THE DIGITAL INFLUENCE ON ARCHITECTURE

on how computer-aided design and manufacturing technologies influenced architectural design

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Content

List of abbreviations

Introduction

Chapter 1, Emerging technologies:
What were the digital technologies that emerged with a connection to architecture?

Chapter 2: The view on architectural design in relation to CAD/CAM:
How does the view on architectural design relate to CAD/CAM technologies?

Chapter 3: The earliest digital architectures:
What were the earliest cases implementing these digital technologies and how were they implemented?

Conclusion:
How did the development of computer aided design and manufacturing technologies influence architectural design?

References
List of abbreviations

CNC – Computer numeric(al) control(led)
MIT – Massachusetts Institute of Technology
APT – Automatically Programmed Tools
CAM – Computer aided manufacturing
CAD – Can refer both to computer aided drafting and computer aided design
AMG – Architecture Machine Group
DAC-1 – Design Augmented by Computer 1
NURBS – Non-uniform rational basis spline
CATIA – Computer Aided Three-dimensional Interactive Application
CAE – Computer aided engineering
Introduction

‘Architecture is one of the most urgent needs of man, for the house has always been the indispensable and first tool that he has forged for himself. Man’s stock of tools marks out the stages of civilization, the stone age, the bronze age, the iron age. Tools are the result of successive improvement; the effort of all generations is embodied in them.’ (Corbusier & Etchells, 1986)

The development of tools is one of the defining characteristics of human evolution. They are generally the devices that enable us to make other tools. According to Shodek (2005), one of the latest and most remarkable events is the development of computer aided design and computer aided manufacturing technologies.

In architecture, the seemingly human-embedded quest to generate new and better tools resulting in these relatively new technologies has had a profound impact on the way architecture is designed and built. The use of these technologies in the architectural profession and building industry has become ubiquitous, as we can perceive from examining images of famous architectural practices thirty to forty years ago and comparing them to their current situation; the drawing tools of which many wouldn't even remember the name, seemed to have made place for computers.

The cover of this paper displays Ivan Sutherland and his invention that he termed the 'Sketchpad system,' marking a distinct point in time from where the development of computer aided design systems took off. But the front page of this thesis could equally have been an image of the first computer numerical control machine developed at the Massachusetts Institute of Technology. Not only the development of computer aided design systems are changing the architectural profession. Computer aided manufacturing systems, as CNC-mills and 3D printers, are equally important to describe, and especially, the marriage between the two.

For it might be the synergy between these technologies responsible for their ubiquitous application in architecture; design something on a screen, click a button, and it is produced, or so it seems.

In pursuit of researching the effects of the omnipresence of digital technologies on architectural design, the main question this thesis will attempt to answer is; 'How did the development of computer aided design and manufacturing technologies influence architectural design?' Since this question is rather broad, it will be broken down in several sub-questions.

Considering the development of computer aided design and manufacturing technologies, the first sub-question is 'What were the digital technologies that emerged with a connection to architecture?'

With an interest in the interrelationship of these technologies and architectural design, it is necessary to conduct research towards the view on architectural design in relation to the digital technologies. Hence the following sub-question; 'How does the view on architectural design relate to CAD/CAM technologies?'

To research how the technologies are implemented in the process of designing and fabricating architecture, the final question states; 'What were the earliest cases implementing these digital techniques and how were they implemented?'
Chapter 1:
Emerging technologies
What were the digital technologies that emerged with a connection to architecture?

'The digital revolution in architectural design and the adoption of CAD/CAM processes in the building industry can be considered as one of the most radical shifts in architectural history concerning their immense formal and procedural implications.' (Kocaturk & Veltkamp, 2005)

The origin of digital technologies changed many industries, including the building industry. Not only the way we build, but also the way we design has been affected by the recent digital developments. In pursuit of the answer to the main question of this thesis, this chapter starts with an exploration of the emerging technologies with a connection to architecture. It will discuss the development of computer aided design and manufacturing technologies.

The earliest computer numerical control system
‘...it seems entirely likely that ultimately the inanimate machine can behave more rapidly and more reliably in response to situations that are far too complex for the animate machine to handle.’ - Steve Coons as quoted by Negroponte (1975)

Coons vision on digital possibilities was correct in the way humanity has managed to build machines controlled by computers that can produce products faster and with a higher accuracy than humanly possible. This possibility originated with the invention of the CNC machine. Though the basic underlying idea of numerical control was not new, it was the MIT Servomechanism Laboratory that took the technology to a new level.

In 1949, John T. Parsons worked with the MIT Servomechanism Laboratory to propose specifications for the ‘cardmatic milling machine’ which would be a machine operated by a computer via input by punched cards. Since Parsons was the sponsor of the project and expected to have to spend large amounts of money and time on the development of the machine he cancelled the project in 1951. The U.S. Air Force thought of the technology to be of great potential for the aircraft industry and chose to continue the project. Ultimately, the components of the machine developed; ‘the tape preparation unit’, ‘the director’ and ‘the machine’ (image 1 and 2). The director unit was a digital processor that accepted instructions from the paper tape and translated them into electrical pulses that drove the machines servomechanisms. The project culminated in a major demonstration in 1952 to a large amount of representatives of 130 government groups. (Reintjes, 1991; Shodek, 2005).

![Image 1(left) and image 2 (right): elements and picture of the first CNC (Reintjes, 1991).](image)
The technology continued to evolve at the MIT. Since the punch-card system proved to be troublesome and subject to breakdown, new methods were sought to input instructions. This led to the development of the English like programming language; APT (Automatically Programmed Tools) in 1959. APT can be interpreted as the predecessor of G-code, the language most current CNC machines are programmed with. The importance of the development of APT follows from a quote from the New Yorker Magazine of March 28, 1959, resulting from a newspaper article covering a press conference held at the MIT, February 25, 1959 (image 2);

Image 2; newspaper article with announcement of the CNC (Ross, 1978).

In the press kit, souvenir aluminium ashtrays were added milled in three dimensions by the first ever existing version of a CNC mill. According to Ross (1978) the event gained extensive coverage throughout the world for the months that followed after it and represented the true inauguration of the era of computer aided manufacturing.

When the project seemed to be cancelled due to a lack of funding, the US Air Force proceeded the contract for seeing potential in the technology mainly for the aircraft industry. Also from the quote in the New Yorker Magazine, it is the Air Force that announced to have made a breakthrough discovery that would enable the United States to ‘build a war machine that nobody would want to tackle.’ In the light of these events happening during the cold war, this quote is not at all surprising.

What can be considered remarkable is that the technology did not only benefit the aircraft industry amongst other engineering industries, but also found ground in the building industry. Currently, CNC technologies are omnipresent (image 3) and extensively used in architectural practices, not just during the design process to create rapid prototypes, but also to prefabricate large and various building components. As from the next chapter, we will see that it was not only the development of the CNC technology that resulted in the use of this technology in architectural design, or, as Shodek (2005) puts it; ‘The brilliance of the marriage between mature fabrication technologies and computer technologies can hardly be overstated.’

Image 3; current common types of CNC machines (Shodek, 2005).
From computer aided drafting to computer aided architectural design

It was another military research program at a laboratory at MIT set up by the US Air Force that resulted into the first drawing interaction with a computer (Goodhouse, 2017). Ivan Sutherland, a young graduate student working at the MIT laboratories, was the first to figure out how to draw directly onto a screen. According to Sutherland (1963) the ‘Sketchpad system’ (image 4) makes it possible for a man and a computer to converse rapidly through the medium of line drawings. Before the development of the Sketchpad system, most interaction between man and computers had been slowed down by the need to reduce all communication to written statements that can be typed. Sutherland states; ‘in the past we have been writing letters to, rather than conferring with our computers’. By eliminating typed statements, the Sketchpad system opened up a new era of man machine communication.

Initially the software was not designed for the building industry or architectural practices. It was designed as general purpose system and had been used to draw electrical, mechanical scientific, mathematical and animated drawings (Sutherland, 1980).

Image 4(left) and image 5(right): Sutherland's Sketchpad system and a worker using the DAC-1 CAD system in the automotive industry (Goodhouse, 2017).

The first commercial applications of CAD (where the D indicates drafting) occurred at larger companies predominantly in the aerospace and automotive field. Various CAD systems were developed such as the DAC-1 in 1964 by General Motors (image 5) and UNISURF in 1971, developed by Renault, used mainly to design the body of cars. The earliest CAD systems only handled two-dimensional data, imitating traditional drawing practices. Throughout the 1970's, the conversion of these systems handling three-dimensional data was developed by the automotive and aerospace industries. Of importance here is the work of De Casteljau in the 1960s at Citroen and the work of Bézier in the 1970s at Renault. De Casteljau and Bézier invented ways of mathematically describing free form curves (currently known as NURBS), necessary for the CAD systems to be able to handle three-dimensional data. What is worth mentioning here is that this invention was kept secretive until the 1980s. The importance of the CAD-systems handling three-dimensional data was not so much to compute complex shapes but simply to produce the information necessary to drive milling machines, allowing for the mechanical production of curved surfaces that were necessary for the production of cars and airplanes. In 1977, Dassault, a French aircraft company, reached the aim of controlling three dimensional geometry by using an interactive program, considered the predecessor of CATIA (Farin, Hoschek, & Kim, 2002).

In confirmation, Scheurer (2010) describes that by the mid-1990s an innovation had finally found its way from the French car industry into the CAD software used by designers. The innovation he is indicating is the development of splines and NURBS developed at the laboratories of Renault and Citroen as mathematical definitions for curves and curved surfaces as described above. Possibly, Scheurer uses the word ‘finally’ to imply the technology from being kept secretive for approximately twenty years. Suddenly these surface modelling techniques appeared in the program menus of designing architects.

The dissemination of computer technology caused CAD systems to also find their way into the toolbox of architects and designers. One of the reasons for this diffusion was the drop in price of the hardware and software systems. It was in 1982 that Autodesk was founded with the idea of making a CAD system available for
everybody at the commercial cost of (only) one thousand dollars (Riccobono, 2014).

During the 90’s CAD systems were used more frequently amongst architectural and engineering studios, but their capacity was only aimed at the potential of representation and alleviating the drawing process. Subsequently it was understood that the potential of CAD systems did not just relate to the architectural representation of the design, but also to the ability of controlling and managing it (ibid). This is where the ‘D’ in CAD truly changed from ‘drafting’ to ‘design.’

In retrospect, Iwamoto (2009) describes that architects have now been drawing digitally for nearly thirty years. Yet for many years, as the process of making drawings steadily shifted from being analogue to digital, the design of buildings did not really reflect the change. CAD replaced drawing with a parallel rule and lead pointer, but buildings looked pretty much the same. This, she argues, is perhaps not so surprising since one form of two-dimensional representation simply replaced another.

Iwamoto (2009) also argues that it took three-dimensional-computer modelling and digital fabrication to energize design thinking and expand the boundaries of architectural form and construction. According to her it is inconceivable today to imagine designing buildings without the use of computers. They are used at every step of the architectural process, from conceptual design to construction. Examples of the current digital practices employed by architects and building consultants are three dimensional modelling and visualization, generative form finding, scripted modulation systems, structural and thermal analyses, project management and coordination, and file-to-factory production.

Yet one should not conclude that during those thirty years of which ‘CAD replaced drawing with parallel rule and lead pointer’ there was no experimentation of using the computer in the design process as a design tool, as we can clearly see from the work of the Architecture Machine Group (AMG) again at MIT, led by Negroponte (Negroponte, 1970). Negroponte states; ‘the design process, considered evolutionary, can be presented to a machine, also considered as evolutionary, and a mutual training, resilience and growth can be developed.’ By doing various, sometimes extraordinary experiments (one experiment even involves gerbils) the AMG tried to position the computer as a design tool into the design process of architects. An example of the work of the AMG is the project ‘URBANS5’ (image 6 and 7) of which the original goal was ‘to study the desirability and feasibility of conversing with a machine about an environmental design project using the computer as an objective mirror of the users own design criteria and form decisions, reflecting responses formed from a larger information base than the users personal experience.’ Though the design process of the machine was not algorithmic, the project is very innovative for its time. The architect could even chose to converse with the machine in English via the typewriter or in a graphic language, using a cathode-ray tube and light pen (invented by Ivan Sutherland). In a way, the AMG-experiments are the first occasions of using the computer as a design tool, paving the way for architects to accept the endless possibilities and advances of using the computer in the design process.

**Image 6(left) and image 7(right); the URBANS project by AMG (Negroponte, 1970)**
Synergetic technologies – and a delayed dissemination in architecture
As hinted at before, one could consider the development of the attitudes, tools and systems that comprise what we now call computer aided design and manufacturing as the marriage between programmable computers and associated digital design and engineering environments, numerical control technology and sophisticated numerical controlled production machines for making objects (Shodek, 2005). What became evident, for instance by examining the reason for the development of surface geometry modelling; mechanically producing free form elements using numerical control machines, is that computer aided manufacturing influenced computer aided design and vice versa.

In relation to architecture, Corser (2010) argues that the building industry has been slow in adopting these new technologies due to a notoriously conservative attitude and faced with narrow profit margins on one-off projects. Except where applicable to produce clear efficiencies in pre-existing business processes: the use of CAD in the production of two dimensional construction documents, for example.

Another reason for this latency in the use of available technology might be that for some time the know how of the three dimensional geometry technology in the automotive and aerospace industry was kept secretive. The automotive and aerospace industry are industries in which curvilinearity is not out of place, they enhance aerodynamics. It is not at all strange this technology was only discovered later by the building industry (image 8).

Starting in the mid 1990’s, three powerful forces began to emerge that are transforming significant aspects of both design practice and project delivery: intelligent, feature based parametric modelling, building information modelling (BIM) and mass customization. Combined with the ability to use numerically controlled processes to directly implement this digital data for the actual construction of buildings, information technologies are undeniably of growing importance. As these technologies become more widespread and affordable, their promise of faster, more flexible and more cost effective building processes is beginning to be realized in the architectural, engineering and construction industries (Corser, 2010). What becomes evident is that the use of digital technologies in architecture (and the marriage of them) has yet to be culminated.

Image 8; from left to right: the Citroën DS, produced from 1955-75, clearly using curvilinear surfaces (Citroen, 2019), Johnsons AT&T building, 1979 (Curtis, 1996), and Fosters Swiss Re Tower, 2004 (Jencks, 2012), suggesting the delay of dissemination of CAD/CAM technologies in architecture.
Chapter 2

The view on architectural design in relation to CAD/CAM technologies

How does the view on architectural design relate to CAD/CAM technologies?

‘Machines will lead to a new order of both work and leisure’ – Le Corbusier (Corbusier & Etchells, 1986)

The previous chapter covers that CAD/CAM technologies emerged in the 1960s and 70s, after which the aerospace and automotive industries were the first to adopt their potential. Only in the 1990s, the distribution of CAD/CAM technologies reached a bigger audience, including the architectural profession and the building industry. In pursuit of answering the main question of the thesis, this chapter aims to answer how the view on architectural design relates to these technologies. It describes how the view on architectural design changed around the beginning of the nineteenth century from having a historical foundation to having a ‘modern’ foundation, and why this influenced the dissemination of technologies within architecture.

On the origins of a modern architectural style

‘...suppose that an architect of the twelfth or thirteenth century were to return among us, and that he were to be initiated into our modern ideas; if one put at his disposal the perfections of modern industry, he would not build an edifice of the time of Philip Augustus or St Louis, because this would be to falsify the first law of art, which is to conform to the needs and customs of the times.’ - Viollet Le Duc (1873)

If a historian were to look back in a century's time at the period 1900-1995 he would not be overwhelmed by some single, monolithic main line of development running from the pioneers of modern design up to the last quarter of the twentieth century. (Curtis, 1996)

Past eras have often referred to their architecture as modern. The modern architecture in this paragraph was an invention of the late nineteenth and early twentieth century and was conceived in reaction to the chaos and eclecticism of the earlier nineteenth century revivals of historical forms. Basic to the ideal of a modern architecture was the notion that each age in the past had possessed its own authentic style, expressive of the ‘geist of their zeit’. A break of this recurrence had happened somewhere around the middle of the eighteenth century, when the Renaissance tradition had become obsolete, leaving a void into which had flowed various ‘inauthentic’ adaptations and recombinations of past forms. The task then, was to rediscover the true path of architecture, to unearth forms suited to the needs and aspirations of modern industrial societies, and to create images capable of embodying the ideals of a supposedly distinct ‘modern age’ (ibid).

Confusion of architectural style can be concluded from a book of an early nineteenth century German practitioner named Heinrich Hübsch whose title; ‘In what style shall we build?’ characterized the discourse of that age. Also, one can conclude the extent of eclecticism from a very illustrative example described by De Botton (2007); where around the middle of the eighteenth century a local aristocrat and his wife, both passionate about architecture, decided to build a castle. The couple could not agree on an appropriate architectural style, the man being more into Classicism and the woman preferring Gothic architecture. Their remarkable solution was to combine both styles in the same building, the front of the house having a classical appearance, the back of the house a gothic appearance (image 9).

Image 9; Castle Ward; same building, front elevation (left) and rear elevation (right) (De Botton, 2007).
Though there are hints of a modern architectural language already around the late eighteenth century by architects as Boulée and Ledoux (image 10), of which latest according to Lemagny (1968) went so far as to do away with all decoration and can be considered one of the forerunners of modern architectural aesthetics, Curtis (1996) describes that around the mid-nineteenth century such theorists as Viollet-le-Duc and Semper were discussing the possibility of a genuine modern style, as we can conceive from the quote cited at the start of this paragraph, but they apparently still had little conception of its form.

![Maison des Gardes Agricoles](image10)

*Image 10; Ledoux, ‘quarters for the rural caretakes,’ ca. 1780 (Lemagny, 1968)*

It was not until just before the turn of the twentieth century, considerably spurred by a variety of intervening structural inventions, that attempts were made at visualizing the forms of a new architecture. This pioneering phase resulted in Art Nouveau and the Chicago School amongst other movements, and was considered the property of the industrial nations of Western Europe and the United States. There was little consensus considering the appearance of that new architecture, rather, there were shared aspirations capable of a visual translation in a variety of ways. Modern architecture was affirmed as to be based on new means of construction and should be disciplined by the necessities of function; form should be disconnected from the apparatus of historical reminiscence, and the meaning of it conform modern experiences; its moralities should suggest a vision of human betterment and its elements should have the potential to be applied to unprecedented situations arising from the impact of the machine upon human life and culture. Simply put, modern architecture should propose a new set of symbolic forms more adequately reflecting contemporary realities than the various applications of the hitherto ‘historic styles’ had done (ibid).

Between 1890 and 1920 more architects took a position which claimed modernity as a principle attribute. By the 1920s it seemed as if broad consensus on architectural style had been achieved, or so it was claimed by some practitioners and propagandists, who wished to persuade their contemporaries. Considerable effort was invested in distinguishing the characteristic of the ‘International Style,’ the expressive language of simple volumes and clear cut geometries, which seemed to be shared by architects as Le Corbusier, J.J.P Oud, Gerrit Rietveld, Walter Gropius, Ludwig Mies van der Rohe, and the rest. They claimed this to be the one true architecture for the twentieth century (ibid).

With the emergence of the International Style, modern architecture, which was supposed to have expunged tradition, founded a tradition of its own. But, creative individuals who seemed to be pushing towards a common aim went their own separate ways and seminal ideas were transformed by followers. In the years after the Second World War, many tributaries and transformations were developed around the world. Reactions, critiques and crises, not to mention widely differing circumstances and intentions, intensified the architectural variety (ibid).
Modern architecture and technology

Considering the relation between technology and architecture, it is interesting to elaborate on the Swiss-born architect Le Corbusier. In his seminal text ‘Vers un architecture’ he argued that the external world had been enormously transformed in its outward appearance and in the use made of it, by reason of the machine. Humanity had gained a new perspective and a new social life, but had not yet adapted the house thereto. Le Corbusier found inspiration in the field of engineering, considering engineered projects as steel bridges full of true beauty, where forms are derived from the principles of nature. Hence he concluded that the house of the modern age should be conceived as a machine for living in (Corbusier & Etchells, 1986).

Striking is the advertisement for the 1927 Mercedes-Benz, set against Le Corbusier’s double house, depicting the relation between the new technologies and attributes of that time with architectural design (image 10), but the interrelationship between modern architecture and technology might be best summarized by Solà-Morales and Whiting (1997), who argue that ‘having abandoned the discourse of style, the architecture of modern times is characterized by its capacity to take advantage of the specific achievements of that same modernity: the innovations offered it by present-day science and technology.’

The abandonment of the discourse of a (historical) style created the opportunity within the architectural profession to utilize the inventions of that time. As concluded from the previous chapter, CAD/CAM technologies are considered inventions of that modern time, and were first adopted by the aerospace and automotive industries. The emergence of a modern architectural style contributed to the acceptance and dissemination of these technologies of different fields within architecture. Repercussions thereof are still visible today.

Image 11; Le Corbusier’s modern architecture inspired by modern times, exampled by the car (De Botton, 2007).
Chapter 3

The earliest implementation of digital technologies in architecture
What were the earliest cases implementing these digital technologies and how were they implemented?

'The digital age has radically reconfigured the relationship between conception and production, creating a direct link between what can be conceived and what can be constructed.' (Kolarevic, 2003)

Concluded in the previous chapter was that a change in perspective on architectural style had a profound impact on the appearance of architecture and tuned it to the modern life and technologies of that time. Though some of the architectures thereafter embedded the ideals of technology and engineering principles, it took some time before the idea of a digital architecture entered the conversation, for the fact that digital technologies were not invented yet. As we have seen, the diffusion of digital technologies only reached the architectural profession at large in the 1990s, and still then the tools available were mainly used to draw digitally and not to design digitally.

This chapter researches architecture in relation to the implementation of CAD and CAM technologies. Architecture that has curvilinear characteristics is sometimes interpreted as 'complex.' A preliminary conclusion could be that new possibilities of the realization of complexity, or curvilinearity, contributed to the quantity of complex architectural forms. But, historically, the appearance of curvilinear and complex geometries can be traced far back, for example in ancient shipbuilding, where the keels of wooden boats have always had a curvilinear form. Also certain elements of historical architectural styles have complex characteristics. More recently, we can think of examples as Mendelsohn's Einstein tower and Le Corbusier's Ronchamp chapel. These might be architectures that have similar characteristics as current 'digital technology architecture,' but they have not employed the opportunities of CAD and CAM technologies in their design or fabrication process.

To select cases that can be researched in detail, a definition is needed of 'digital technology architecture.' Referring to the synergetic relation between computer aided design and manufacturing technologies described in chapter 1, digital technology architecture is defined here as 'architecture that is only realisable trough the means of a combination of CAD and CAM.' Chronologically researching key architectural projects, it is concluded that worth describing here are the Sydney Opera House by Jorn Utzon and some of the later works of Frank Gehry.

The Sydney Opera House (1957-1974)
Image 12 is a sketch of the East elevation from the winning competition entry for the Sydney Opera House. Utzon proposed complex curved shell structures to provoke the forms of billowing sails. The location of the then to be realised design was next to the central harbour of Sydney. Utzon worked in collaboration with the engineering company Ove Arup & Partners, who tried to find the means to describe the building's form in a way to perform structural analysis and to create a method to translate the forms into fabrication. The process of realizing the project took almost two decades (Shodek, 2005).

Image 12; East elevation of the competition entry by Jorn Utzon, retrieved from the website of the Sydney Opera House
The engineers from Ove Arup & Partners used an I.C.L. 1900 series mainframe computer to model complex intersections and faceted glass walls. Also, they used Fortran software to perform structural analysis. According to Arup and Zunz (1973) it was clear that to make it possible to build the structure they would have to use electronic digital computers extensively. Computers were critical to the execution of this project in the surface modelling of the roof shells and glazing, and also for the calculation work.

Considering the use of CAM technologies, the glazing geometries in the Sydney Opera House are worth describing further. The glass enclosures that were installed under the concrete shells that resembled the billowing sails were derived from cylindrical and conical forms. The forms were described as a series of faceted planes, which were in turn divided in panels (image 13) (Arup & Zunz, 1973).

![Image 13; the glass plane tessellation in the cylindrical and conical glass forms (Arup & Zunz, 1973).](image)

Using a computer model, the engineers studied the glazing geometry and its structural behaviour. It was a key aspect in the ability to fabricate the individual glass panels, of which there were seven hundred in different sizes and shapes. The model was used to communicate the information that was needed for the fabrication of the glass panels. The panels were produced by a company in France and had a small margin to allow for final adjustments on site. The machine that cut the glass panes was designed specifically for this task. The data sheet shows an early application of the numerical control technology (image 14) (ibid).

In their technical report, Arup and Zunz (1973) do not describe the handling of the purposely built glass cutting saw. If one analyses the saw (image 15) there is no apparent digital controlling system. Also, from the fact that one would not have to print data on paper to input into a machine (CAM technologies skip this step) concluded here is that the saw was controlled manually. This makes the fabrication process here an innovative predecessor of the CNC-cutting of glass panels, but it is considered as numerical control, and not computer numerical control. The production of the building components show a numerical control logic, but were not fabricated by a CNC machine.

In more ways the design of the Sydney opera house showed innovative means of using the computer in the calculation and fabrication process, and in a way does comply with the definition stated at the beginning of this chapter. The use of the computer in the process of designing and building the Sydney Opera House focusses most on computer aided engineering (CAE) and indicates an early version of numerical control, without the fabrication realised by CNC technology. The process of designing the Sydney Opera House was aided by computers, most likely only after Utzon’s preliminary design sketches. We will have to go further in time to research how CAD technologies were implemented into the architectural design process.

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All dimensions in feet. Refer Drg. No. 1112/7473.
Gehry's Fish – the forgotten hallmark of the digital age (1989-1992)

Located in Barcelona's 1992 Olympic Village redevelopment site, a masterplan was executed wherein Gehry’s office designed commercial structures. Gehry’s portion of the project was bounded by a hotel tower to the north and the beach to the south and included a part of the waterfront promenade. Besides shops, several sculptural elements were realised, including a fish sculpture floating over the retail court, that served as highly visible landmark (image 16). The fish sculpture, approximately fifty meters long and thirty meters tall, serves as an abstract foreground element when viewed from the hotel situated to the north, and is a shading and enclosing device for the retail court (Dal Co, Forster, & Arnold, 1998).

Image 16; Physical model of the fish (Dal Co et al., 1998).

The design and construction of the fish represents an important historical event; the first time Gehry’s office employed a computer in the building process. The project began with a series of sketches and study models. The physical models were used by the office as the control model in the initial attempts to translate the project into built form. One of them was one meter long. After the completion of the model, the task was to accurately reconstruct its curves and to communicate the curves with the contractor to be able to build the fish at full scale. In past projects this was done by measuring the physical model and making two dimensional drawings from those measurements. The office then drew a series of sections of the fish model by sampling points from the physical curves, a process that proved to be time consuming and inaccurate. Gehry’s office had previously built other complex curvilinear structures, but their designs had been limited by what could be described in traditional two-dimensional drawings. The team was on a tight budget and schedule because of the severe time constraints of the Olympics, which led James Glymph, a principle at the firm, to search for an appropriate software and hardware package that could describe the complex three dimensional form to assist manufacturers and contractors in building the structure swiftly and economically (Dal Co et al., 1998; Shodek, 2005).

The search initially led Glymph to the Harvard Graduate School of Design, where they used the sectional drawings prepared from the physical model as the 'ribs' of the fish over which the skin was stretched to make a final surface shape as basis for a computer model. Experimenting with Alias, a rendering program with curve and surface editing features, they created a three-dimensional model, notably different from their original physical model. It convinced the team that their initial section drawings were flawed, and a new computer model was created and approved by Gehry. In contrast to the first computer model, this second computer model was accurate, but it could not be used to transfer dimensional information digitally to the contractor, for the software Alias did not have this capability. A solution was found in the in chapter one mentioned CAD software CATIA, initially developed for the aerospace industry, which had all the necessary modelling capabilities and allowed for interface with structural programs. CATIA models curved surfaces with complete
numerical control, one can define precise locations of every point in a CATIA model, making it perfect for the construction of the fish. Interesting to mention is that the aerospace industry, like Gehry, designs from the skin inward (ibid).

With the aid of consultants, the architects created a CATIA model of the fish (image 17) and tested its accuracy through the construction of a laser-cut paper model based on the CATIA data. The data was also converted into a software that could perform structural engineering. The engineers and architects went back and forth with the data between the different programs. Also here, the structure had to follow the skin. The skin was made out of strakes of bend steel. Flat strips wove in and out among strips that were pinned to the structure, to form the basketlike fish skin. In pursuit of determining the maximum curvature of the steel strakes, the team made a full scale mock up (image 18) (ibid). By working closely together with the contractor on these full scale mock ups, extracting data from the computer model, Gehry’s team developed a set of flexible but nonetheless standardized component fittings, adjustable to different geometries and rotation angles. The data provided the contractor with all the necessary information, making a complex structure relatively easy to assemble (Dal Co et al., 1998).

Gehry’s office desired a system that would allow them to continue working with physical models, simultaneously being able to describe to contractors how to build the unique structures. They sought after demystifying the material behaviour, surface geometries and structural principles of complex curves so that time and money expended on the project would reflect the true cost of assembly rather than the costs associated with misunderstanding (Dal Co et al., 1998). CATIA made a complex form possible to understand and build quickly and efficiently. The project came in under budget, and it took a period of six months from the preliminary design to completion. The final construction was remarkably accurate, and created without drafted construction documents. The process began with traditional physical models, and embraced the computer as a means to facilitate the design and construction process, to get closer to the craft (Shodek, 2005).

Image 17; The model of the fish in CATIA (Dal Co et al., 1998).

Image 18; Full scale mock-up of the fish after the model (Shodek, 2005).
The Guggenheim Bilbao (1991-1997) and Gehry’s approach

‘Thirty years ago I was trying to emulate the world of movement, cars, planes, everything moving, and, I couldn’t build it. I tried. It was difficult and expensive and I went to IBM and they connected me with Dassault systems in France, who builds airplanes. I knew this was the future. They gave me the stuff to try and the first time I found success with it is in Bilbao.’ – Frank Gehry in the documentary Frank Gehry: The architect says ‘Why can’t I?’ (Aitken, 2015)

‘If Frank Gehry had lived fifty years earlier, he might not be Frank Gehry. He might be a lesser Frank Gehry. The fact that he lived at the cusp of the digital age, enabled him to realise his dreams, in a way that he really might not have, otherwise. If you’d had to pick one building, over the last twenty years, that stood for the time in architecture that expressed this technology, its aspirations and its effects on cities, it would be the Guggenheim in Bilbao.’ – Blair Kamin (ibid).

The Guggenheim museum in Bilbao (image 19), completed in 1997, is the result of collaboration between the Basque Country Administration that financed and owns the project, and the Solomon R. Guggenheim Foundation that operates the museum and provides the core art collection. The museum represented the first step in the redevelopment of the former trade and warehouse district along the south bank of the Nervion river (Dal Co et al., 1998). The location was initially not imagined by the city to be that of the new museum, originally the city thought of the museum to be positioned somewhere in the centre. After a guided tour as part of the limited competition – competitors were Arata Isozaki and Associates and Coop Himmelblau – Gehry pronounced his doubts about the original site and proposed the museum to be positioned at the bend in the Nervion River, a former industrial site (Aitken, 2015; Ragheb, Gehry, Cohen, & Friedman, 2001).

The Guggenheim museum in Bilbao was the first building that captured the gestural quality of Gehry’s sketches in built form. As we have seen, CATIA had been in use since Gehry worked on the fish sculpture. The Guggenheim Museum in Bilbao was the first major project using CATIA, illustrating the full potential of the program. It was of enormous significance from both aesthetic and technical points of view. It afforded greater freedom in the design of Gehry’s distinctively organic forms, and also simplified the construction by providing digital data that could be employed in the manufacturing process, thus controlling costs (Ragheb et al., 2001).

Image 19; The Guggenheim museum in Bilbao (Dal Co et al., 1998).

According to (Mitchell, 2001) Gehry had created a way of designing and building that is more in line with the realities of our digitalizing and globalizing age than the still dogmas of machine age Modernism would be. Gehry created a powerful new architectural language of computer constructed curvilinearity, unique parts, free form compositions, digital analysis and globally distributed CAD/CAM fabrication. But at first, Gehry was not very keen on using the computer in his design process. He considered the program to be limiting architecture to symmetries, mirror imagery and other simple ‘Euclidean’ geometries. However, questions of how to create Gehry’s sculptural architecture, and translating them into a large scale version, were unresolved. Frank Gehry as quoted in Bruggen (1998): ‘I just didn’t like the images of the computer, but as soon as I found a way to use it to
build, then I connected.’ The firm decided to put together pieces of equipment to improve the process. At first they were slightly losing the physical approach, but they developed a process capturing the physical model. Unlike others, the firm always went back to the physical model (Bruggen, 1998).

In Gehry's office the process starts with the use of an accurate three-dimensional digitizer (a 3D scanner basically) to capture the vertexes, edges and surfaces from a large physical model. By using CATIA, mathematical curves and surfaces are then fitted as closely as possible to the scanned model. Rapid prototyping is used to 'build back' the physical model, a copy of the original, to perform visual inspection on in relation to the original. It is a process of iteration, adjusting the digital model until the design team is satisfied (image 20). It is a similar strategy most favoured by automobile designers. Curved surface modelers have not made them give up free hand sketches and models of clay. They value the direct tactility of a physical model and the speed, freshness and energy of the free hand gesture (Mitchell, 2001).

It was not uncommon for Gehry to be frustrated with contractors or manufacturers he consulted who claimed that his sculptural shapes could not be built or were not economical. He started to lean more towards the idea of the architect also being the master builder. A change occurred in the office to manage projects and break the pattern of having to rely on outsiders. By using the new computer program the layout process was accelerated, sculptural shapes could be computed and a more time saving and thus economic way of building was developed. This new process was applicable on both high technology in terms of construction (numerically controlled machines) and traditional craft equally well. Designs were brought closer to their immediate realization and Gehry became aware of the computers ability to generate forms (Bruggen, 1998).

According to Glymph as quoted by Bruggen (1998); 'Many of the forms he is developing now are only possible through the computer. Bilbao is a perfect example. Prior to the development of the computer applications in the office, they would have been considered something to move away from. It might have been a sketch idea, but we would never be able to build it. Bilbao could have been drawn with a pencil and straight edge, but it would take us decades.'

The Guggenheim museum in Bilbao has contributed to an irrefutable change in Gehry's way of practicing architecture. According to Gehry as quoted by Bruggen (1998); 'We found early in our explorations of developing relations with builders that the more precise the delineation, the more it could be demystified and reduced to the ordering of materials of a certain shape and almost the ability for the contractor to paint by the numbers. It gave the contractors security in their bid and prevented inordinate premiums. Of course it was more expensive but not outrageously so. It is this new process that was first tried on a large scale in Bilbao. It had resulted in a completed building within a reasonable budget, and within a reasonable space of time. What it all leads to, is the architect eventually taking more responsibility and becoming once more the master builder.'

Crucial in constructing the Guggenheim museum in Bilbao was the way in which numerically controlled machines can now shape, cut and drill steel sections with great efficiency. With the advance of CAD/CAM technologies, steel frames can now be economically formed into complex shapes, and resulting complicated joints present little difficulty. The construction photographs of the naked steel frame are very impressive (image 21) A growing body of successfully completed projects convincingly demonstrates that CAD/CAM technology and fabrication works. Within schedule and budget frameworks that don't need to be extraordinary, it opens up an exciting new way of conceiving and making buildings (Mitchell, 2001).
Image 21; The Guggenheim museum steel frame in construction, retrieved from the website of the Guggenheim museum.

Image 22; Gehry's Santa Monica studio in 1994, many physical models and not a computer in sight, though it was extensively used already by the studio by this time (Bruggen, 1998).
Conclusion

How did the development of computer aided design and manufacturing techniques influence architectural design?

The development of computer aided design and manufacturing technologies started in the 1960s, diffused in the automotive and aerospace industries in the 1970s and 1980s, and reached the architectural profession and the building industry only by the 1990s, possibly due to one of the inventions to create three dimensional computer models being kept secretive for nearly twenty years. Also, the building industry is known for having a conventional attitude and a small profit margin on one off projects.

It was the collaboration between Utzon and Arup that initially tried to implement the advantages of their time, mainly in the process of engineering and constructing the Sydney Opera House, an expressive, sculptural building Utzon envisioned. The project indicates the use of computer aided engineering and numerical control logic within the fabrication process, but they might not have been too ready to be utilized; the project costed more and took longer than expected, and to a serious extent. Utzon and Arup contributed to the body of knowledge of constructing challenging sculptural forms by using digital technologies.

Though it is not published as much as the famous Guggenheim museum in Bilbao, it was Gehry’s Fish sculpture that was the true inauguration of the combination of CAD and CAM in architecture. With the desire to be able to communicate construction information directly with the contractor, Glymph, one of Gehry’s associates, landed on using CATIA, a program originally developed by Dassault in France for the aerospace industry. CATIA soon proved to be advantageous, not to the least for Gehry having a similar design logic to the aerospace industry; designing from the skin inwards.

The Guggenheim museum in Bilbao is considered the project in which Gehry ‘found success’ with CATIA for the first time. Considering sculpturality, the Fish is indeed less moving. Gehry utilizes a 3D scanner to create a point cloud from a physical model, which is then reproduced digitally to confirm resemblance. Though the projects of Gehry generally start with a physical model, they are only producible by means of digital technologies. Considering architectural design, it is Kolarevic (2003) that accurately advocates that the first crystal palaces and Eiffel towers of the new information age have just been built, of which the Guggenheim museum in Bilbao is probably the best known example that captures the zeitgeist of the digital information revolution – truly consolidating the marriage between CAD and CAM.

Though historically it is not completely out of the ordinary for other industries (or crafts) to aid to architectural design, we should not forget that it was the birth of the modern movement that created the conditions for technology to disseminate within architecture. At this point in time, architecture wanted to abandon historical style and was inspired by modern times and modern technologies – beautifully depicted by image 11, the Mercedes in front of Le Corbusier’s architecture. Le Corbusier even went so far as designing the curvature of the geometry of the ground floor of the Villa Savoye to be precisely that of the turning circle of the car. Might this not be the basis for Gehry designing ‘from the skin inward’ and turning to CATIA, the aerospace application?

On a different note, Mitchell (2001) advocates that architects draw what they can build, and build what they can draw. The revolution of digital technologies might be similar to the invention of paper. We now draw digitally, and what is imaginable in those screens waves Euclid goodbye. Any form seems to be feasible. Also, it brings the architect closer to the production process, something that used to be commonplace in the profession. The idea of the architect as master builder has returned.

If Paxtons’ Crystal palace and Eiffels’ Tower resulted in the extraordinary heights that buildings could reach and the utilizalation of steel and glass within architecture, after which it took another hundred years for these features to gain presence on a world scale, we should expect CAD/CAM technologies and the architectures they provoke to similarly gain more presence on a world scale in the coming decades – as long as architecture will feel the necessity to express the image of its time.
References