet and the Algorithm,* 16-17

14 Carpo, *The Alphabet and the Algorithm,* 21

15 Carpo, *The Alphabet and the Algorithm,* 27

16 Carpo, *The Alphabet and the Algorithm,* 13-15

17 "Mario Carpo. Conference "Space and Digital Reality"", Youtube video, 1:06:52, EKA arhitektuur, October 31, 2019, https://www.youtube.com/watch?v=1uEb73llOOM&ab_channel=EKAarhitektuur

18 "Mario Carpo. Conference "Space and Digital Reality"", Youtube video

19 "Mario Carpo. Conference "Space and Digital Reality"", Youtube video

20 "Mario Carpo - Form-Making to Form-Finding", Youtube video, 1:14:18, AA School of Architecture, September 30, 2015, https://www.youtube.com/watch?v=CBtp-meUJhw&t=2246s&ab_channel=AASchoolofArchitecture

21 Carpo, *The Alphabet and the Algorithm,* preface X

22 "The Digital in Architecture: Then, Now and in the Future." SPACE10, January 9, 2020, visited 1.04.2021, https://space10.com/project/digital-in-architecture/.

23 "Archaeologists of the Digital." Canadian Centre for Architecture, Accessed April 23, 2021, visited: April 2 2021 https://www.cca.qc.ca/en/articles/issues/4/origins-of-the-digital/2077/archaeologists-of-the-digital.

24 Andrea Betella, *Re: working Eisenman* (Berlin : Ernst & Sohn, 1993), preface

25 Archaeologists of the Digital.",Canadian Centre for Architecture

26 Peter Eisenman, ed. Greg Lynn, Biozentrum (Montréal: Canadian Centre for Architecture2014): 6

27 Peter Eisenman; Arie Graafland, *Peter Eisenman : recente projecten, recent projects* (Nijmegen: SUN, 1989) 108-127

28 "Biocenter 1987." EISENMAN ARCHITECTS. Accessed April 23, 2021. https://eisenmanarchitects.com/Biocenter-1987.

29 "Biocenter 1987." EISENMAN ARCHITECTS. Accessed April 23, 2021. https://eisenmanarchitects.com/Biocenter-1987.

30 “The Digital in Architecture: Then, Now and in the Future.” SPACE10

31 Eisenman, Lynn, Biozentrum, 6-8

32 Eisenman, Lynn, Biozentrum, 7

33 Eisenman, Lynn, Biozentrum, 10

34 Eisenman, Lynn, Biozentrum, 1

35 Eisenman, Lynn, Biozentrum, 7

36 Eisenman, Lynn, Biozentrum, 15

37 Eisenman, Lynn, Biozentrum, 11

38 Mario Carpo, *The second digital turn : design beyond intelligence* (Cambridge, MA : The MIT Press, 2017) 25

39 “The Second Digital Turn | Mario Carpo | Talks at Google”, Youtube video, 00:57:53, Talks at Google, March 21, 2018, https://www.youtube.com/watch?v=UVerq5DSdKU&t=1907s&ab_channel=TalksatGoogle

40 “The Second Digital Turn | Mario Carpo | Talks at Google”, Youtube video

41 Eisenman, Lynn, Biozentrum, 17

42 Carpo, *The second digital turn : design beyond intelligence,* 61-64

43 Carpo, *The Alphabet and the Algorithm, 37*-39

44 Carpo, *The Alphabet and the Algorithm,* 39

45 “The Digital in Architecture: Then, Now and in the Future.” SPACE10

46 Carpo, *The Alphabet and the Algorithm,* 86

47 Carpo, *The Alphabet and the Algorithm,* 39

48 “The Digital in Architecture: Then, Now and in the Future.” SPACE10

49 “Odawara Municipal Sports Complex, Odawara, Japan (1990-1991) - Shoei Yoh Fonds.” Canadian Centre for Architecture, Accessed April 24, 2021. https://www.cca.qc.ca/en/archives/435185/shoei-yoh-fonds/468495/architectural-projects/437479/odawara-municipal-sports-complex-odawara-japan-1990-1991.

50 Greg Lynn, ed., “Folding in Architecture”, *Architectural Design 63,* no. 3-4 (1993): 79

51 “Chuck Hoberman.” Harvard Graduate School of Design, April 24, 2021. https://www.gsd.harvard.edu/person/chuck-hoberman/

52 “Expanding Sphere / Iris Dome.” Canadian Centre for Architecture, Accessed April 24, 2021. https://www.cca.qc.ca/en/events/41542/expanding-sphere-iris-dome

53 “The Digital in Architecture: Then, Now and in the Future.” SPACE10

54 “Mario Carpo - Form-Making to Form-Finding”, Youtube video

55 Carpo, *The Alphabet and the Algorithm,* 33-35

56 Carpo, *The Alphabet and the Algorithm,* 42

57 “Mario Carpo. Conference “Space and Digital Reality””, Youtube video

58 “The Foundations of Digital Architecture: Peter Eisenman”, Youtube video, 00:54:59, CCAchannel, May 21, 2013, https://www.youtube.com/watch?v=hKCrepgOix4&t=1594s.

59 Carpo, *The second digital turn : design beyond intelligence,* 47

60 Carpo, *The Alphabet and the Algorithm,* 35

61 “Mario Carpo - Form-Making to Form-Finding”, Youtube video

Bibliography

Books and Articles:

Betella, Andrea. *Re: working Eisenman*. Berlin: Ernst & Sohn, 1993.

Carpo, Mario. *The Alphabet and the Algorithm*. Cambridge, Mass.: MIT Press, 2011.

Carpo, Mario. *The second digital turn : design beyond intelligence*. Cambridge, MA: The MIT Press, 2017.

Fanelli, Giovanni. *Brunelleschi*. Harper & Row, 1980.

Goodman, Nelson. *Languages of Art: An Approach to a Theory of Symbols*. Indianapolis: Bobbs-Merrill, 1976.

Graafland, Arie and Peter Eisenman. *Peter Eisenman : recente projecten, recent projects*. Nijmegen: SUN, 1989.

Kostof, Spiro. *The architect : chapters in the history of the profession*. Berkeley: University of California Press, 2000.

Lynn, Greg,ed.. "Folding in Architecture". *Architectural Design 63,* no. 3-4 (1993).

Lynn, Greg. *Folds, bodies & blobs : collected essays*. Bruxelles: Lettre Volée, 2004.

Lynn, Greg, ed. and Peter Eisenman. *Biozentrum*. Montréal: Canadian Centre for Architecture, 2014.

Mitrović, Branko. "Leon Battista Alberti and the Homogeneity of Space". J*ournal of the Society of Architectural Historians* 63, no. 4 (Dec., 2004): 424-439.

Pevsner, Nikolaus. *The Term 'Architect' in the Middle Ages*. The University of Chicago Press, 1942.

Online Sources and Online Lectures:

AA School of Architecture. "Mario Carpo - Form-Making to Form-Finding". Youtube video, 1:14:18, September 30, 2015.
https://www.youtube.com/watch?v=CBtp-meUJhw&t=2246s&ab_channel=AASchoolofArchitecture

AA School of Architecture. "Re-Reading Palladio - Part 1". Uploaded July 16 2015, Youtube Video, 1:37:05.
https://www.youtube.com/watch?v=BeAdEfJ6eJQ&t=4099s

AA School of Architecture. "Re-Reading Palladio - Part 2". Uploaded July 16 2015, Youtube Video, 28:33.
https://www.youtube.com/watch?v=NFTc9ELLt3k

Canadian Centre for Architecture. "Archaeologists of the Digital.". Accessed April 2, 2021.
https://www.cca.qc.ca/en/articles/issues/4/origins-of-the-digital/2077/archaeologists-of-the-digital.

Canadian Centre for Architecture. "Expanding Sphere / Iris Dome." Accessed April 2, 2021.
https://www.cca.qc.ca/en/events/41542/expanding-sphere-iris-dome

Canadian Centre for Architecture. "Odawara Municipal Sports Complex, Odawara, Japan (1990-1991) - Shoei Yoh Fonds." Accessed April 24, 2021.
https://www.cca.qc.ca/en/archives/435185/shoei-yoh-fonds/468495/architectural-projects/437479/odawara-municipal-sports-complex-odawara-japan-1990-1991.

CCAchannel. "The Foundations of Digital Architecture: Peter Eisenman". Youtube video, 00:54:59, May 21, 2013.
https://www.youtube.com/watch?v=hKCrepgOix4&t=1594s.

Columbia GSAPP. "X: The Problematic of Homogeneous Space". Youtube video, 1:40:52, September 12, 2013
https://www.youtube.com/watch?v=0_b5COTxHuc&t=521s&ab_channel=ColumbiaGSAPP

CosmoLearning. "History of Arch Lecture 21 Alberti". Youtube video, 00:44:33, August 22, 2017.

https://www.youtube.com/watch?v=b55rOrtawlE&t=653s&ab_channel=CosmoLearning"Eisenman/Wigley

Eisenman Architects. "Biocenter 1987." Accessed April 23, 2021. https://eisenmanarchitects.com/Biocenter-1987.

EKA arhitektuur. "Mario Carpo. Conference "Space and Digital Reality"". Youtube video, 1:06:52, October 31. 2019, https://www.youtube.com/watch?v=1uEb73llOOM&ab_channel=EKAarhitektuur

Harvard Graduate School of Design. "Chuck Hoberman." Accessed April 2, 2021. https://www.gsd.harvard.edu/person/chuck-hoberman/

SPACE10. "The Digital in Architecture: Then, Now and in the Future.". January 9, 2020, Accessed April 1, 2021. https://space10.com/project/digital-in-architecture/.

Talks at Google. "The Second Digital Turn | Mario Carpo | Talks at Google", Youtube video, 00:57:53, March 21, 2018. https://www.youtube.com/watch?v=UVerq5DSdKU&t=1907s&ab_channel=TalksatGoogle

Figures

Zofia Sosnierz
5352436

AR2A011 Architectural History Thesis
TU Delft 2020/2021