MASTERARBEIT

How Digital Tools Shape the Way Architects Think

The Digital Design Process in Architecture

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Abstract

Digital technologies have not only infiltrated almost every aspect of our everyday lives but have become an omnipresent tool in architecture practice and an integral part of the design process itself. There is broad consent that the digital tools significantly changed the way architecture is developed and conceived today. Digital technologies are used in almost all phases of architecture projects. However, little research has focused on the driving forces and the impact of computerization in the design process. This thesis explores how digital design tools shape the architectural design process and analyses digital design methods. Many popular design tools and methods in contemporary architecture have primarily been developed in other disciplines, such as car manufacturing, aerospace, shipbuilding, and product design. Some technologies diffused into architecture and became popular design tools. Parallel developments in other fields, such as computer science, mathematics, and engineering, together with societal changes form the basis of the digital revolution in architecture. Digital technologies extended the design vocabulary and liberated architects from former constraints. Increasing computational power enhanced the efficiency and speed of the design and production processes, enabling architects to handle geometrically complex forms. Parametric design in combination with production techniques such as rapid prototyping are hard to imagine without the support of digital technologies. Architecture projects of the last decades are juxtaposed with advances in digital technologies, looking beyond computer-aided design for drafting and visualization to the creative and generative potential of digital media. Upcoming digital technologies are investigated regarding their potential integration in future architectural practice and software programs.

Keywords: digital architecture, design process, CAAD, design tool

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The title-page is inspired by an image by John Maeda in the book *Creative Code* (2004) on page 112.

Contents

Acknowledgements

The interest to research the subjects of this thesis grew out of the conference, "The Virtue of the Virtual" held at McGill University, School of Architecture in May 2011. In the following months, the idea was further developed and shaped into the topic of this work.

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1. Introduction

> *"The shift to a digital paradigm is the most fundamental technological shift humanity has probably ever encountered; the change from hieroglyphs to alphabetics codification, or the invention of mechanical print, are both seemingly minor by comparison."*
> *(Goulthorpe, 2003a, p. 292)*

Today, the computer has become the central workspace in almost all architecture practices. An architecture office is hard to imagine without the support of digital drawing and visualization tools. Architecture offices seek architects with good design skills, practical experience, and demand an increasing plate of computer-aided design (CAD) skills. Applicants often choose an architectural office according to the software the office uses and vice versa. CAD software also differs amongst each other, are not necessarily interchangeable and are often platform dependent. Therefore, general experience with CAD software might not be sufficient, as job offers often request knowledge of a specific modeling software like AutoCad, ArchiCad, or Revit, as well as experience with specific 3D visualization software such as 3ds Max, Rhino, or Maya. Often firms prefer candidates with skills in programs rather than solid design skills. The reason being that today's CAD software have become rather complex and they are hence time and cost-intensive to master. Aside from the afore mentioned aspects, economical issues such as licensing costs need to be considered in a professional environment.

In the author's personal experience, the computer has been an omnipresent tool for his entire architecture studies. Being thoroughly exposed to a digital environment from the first days, raised the question which changes digital technologies brought to the profession and how this profession would perform without it. There is a broad consent, that the digital tools significantly changed the way architecture is developed and conceived today. However, little research has focused on the driving forces and the impact of computerization in the design process. This thesis explores how digital technologies shape the architectural design process and analyses common digital design methods. Here are some of the questions, that began this thesis:

- How do digital tools shape the design process?
- Is the architect at risk to see the solutions facilitated by CAD software as the only possible solutions of a design problem?
- What is the new role of an architect in a digital environment?
- What skills do future architects need?

From a historical perspective, architecture has always developed and defined itself in relation to social, technological, and political developments. More than ever, architecture reflects the distribution of power in contemporary society. Societal movements are manifest in the built and unbuilt environment. The role and the social status of the architect has changed throughout the course of history. Not only social status, but also the remit of architects has changed over time. In antiquity and the Middle Ages, the master builder was responsible for all aspects of the design process - from design to the construction of a building. Similar to other professions, a differentiation of labour occurred and the unity of the architect as a designer, manager, builder, and engineer was resolved (Fig. 1.1). The knowledge and involvement of the modern architect in the actual building process is much less compared to the historical role of the architect-master builder.

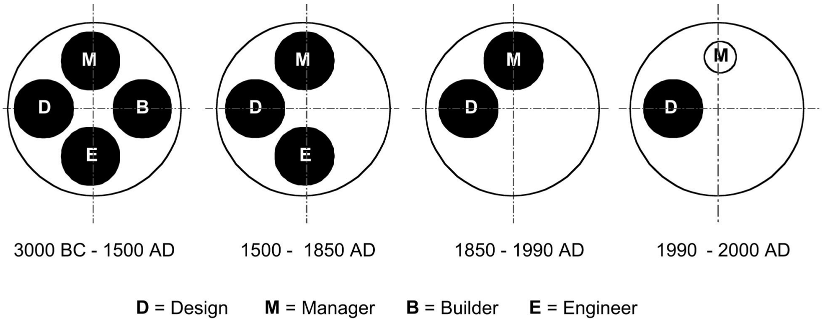

Figure 1.1 Evolution of the architect (Barrow, 2002, p. 106).

Historically, the birthplace of the modern architect was during the Renaissance, where architects retract from the building site and separate themselves from direct involvement in the building process (Barrow, 2002). As a result, the fields of design and construction split and led to a decomposition of the former "master builder" into an artist-designer, practicing architect, and builder. In the last decades, the evolution of digital technology gave direction to the design and building process in architecture. Digital technologies, continuously permeating all aspects of architecture, have a game-changing effect on the remit of architecture and the building industry as a whole. Consequently, technological developments are critical to the role of architects and how architects define themselves in the future. Yet the question remains, what are the consequences for the profession?

2. Methodology

The purpose of this thesis is to compile the evolution of digital tools in architecture and to study their effects on the design process. Case study projects are being described in Chapter 4.1, Case studies of digital design methods. The hypotheses and findings in this work, especially those outlined in Chapter 4.3, Effects of digital tools on the design process, are based on interviews, analysis of case study projects, and literature reviews. Personal interviews were conducted with the following architects and theorists in the field of digital design:

- Georg Franck: professor at the Institute of Architectural Sciences, Department Digital Architecture and Planning, Vienna University of Technology; date of interview: February 26, 2013
- Nicole Franken and Robin Heather: *franken architekten*; date of interview: March 12, 2013
- Stefan Krakhofer: formerly employed by *Foster + Partners*, Specialist Modelling Group; date of interview: May 30, 2013
- John Marx: principal of *Form4 Architecture* and lecturer in the Department of Architecture at the University of California at Berkeley; date of interview: March 6, 2013
- Heinz Schmiedhofer and Martin Reis: principals and founders of *feasible geometry-consulting*; date of interview: June 6, 2012.

For the scope of this thesis, published interviews with the following people have been analyzed: Robert Aish, Ulrich Flemming, Bernhard Franken, James Glymph, Mark Goulthorpe, Chris Luebkeman, Branko Kolarevic, William J. Michell, Hugh Whitehead, and Chris I.Yessios.

3. Architectural planning gets digital

3.1. Why CAAD?

Computer-aided architectural design (CAAD)[1] software programs are omnipresent in today's architecture practice. In the early years of digitization, three reasons for introducing digital design tools to architecture were identified (Love, 1985): (1) efficiency, (2) new operations, and (3) "fashion". More than 25 years later and with significant advances in the digital era, it still seems valid to discuss today's digital technologies in architecture following Love's three points.

Addressing efficiency issues, Love states that CAD is used to increase the speed of existing operations and therefore make the design process faster and more efficient. Looking at the efforts over the period of a project, Mitchell suggests that in a non-digital environment most design efforts are required during the production and construction phase while in a computer-aided environment, more emphasis is laid on the early design stages (Mitchell, 1977, p. 88). As a consequence of speeding up the drafting process and document production activities, it becomes possible to consider more alternatives in the early design stages when designing using CAD. By spending more resources on the initial

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[1] In most cases, the more general abbreviation CAD is used instead of CAAD, as the majority of the discussed software is not specifically developed for architectural use. This also supports the general idea of this work, that digital design tools are not limited to the one or other profession.

design concept, it can be argued, that by using computational design tools, it is possible not only to arrive at a design solution more quickly but at a conceptually more reasoned, sound, and justified design solution.

The efforts of Building Information Modelling (BIM) as an integrated design system can also be seen as an approach of making the design process and project documentation more efficient. Ideally, a building information model contains all the information related to a building in a single project database. The database is structured to facilitate information exchange between the different participants in the design and construction processes. From the virtual building model, different graphical representations (e.g. floor plan, section, and 3D view) as well as non-graphical information (e.g. room schedule, total floor area, and construction information) can be derived. The concept of BIM replaces purely graphical symbols with "intelligent" or parametric building objects, such as walls, doors, and windows. Geometrical dimensions, non-graphical properties (such as insulation value, weight, and cost) and functional relationships are assigned to 3D building elements. Examples of BIM software solutions are AllPlan (by Nemetschek), ArchiCAD (by Graphisoft), Architectural Desktop (by Autodesk), Bentley Systems, and REVIT (by Autodesk). Potentially, the idea of BIM goes beyond the design and construction phases of a building and serves as a living record for the whole lifecycle of a building.

As shown in Fig. 3.1, the fields of automation in architectural design, engineering design, and construction evolved separately from each other. Within the "island" of architectural design, technologies for 2D drafting and 3D visualization developed separately from structural analysis or production automation. Despite approaches to connect the "islands", a fully integrated design system is still not reality in architecture practice.

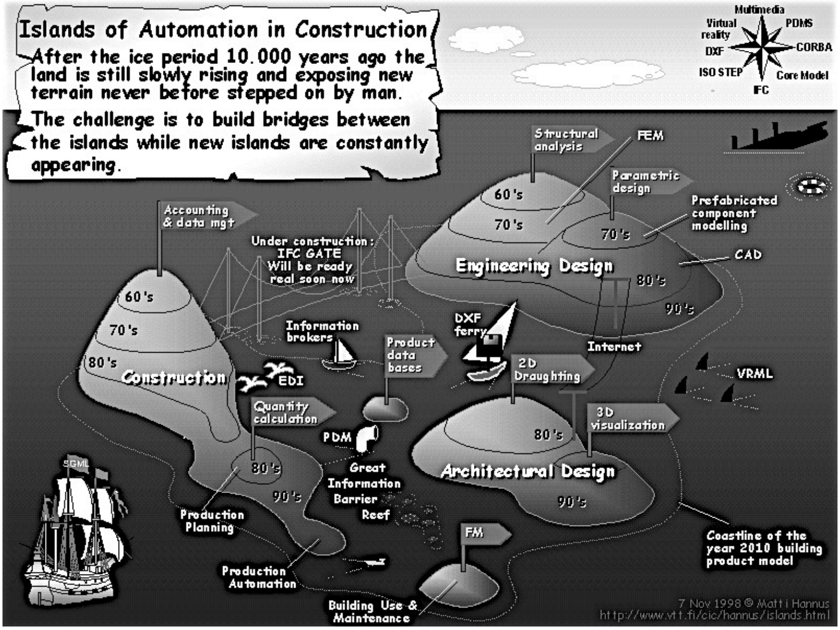

Figure 3.1 Evolution of automation in construction over the last decades (© Hannus, Penttilä, Silén 1987).

Secondly, besides efficiency aspects, architectural design software also enables the architect to perform new operations and increase their scope of activity. Love argues that using CAD increases the emphasis on the problem definition as well as the conceptual design, compared to conventional (manual) design (Love, 1985, p. 4). Further, CAD tools allow the architect to approach design more as a process of discovery, and therefore shifts the emphasis "from finding an acceptable solution to weighing alternatives" (Love, 1985, p. 5). Similar, Terzidis makes a distinction between computerization and computation. Computerization involves predetermined and well defined processes, increasing efficiency and speed of operations, based on automation, mechanization, digitization, and conversion (Terzidis, 2003, p. 67). In contrast, computation is a procedure of determining something by mathematical and logical methods; it is about exploring indeterminate, vague, unclear, and often ill-defined problems, and processes (Terzidis, 2003, p. 67). An interesting point, is that computerization involves digitization, which is not necessarily the case with computation (Terzidis, 2003, p. 67). However, the implementation on computer systems allow computational methods to explore complexities going beyond human capabilities.

Thirdly, trends and fashions play an important role in architecture. Pressure to keep up technologically in an increasingly digitally-dominated professional field should not be neglected. Due to the massive change digital technologies brought along, there is something which can be described as "digital fashion". However, Terzidis criticizes that often "theories of design and form are 'translated' into computational ones, merely to participate in the digital fashion" (Terzidis, 2003, p. ix). Established tools, methods and equipment are soon considered to be outdated in a society, directed by accelerated technological transitions. Thus, cliental expectations pressure architects to keep up with new technologies which are generally considered as forward-oriented and progressive.

3.2. The basis of digital success

Advances in various professional fields, such as material science, computer science, and manufacturing, enabled digital success and goes hand in hand with the digital revolution of architectural design tools. The core of digital success in architecture can be seen in the development of computer-aided design (CAD) software. Enabled through the invention of graphical user interfaces (GUI) and significant increase of computer's processing power, CAD has become a common standard in almost every architecture studio. In a GUI on an electronic device, the user interacts with images instead of text commands. First attempts of GUI in CAD software date back to the early 1960s, when Ivan Sutherland at the MIT Lincoln Laboratory first developed an interactive device called Sketchpad to draw vector lines on a computer screen (Fig. 3.2). With the Sketchpad, Sutherland introduced the first drawing interface and many intuitive interaction techniques, which are standard in contemporary CAD programs, such as the selection of objects by clicking or the "drag-and-drop" function. Since this pioneering breakthrough in human-computer interaction, a long path of multidisciplinary research and development has been followed to develop contemporary high-end CAD and building-performance simulation tools (Fig. 3.3).

Figure 3.2 The Sketchpad developed by Ivan Sutherland in 1963 uses a light-pen to interact with objects on the screen (Schwarz, 1997, p. 61).

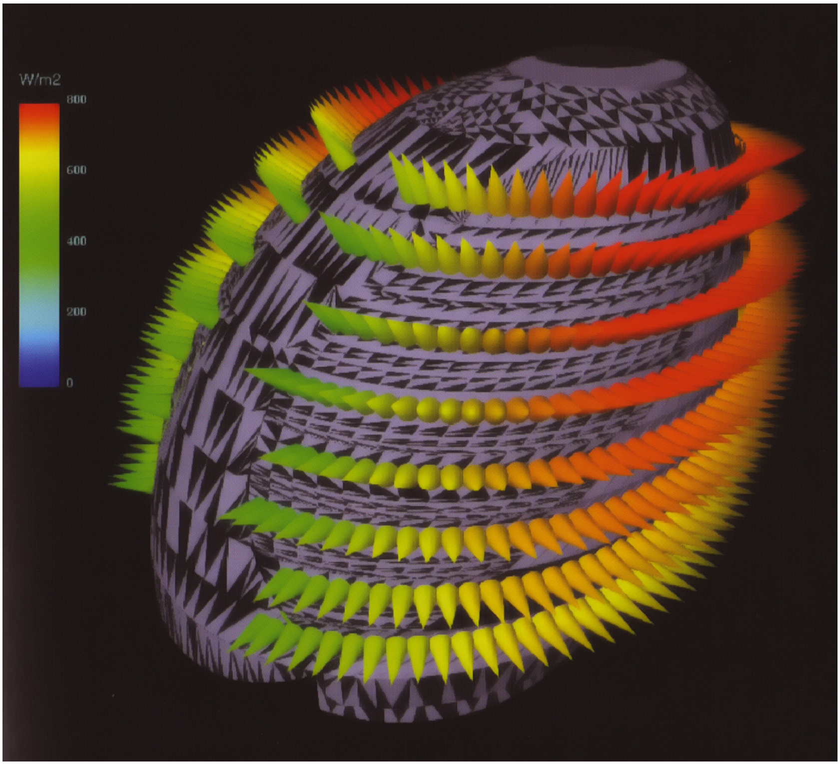

Figure 3.3 Solar studies (by Arup) of the City Hall (2002) in London, UK, by Foster + Partners (Whitehead, 2003, p. 87).

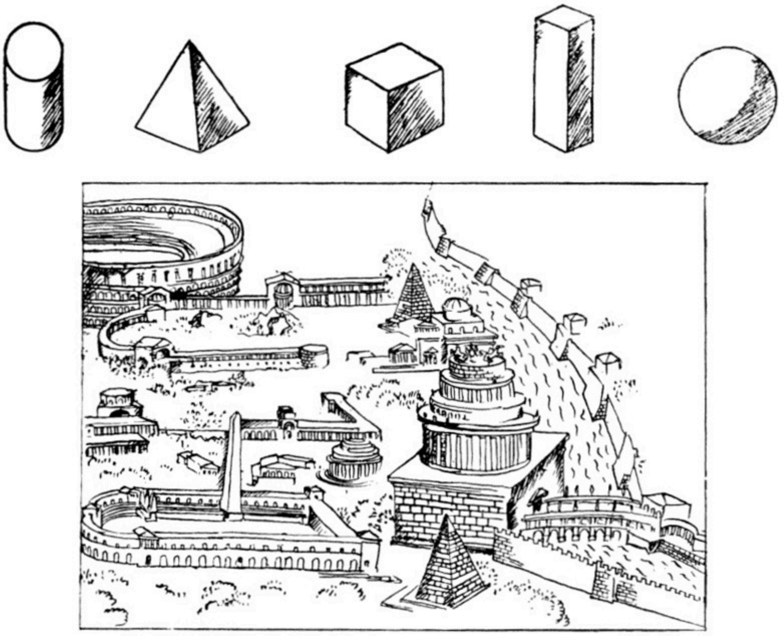

Figure 3.4 Le Corbusier's sketch of the volumetric composition of ancient architecture (Corbusier, 2008, p. 200).

In pre-digital architecture, forms were mainly based on the geometrical solids such as the cylinder, pyramid, cube, prism, and sphere (Fig. 3.4). This vocabulary of shapes have been firmly established in architectural practice over the last few decades. Most designs could be geometrically constructed using linear transformations, such as affine (e.g. translation, rotation, reflection, and scaling) and perspective transformations.

In the last decades, CAD allowed to compute these free form curves using geometric algorithms. The curves are mathematically defined by a control polygon and can easily be modified by changing the position of the control points. While manual tools to construct free form shapes did exist, the popularity of complex geometry dramatically increased as the computer facilitated the construction of free form curves. NURBS (Non-Uniform Rational B-Splines) curves and surfaces are popular examples used in current digital modelling software today. Using the mathematical concept of NURBS, allows a geometrical description of a broad range of geometrical forms, from simple lines, to solids, and further complex spatial freeform surfaces (Pottmann, Asperl, Hofer, & Kilian, 2007, p. 255). New geometrical concepts include "primitives" as special cases of parametrically-defined surfaces. Curves and surfaces based on NURBS are parametrically-defined using control points, weights, knots, and the degree of the curve[2] (Fig. 3.5 and 3.6).

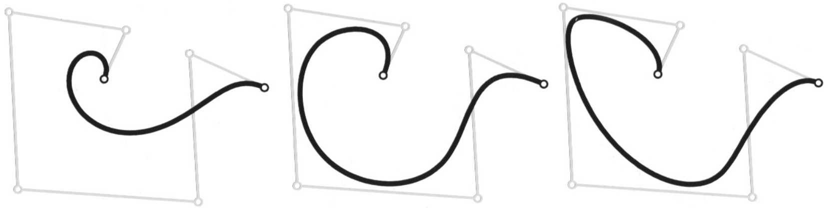

Figure 3.5 Control polygon and freeform curve: Bézier curve (left), B-spline curve (middle), NURBS curve (right) (Pottmann, et al., 2007, p. 255).

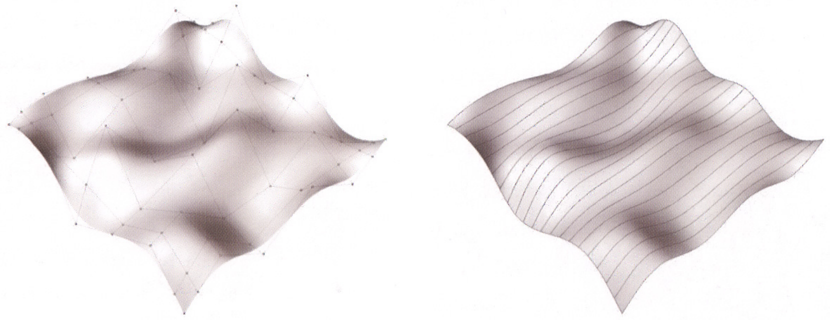

Figure 3.6 Control lattice (left) and isoparametric contours (right) of NURBS surfaces (Kolarevic, 2003a, p. 17).

From a computational point of view, NURBS are an efficient data representation and it takes relatively few steps to compute their shapes (Kolarevic, 2003a, p. 15). Other curves used in today's CAD software,

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[2] A comprehensive description of the mathematical and geometrical principles of free-form curves and surfaces is given by Pottmann et al. (2007) in Architectural Geometry.

such as B-splines and Bézier curves, are computed as special cases of NURBS curves. For example, B-splines are NURBS with equally weighted control points, and Bézier curves are defined as B-splines with equal knot spacing. The term "spline" originates from flexible strings out of plastic, wood, or metal used in shipbuilding which were bent into smooth curves to form ship hulls (Kolarevic, 2003a, p. 15). Interestingly, in the late 1950s and early 1960s, Bézier curves were developed in the French automobile and airplane industries at Citroën and Renault, when geometrical concepts for more complex curves were needed to accurately describe the forms of automobiles and airplanes (Pottmann, et al., 2007, p. 259). In the late 1990s, the design vocabulary of NURBS and other free form curves were implemented in several CAD software. These shapes have became part of the standard toolbox in every major modelling software today.

Important to note in this context is that the possibility to represent more complex geometry with CAD is not primarily about making "blobby" forms or rendering pretty pictures. The concept of parametrical surfaces comprises linear as well as curvilinear forms and thereby enhances the existing architectural design vocabulary. This allows an understanding as different instances on a discrete scale of formal complexity instead of as opposites (Kolarevic, 2003c, p. 7). Along with the architectural interest in new forms in the last decades, there is an emerging concern with new materiality. Progress in material science allows the design of "intelligent" materials with certain functional and aesthetic properties. Similar to the 1950s and 1960s, where free formable materials such as concrete and plastics fostered an interest in "blobby" forms, contemporary advances in material science and engineering technology produce a wide range of new materials. Conventional materials are also reconceptualized, as common materials such as bricks or reinforced concrete are being used in new applications. For example, the walls of the Zollhof Towers (2000) in Düsseldorf, Germany, by Frank Gehry are constructed using a steel structure filled with masonry bricks. What is noticeable is that the weight of materials in relation to structural performance gains importance. For example, steel in reinforced concrete can be replaced by non-corroding carbon fiber, which is much stronger and lighter than conventional steel (Kolarevic, 2003b, p. 49). The composition and microstructure of materials in combination with joining methods has led to high-performance materials which are especially interesting for both the bearing structure and the exterior cladding of buildings (Fig. 3.7). Higher performance materials enable to new shapes to be built which was not possible to construct with conventional materials and means.

Figure 3.7 Triangulated glass roof in the DG Bank (2001) in Berlin, Germany, by Frank Gehry (Gehry, 2001, p. 219).

Free form geometries in CAD demand accurate and efficient manufacturing techniques to build the complex forms. Computer Aided Manufacturing (CAM) is the use of computer software to drive computer numerically controlled (CNC) machine tools. CNC machining is digitally supported techniques which, with the help of machinery such as computer controlled milling machines, removes material from a block of material to carve the desired shape (Pottmann, et al., 2007, p. 569). These fabrication techniques allow to shape high-performance materials in an automated fashion with the necessary precision. CAD software in combination with digitally supported production techniques open the door for affordable mass-customization in architecture. Components for free-form structures especially require mass-customization, as can be seen in projects like the BMW Exhibition Pavilion (1999) at the IAA Auto Show in Frankfurt, Germany, by Bernhard Franken and ABB Architekten (Fig. 3.8). CAM also played an important part at the construction of the DG Bank (2001) in Berlin, Germany, by Frank Gehry. Each nodal connector of the triangulated roof was unique. The nodes and approximately 1,500 glazing panels were constructed using digital fabrication (Kolarevic, 2003b, p. 45). CNC milled molds were also used to bend the double-curved acrylic glass panels of the BMW Exhibition Pavilion. Similar techniques had been used to construct the glass roof of the Great Court in the British Museum (2000), London, UK, by Foster + Partners (Fig. 3.9).

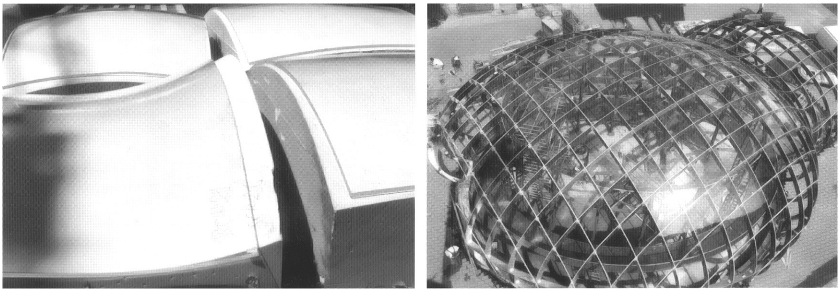


Figure 3.8 Double-curved acrylic glass panels of the BMW Exhibition Pavilion at the IAA Auto Show in Frankfurt, Germany, by Bernhard Franken and ABB Architekten (Kolarevic, 2003b, p. 35).

Figure 3.9 Triangulated glass roof structure in the Great Court in the British Museum (2000), London, UK, by Foster + Partners (Young, 2004).

The digital revolution in architecture and the emergence of curvilinear forms is also tied to a broader cultural and design discourse (Kolarevic, 2003c, p. 6). Smooth and organic-like shapes are already ubiquitous in our everyday lives (Fig. 3.10 and Fig. 3.11). The architectural culture, however, seemed to ignore this trend and the technology behind it for a long time. For decades, other design fields, such as product, aircraft, or automobile design, already used the generative potential of new technologies in the design and manufacturing processes, while architectural design was historically the last to adopt these new technologies (Kolarevic, 2003c, p. 6). Aside from economic and functional aspects, integrating CAD and other digital technologies into the design process can also be understood as the architectural response for the societal and cultural zeitgeist of the Digital Age.

Figure 3.10 Apple iMac G3 (1998).

Figure 3.11 BMW Z3 Roadster (1995).

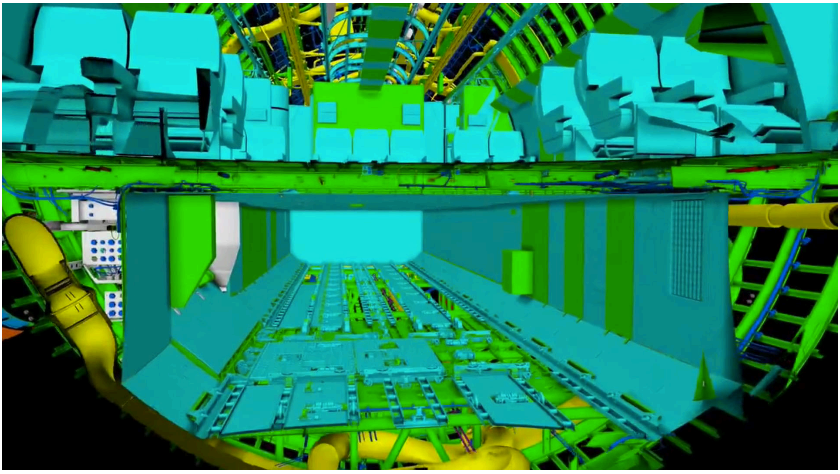


Figure 3.12 3D section of a Boeing 777 in CATIA (1995). The Boeing 777 was the first completely digitally designed aircraft (© Boeing Company).

Looking at these developments in the last decades, it is difficult to pick a starting point as advancements on different fields sometimes happened simultaneously and in coevolution with each other. As with technological changes in other disciplines, there is a lag until research advances become mainstream (Pittman, 2003, p. 256). This lag is mostly due to business and economic reasons and less because of technological aspects.

Certainly, the parametric definition of curves and surfaces has set the basis to computationally handle complex free-form geometries. Advancements in manufacturing techniques, material and computer science, together with contemporary cultural, societal, and economic demand for new technologies have pushed the development of digital architectural tools. It can be said, that digital success has deeply changed the profession of architecture and is going to be a stronger driving force in the future.

3.3. Stages of architectural digitization

> *"Architects tend to draw what they can build, and build what they can draw."*
> *(Mitchell, 2001, p. 354)*

Digital technologies have created a new mindset for the way architecture is developed and conceived today. While sketching is still the most direct way for architects to express their design ideas, most other devices of the pre-digital era have since long been outdated and banned from almost all architecture practices. Today, computers and other digital equipment for drafting and visualization have replaced most drafting boards and other manual drawing tools. As architects operate within finite time periods and limited resources, the available design tools always established and constrained a current shape of economy (Mitchell, 2003b, p. vii). In the course of history, technological advances and innovations expanded and restructured these shape economies. The digitization of architecture fundamentally redefined the tools being used. Therefore it is important to define what is being understood as a design tool. In a general sense, a tool is defined as an "instrument used in the performance of an operation" whereby the "capabilities, potency, and limitations of a tool are known or estimated in advance" (Terzidis, 2003, p. 68). A design tool is any object or device that is being used physically or virtually to create, document, or generate a design. Classical tools in architecture are among others the pencil, straightedge, and compass. These tools are used on media such as sketchbooks, paper, trancing-paper and other materials to express a design in the form of sketches, plans, perspectives or other forms of representation. For example, a pencil is generally considered as a tool to perform the operation of writing and drawing. Certainly, almost any tool can be used in different and often surprising ways. Today, CAD software is the prevailing "drawing tool" used in architecture today. The creator of form.Z, Chris I.Yessios, notes that the most accomplished architects did not simply allow the tools to drive their imagination, but "stretched the capabilities of digital tools into areas never consciously intended by their developers" (Yessios, 2011, p. 9). It is debatable to define appropriate and inappropriate uses of tools from a theoretical perspective, as particularly unconventional ways of using tools often produce interesting and novel results. From a technological perspective, one can identify different phases of how digital media and tools were integrated in the design process.

Pre-digital

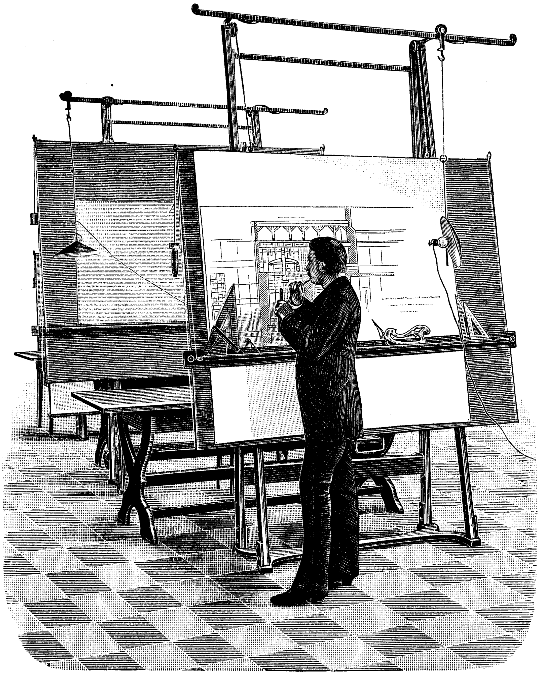


Figure 3.13 Architect at his drawing board (Teknisk Ukeblad, 1893).

Prior to the integration of digital tools in architecture, manual drafting instruments dominated the architectural workplace. Until the early 1980s, the straightedge, scale ruler, parallel bar, protractor, compass, and divider were the classical tools architects used for design work (Mitchell, 2001, p. 353). Everything, from the initial sketch to final construction plans, was produced by hand with the help of manual drawing tools. These traditional drafting instruments defined a prevailing and manageable shape universe of straight lines and circles, parallels and perpendiculars, triangles, squares, polygons and so on (Mitchell, 2003b, p. vii). The existing shape economy, so Mitchell argues, has changed when tracing paper, gridded paper, and the photocopier became available. Translucent tracing paper made it easier to work with translated, rotated and reflected shapes. Similar, gridded drafting paper facilitated more modular designs; the availability of a photocopier largely reduced the time and costs of scaling transformations. In the the pre-digital stage, physical models and prototypes were also fabricated by hand with the support of machines in the workshop, such as cutting or drilling machines. Similarly, fabrication and assembly techniques were designed to produce straight cuts and planar surfaces. Within these limitations of representability and constructability, "architects tend to draw what they can build, and build what they can draw" (Mitchell, 2001, p. 354). This reciprocity between means of representation and production has not entirely disappeared in the digital age (Kolarevic, 2003b, p. 32).

Figure 3.14 Architectural office around 1940 (Farm Security Administration - Office of War Information Photograph Collection, 1940).

Imitating manual tools

In the early 1980s, the first digital workstations replaced drafting tables in architecture offices. However, at that time workstations had been extremely expensive and were only affordable by larger offices. With the advent of the personal computer (PC) around 1985, computers became more affordable. In the early 1990s computers were already used by mainstream offices. In an interview with Chris Luebkeman, Director of Research and Development at Arup (Arup Group Limited), he argues that whenever a new technology is introduced, it first goes through a phase of imitation (Luebkeman, 2003a, p. 291). With the introduction of GUI on computers, the first CAD softwares featured digital equivalents of traditional drawing equipment and tools (e.g. worksheet, layer, pen, and filling tool). CAD software for architecture such as AutoCAD or ArchiCAD as well as general graphic applications like Photoshop or Illustrator were in their GUI mimicking physical equipment and drawing techniques (Fig. 3.15).

Figure 3.15 Direct analogy of the digital moving tool (Maeda, 2004, p. 115).

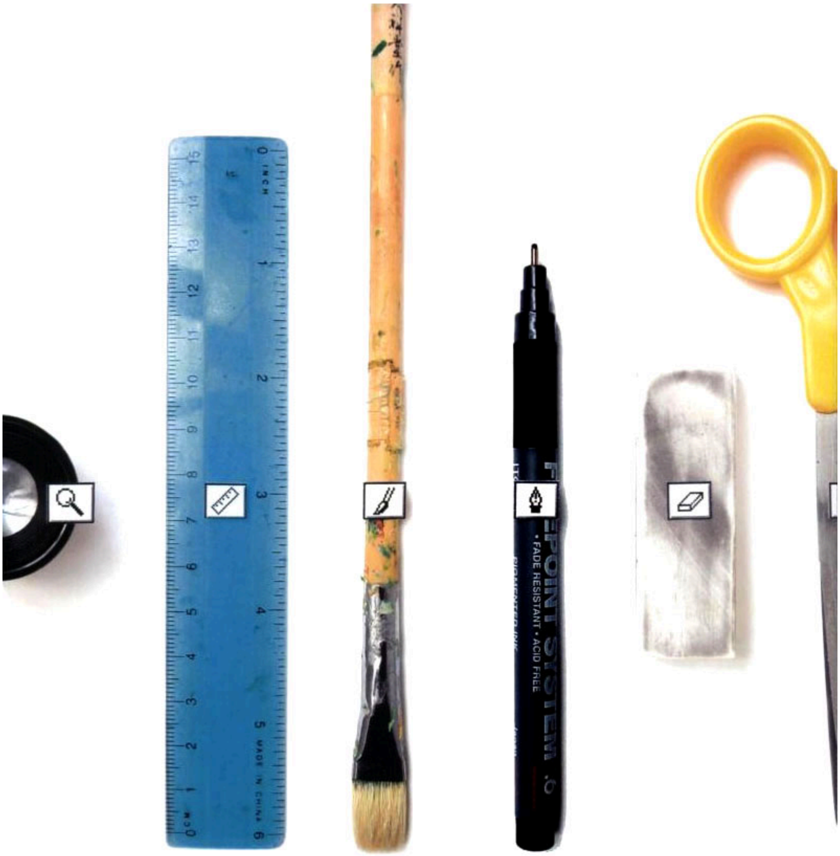


Figure 3.16 Manual tools and their digital equivalent (Maeda, 2004, p. 112).

In this phase of accommodation and adoption, the computer was mostly used as a replacement for traditional drafting instruments (Mitchell, 2001, p. 354). Early CAD systems were based on the graphic primitives such as straight lines, arcs, and circles. Geometrical transformations, such as cut, copy, and rotate were translated into equivalent digital operations (Fig. 3.17).

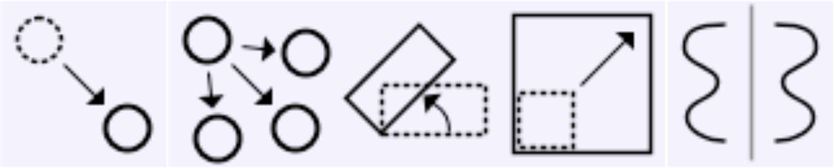


Figure 3.17 Common transformations in CAD software: move, copy, rotate, scale, mirror (Copyright by MoI).

Other functions, such as scaling or mirroring took analogies of physical operations but already significantly increased the speed at which these operations could be performed. A digital worksheet literally replaces a physical sheet of paper. Drawing on "layers" can be seen as a metaphor for using layers of transparent tracing paper. In most CAD software, the cropping tool uses the metaphor of a pair of scissors, the delete tool is depicted as a physical eraser, and the zoom button is symbolized by a magnifying glass. Input devices, such as graphic tablets also take advantage of established conventions. Styluses are pen-like drawing devices imitating the practice of manual drawing. Conventions, such as the thickness of a line in relation to the pressure on the tablet surface by the stylus or the eraser at the top end of a stylus. Using analogies of physical tool, which are familiar to most users, facilitates the transition from the manual to the digital. However, digital manipulation techniques do not necessarily need to be physical equivalents.

In this stage of CAD development, the computer was mainly used as a digital drawing board and later as a virtual modelling space creating digital 3D models. CAD mostly replaced traditional drafting instruments in architectural offices and thereby increased the speed and precision in the production of construction documents (Mitchell, 2001, p. 354). As CAD evolved, it became possible to compute and represent various types of curves and surfaces such as B-splines or NURBS. Implementing these forms based on mathematical functions in CAD opened up a new shape universe. Digital technologies in both representation and fabrication extended the design vocabulary and liberated architects from former constraints. With the help of digital fabrication techniques, the constructability in building design has become a direct function of computability (Kolarevic, 2003b, p. 33). However, CAD software did not completely replace manual drawing devices in architecture offices. Especially during the conceptual phase of a design, the sketch remains the preferred way to express and document an idea and to stimulate creative thinking. CAD is still mainly seen as a technical support system and the digital media is not integrated into the creative process of design thinking. Historically, most of the technological research in the field of CAD focused on visualization and rendering (since the 1980s), then on 3D model-based design (since the 1990s), and lately on integrating the fourth dimension of time, developing collaboration platforms and various input/output devices (Pittman, 2003, p. 256). Looking at the early applications of CAD, Asanowicz describes the computer metaphorically as an "incompatible pencil" and argues that the computer has far more to offer than looking at it purely as a technical pen or pencil (2002, p. 38). The creator of form.Z, Chris I. Yessios , reports that since the beginning of CAD development it is debated whether digital tools should imitate established professional practices, or whether they should introduce new and more effective methods, which would require retraining the architects (Yessios, 2011, p. 9). A combination of both approaches would probably be the ideal solution, where new methods could be intuitively understood by the user. Advances in both computer software and hardware certainly allow to go beyond digital drafting or visualization. Using the computer not only as a digital "pen" but as a creative and generative medium began.

Generative stage

> *"It is not a tool; it is a new material for expression."*
> *(Maeda, 2004, p. 113)*

Frank Gehry was probably the first pioneer who used state-of-the-art CAD technology as a creative tool to design and develop innovative yet well-planned buildings (Szalapaj, 2005, p. 207). In order to analyze and resolve complex free-form building geometries, Gehry relied on digital technologies from the initial exploration of form, structural analysis, and digital fabrication. Since architecture CAD software did not offer the required functions, Gehry used applications from other engineering disciplines such as aircraft and shipbuilding to realize the buildings in an effective way (Szalapaj, 2005, p. 207). Gehry's approach is just one way of using digital technologies as a part of the design process. The BMW Exhibition Pavilion (Fig. 3.18) is an example of the generative use of digital media. The shape of the pavilion follows isomorphic polysurfaces which were dynamically generated following the physical behaviour of two joining water drops. Further examples of generative design methods are discussed in more detail in Chapter 4.1, Case studies of digital design methods.

Figure 3.18 BMW Exhibition Pavilion (1999) at the IAA Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten (Franken, 2003, p. 123).

While CAD software is particularly efficient and useful for creating accurate drafting plans or rendering 3D models, it can also be hindering in early design stages. Most CAD applications require or implicitly create a level of precision which is not necessary relevant at an early design stage. Even in many highly technologically equipped practices, sketching is used to express and document a spontaneous design idea. Besides CAD as a drafting and representational tool, generative digital design looks at digital technologies as an medium of expression. The creative and generative use of digital technologies allows architects to think of design in a new perspective and in ways where there is no or hardly any analogue alternative. This generative use, sometimes described as "digital morphogenesis", enables not only to compute operations faster, which is already a crucial issue, but to arrive at design concepts which had not been able to be developed, controlled, and grasped with conventional means. Generative processes include computational mechanisms, such as iteration, recursion and the conditional application of rules (Mitchell, 2003b, p. viii). Using generation procedures to generate forms results in a less restricted shape economy, which is less dependent on factory-set limitations of CAD software. A crucial question in this context, is how digital media can support the creative design process and become a genuine medium of expression, similar to the way sketching on paper helps to develop, formulate, and document a design idea. A generative design idea can be expressed in an algorithm, a line of code, an animation, or a set of rules which defines or generates a form.

The imitation and the generative approach show different strategies of how digital technologies are exploited; however, there is no sharp dividing line between them. From a theoretical point of view, Terzidis describes two approaches of understanding the new formal possibilities: either as a reevaluation of past theories looking for parallel and reoccurring themes, or as concepts and mechanisms of new and unprecedented themes, foreign, alien or external to the discipline of architecture (Terzidis, 2003, p. 3). The first approach looks at digital tools as recording and representational devices. The problem with this approach is that creativity and interpretation is limited by the potentials of the human mind as it does not allow thoughts to transcend beyond human understanding. The second approach is based on a new theoretical framework looking at computational mechanisms outside the context of predictable understanding. Digital devices are used "not as tools for exploring what is known but as portals for entering into what is unknown" (Terzidis, 2003, p. 3). In this process, the tools or devices become part of the exploration of form going beyond the limits of perception. What combines these two opposed strategies is the notion of expressiveness whether it is computational, artistic, architectural, theoretical, or fictional.

While CAD has widely enhanced the efficiency and speed of the design and production process, the implementation in aesthetics and formal theories has been limited (Terzidis, 2003, p. 65). Little research has focused on the creative potential of digital media. Architects maintained an ethos of artistic sensibility and intuitive playfulness in their profession, contradicting the common deterministic approach of algorithmic logic (Terzidis, 2003, p. 65). Further, algorithms usually convey attitudes such as rationality, consistency, coherence and systemization, which seem to contrast novelty, creativity, or intuition. However, there are certain kinds of algorithms not aiming at predictable results but exploring generative processes. These algorithms are based on principles, including fuzzy logic, genetic algorithms, and Bayesian probability (Terzidis, 2003, p. 66). In a design context, these algorithmic processes explore uncommon and unpredictable solutions, involving shape grammars, mathematical models, topological properties, genetic systems, mapping, and morphing (Terzidis, 2003, p. 66). As Lynn notes, few architects attempted using the computer as a schematic, organizing and generating medium because of the fear of releasing control of the design process to software (Lynn, 1999, p. 19).

An argument often raised against computational design techniques is that digital tools limit intuition, creativity, and imagination. Computational tools are mainly associated with automated and efficient mechanisms determined by rationalistic procedures, resistant to emotion, humour or irony (Terzidis, 2003, p. 6). Usually architects follow a mode of thought driven by analogy, metaphors, inspiration or intuition. In order to use the full potential of both artistic creativity and computational capabilities, both modes of thought processes need to be combined into a complementary and harmonious mix. In this sense, computational tools should be less regarded as restrictive elements, but considered as an extension or a different mode of expressing intuition and creativity.

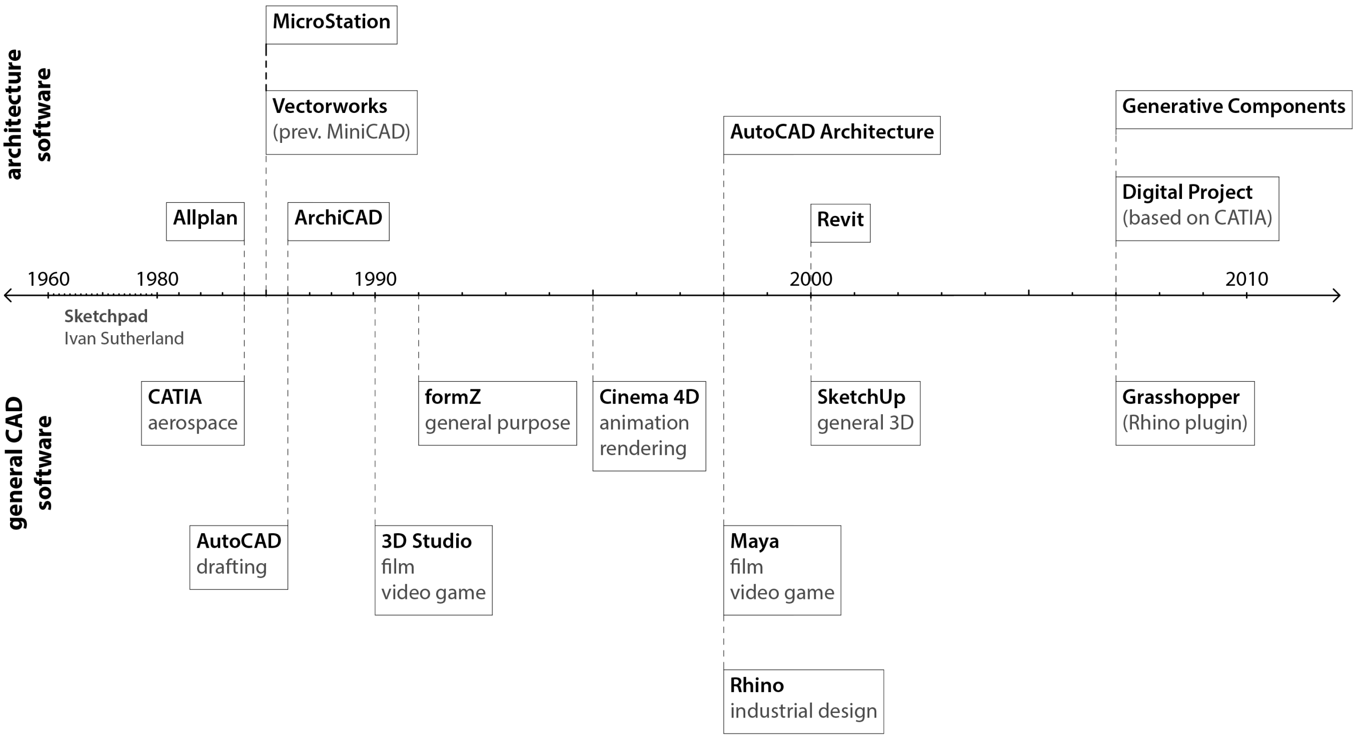


Figure 3.19 Release dates of CAD software between 1960 - 2010 (selection) (compilation based on various sources).

3.4. CAD usage

Today, architecture offices design almost exclusively with the support of digital equipment using a wide range of different CAD software. Common CAD software can generally be categorized in three groups. The first group is software operating on a low semantic level based on elements such as lines, arcs and splines, e.g. AutoCAD, which is mainly used for drafting and the production of 2D plans. The second group includes 3D modelling software such as Maya, Cinema 4D, 3D Studio, or Rhino and is mostly used for formal exploration, visualization, and rendering. The second type of software is not primarily targeted towards architects and offers - similar to drafting software - elements on a low semantic level. Hence, capitalizing on mathematics and advanced geometry, 3D modelling software have the ability to invent new forms and produce shapes that traditional manual means cannot conceive (Yessios, 2011, p. 10). It allows to explore a wide range of geometrical forms and gives a level of freedom which is usually not found in specific architecture software. However, 3D modelling software is often not directly involved in the production of plans.

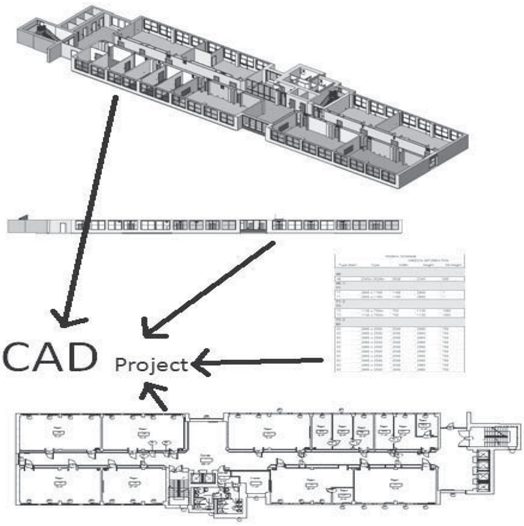


Figure 3.20 A CAD project with several, mostly uncorrelated and independently created files (Gaidytė, 2011, p. 154).

The third group of tools, BIM software, such as ArchiCad or Revit, is based on a high semantic level using parametric building objects like walls, windows, or doors. A BIM project comprises all information related to a building in a single project database. BIM software packages offer solutions for all design phases, from planning, bidding, to the construction process. The difference between BIM and traditional CAD (especially 2D) is that individual CAD files or documents (e.g. floor plan, section, elevation, and listings) consisting of lines and texts have no inherent meaning or intelligent connection between building elements. As an example, changes made to the floor plan are not automatically reflected in the section or the 3D model.

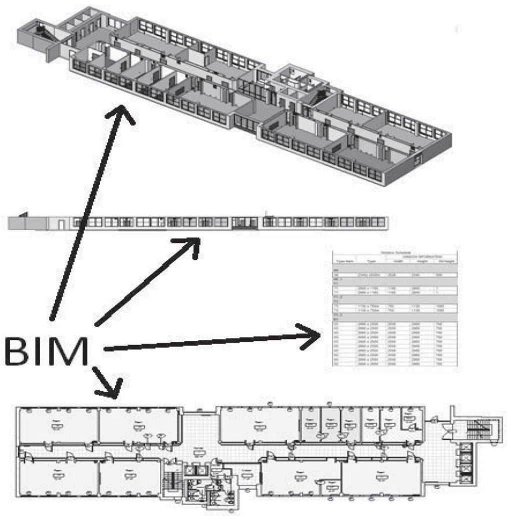


Figure 3.21 A BIM project with all information related to a building in a single project database (Gaidytė, 2011, p. 154).

The vast majority of architecture and construction has a conventional approach to design and uses standard construction methods and details (Aish, 2003b, p. 245). This is also reflected in the choice of software used in mainstream architecture. BIM and conventional 2D CAD software dominate the computer use in architecture today. What is common to both is that "entities or processes that are already conceptualized in the designer's mind are entered, manipulated, or stored in a computer system" (Terzidis, 2003, p. 67). As a result, highly specialized software often reenforces architectural conventions and leaves little exploratory freedom (Aish, 2003b, p. 245). Particularly BIM systems have "little concern about the generation of innovative forms, but rather concentrate on recording and making available the data required to support the production of construction drawings, engineering calculations, and ultimately the management of the completed building" (Yessios, 2011, p. 10). Still, the benefits of BIM software in the building process often outweighs its limitations on the design side. In 2010, a report by McGraw-Hill Construction surveyed BIM adoption in three European countries. The report showed that 60% of the architects in the United Kingdom, 40% in France, and 43% in Germany adopted BIM in their practices (McGraw-Hill Construction, 2010). A similar survey conducted by McGraw-Hill Construction among North American companies in 2009 revealed that the overall BIM adoption levels are lower in Western Europe compared to North America.

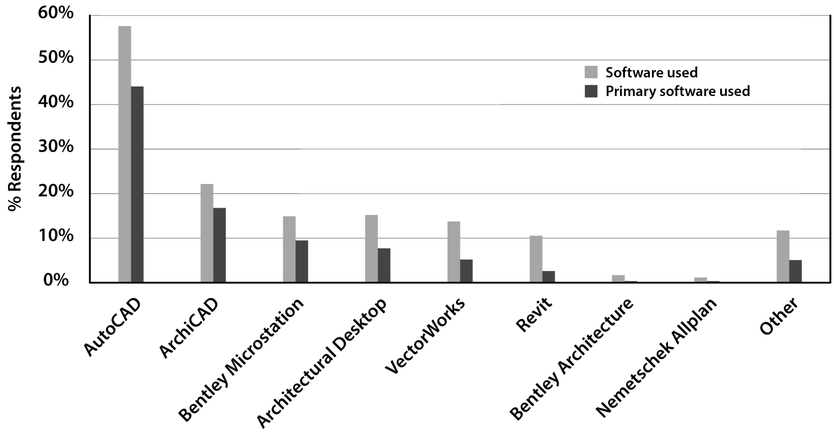


Figure 3.22 CAD products used by architects in the UK in 2008 (sample size = 839) (after Revelation Research, 2009, p. 3).

However, comprehensive studies of individual CAD software used in international architecture offices are rare to find. A user survey, conducted in 2008 among the architectural community in the United Kingdom (Revelation Research), showed that AutoCAD dominates the architectural sector with 58% using this software, followed by ArchiCAD adopted by 22% (Fig. 3.22). The study also shows that over 40% of architects use 2D drafting software as their primary product.

Looking at user satisfaction, the functions offered by the CAD software seems to satisfy the majority of the market (Fig. 3.23). Among all products surveyed, ArchiCAD and Revit, both using BIM technology, receive the best satisfaction ratings in almost all categories. The only weakness of these two products seems to be collaborating with consultants, which can be compensated using AutoCAD with the best rating for collaboration. Conversely, AutoCAD and Architectural Desktop receive low ratings and ArchiCAD receives over 90% user satisfaction for quality visualizations. An interesting result of this study is that 65% of all CAD users said they are "very likely" or "quite likely" to recommend their primary CAD product to others. According to this study, only 10% are unlikely to do so.

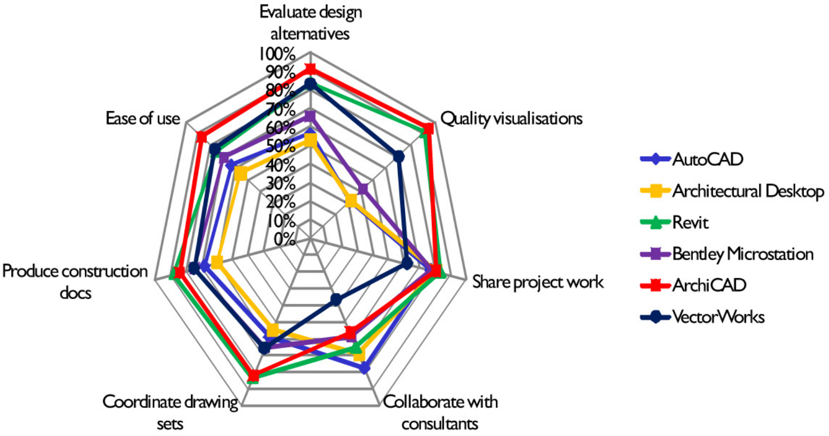


Figure 3.23 User satisfaction with CAD product functionality (sample size = 751) (Revelation Research, 2009, p. 4).

Despite high user satisfaction with commercial CAD software, each application creates a framework of possible and impossible shapes and operations. Depending on these design possibilities, architecture is at risk of being dictated by the language-tools software applications use

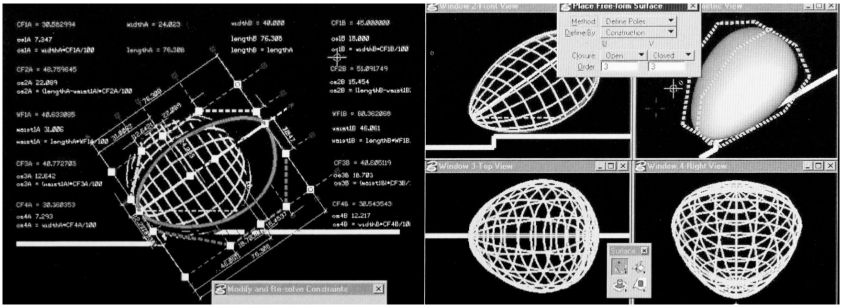
(Terzidis, 2003, p. 69). Contrary to conventional architecture projects, the majority of the avant-garde projects challenge common geometrical concepts and design processes. Especially generative and algorithmic design expands the restrictions and limits of mainstream CAD modelling language. Algorithmic design "involves the designation of software programs to generate space and form from the rule-based logic inherent in architecture programs, typologies, building code, and language itself" (Terzidis, 2003, p. 68). Algorithmic design utilizes computational power and complexity, and presents a creative use of computers in the design process. Using scripting tools, allows to overcome the factory-set limitations of prevalent standardized and centrally developed software products (Terzidis, 2003, p. 68). Software tools used in offices such as Gehry Partners, Foster + Partners, dECOi Architects, or ABB Architekten have either been adopted from other design disciplines or are custom-developed solutions for a specific project. Technological developments in other industries such as automobile, ships and airplane led to a complete reinvention of how products like cars, ships, and airplanes are designed, developed, analyzed, and tested (Kolarevic, 2003c, p. 10). In comparison to other design industries, architecture operates under different framework conditions. There are still potentials in design and production which architecture could take advantage of during various stages of the design process.

3.5. Mechanisms of know-how transfer

Architecture has always been a heterogeneous professional field, situated between arts, science and engineering. With the advent of digital design and production, the architectural realm is also influenced by developments in the digital field. Many design tools and methods used in architecture today have primarily been developed in other disciplines, such as car manufacturing, aerospace, computer science or the film industry. With time, technological know-how from these disciplines diffused into architecture and was integrated into mainstream architecture. As an example, the development of digital rendering techniques in computer graphics led to visualization of architecture projects using digital modelling and rendering software which became a professional specialization within architecture. As a result, drawing project visualizations for competitions or clients was often outsourced to specialists. With time, rendering algorithms became standard tools in most CAD software. Today, 3D modelling and digital rendering are an elemental skill of any architecture graduate, and in most cases architectural visualizations are again created in architecture offices by younger architects. New fields are emerge for architecture consultants, especially in the area of complex geometry and building performance consulting.

It seems that architectural education plays an important part in the adaption of skills and technologies in architecture. Until the late 90s, students were often not allowed by their professors to use CAD for their projects and threatened to receive a failing grade if they would (Marx, 2013). The design process as an individual act is established and very much shaped by an architect's education. The generation of architects that preceded CAD use during their studies is probably unlikely to organize their design process around digital tools.

Today's examples of technological developments and know-how which are diffusing into mainstream architecture are design by scripting, optimization of complex shapes, digital production techniques, and building performance simulation amongst others. The demand for skills in these areas offers the opportunity for specialists not necessarily trained as architects to act as architectural consultants. The realization of geometrically complex forms requires advanced knowledge of geometrical principles and application in architectural geometry. However, this know-how is for the most part not available in mainstream offices. In order to understand the design process behind projects such as the Walt Disney Concert Hall (Gehry) or the London City Hall (Foster + Partners), it is important to take a closer look at the office structure of some of these studios. Besides design teams, these offices often have specialized groups which are dedicated to research and development of digital media. In 1997, Foster + Partners established the Specialist Modelling Group (SMG) as part of the office structure. With only seven members in 2006, the SMG was involved in over 100 projects, and played a crucial part in the most prestigious projects of Foster + Partners. The SMG comprises knowledge of architecture, design, mathematics, geometry, and computing to consult the design team in project workflow, advanced 3D modelling, and the creation of custom-built design tools (Peters & DeKestellier, 2006, p. 2). Offering consultancy within the office, the SMG is involved in all stages of the design process from concept design to manufacturing. Built examples are the City Hall (Fig. 3.24) and the Swiss Re office tower in London. The design process at Foster + Partners is characterized by a variety of digital and non-digital means, whereby rapid prototyping closes the loop between digital and physical (Whitehead, 2003, p. 86). The SMG closely collaborates with the design team as well as the model shop.



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CF1A = 30.582994          widthA = 24.023      widthB = 40.000      CF1B = 45.000000
os1A 7.347                                     lengthB 76.308       os1B 18.000
os1A = widthA*CF1A/100    lengthA = 76.308     lengthB = lengthA    os1B = widthB*CF1B/100

CF2A = 48.759845                                                    CF2B = 51.091749
os2A 22.089                                                         os2B 15.454
os2A = (lengthA-waist1A)*CF2A/100                                   os2B = (lengthB-waist1B:

WF1A = 40.633085                                                    WF1B = 60.362068
waist1A 31.006                                                      waist1B 46.061
waist1A = lengthA*WF1A/100                                          waist1B = lengthB*WF1B.

CF3A = 40.772703                                                    CF3B = 40.605119
os3A 12.642                                                         os3B 18.703
os3A = (waist1A)*CF3A/100                                           os3B = (waist1B)*CF3B/:

CF4A = 30.360353                                                    CF4B = 30.543543
os4A 7.293                                                          os4B 12.217
os4A = widthA*CF4A/100                                              os4B = widthB*CF4B/10
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Place Free-form Surface
Method: Define Poles
Define By: Construction
Closure: U Open V Closed
Order: U 3 V 3

Figure 3.24 Parametric model of the London City Hall, UK, built in 1998 by Foster + Partners (Whitehead, 2003, p. 85).

Challenging conventional forms also opened a market niche for independent geometry consultants in architecture. Geometry consultants assist architects in realizing geometrically complex forms. The firm "designtoproduction", based in Zurich and Stuttgart, describes itself as a consultancy for the digital production of complex designs. It was involved in projects such as the Mercedes Benz Museum (2005) in Stuttgart, the Zentrum Paul Klee (2004) in Bern or the Weltstadthaus Peek & Cloppenburg (2005) in Cologne. To aid the design and construction processes, "designtoproduction" developed a parametric model of interlinked geometry (e.g. Fig. 3.26). The parametric model allows changes made to one part of the building to be immediately reflected in the overall design.

Figure 3.25 Mercedes-Benz-Museum (2006) in Stuttgart, Germany by UN-Studio (UNStudio, 2012).

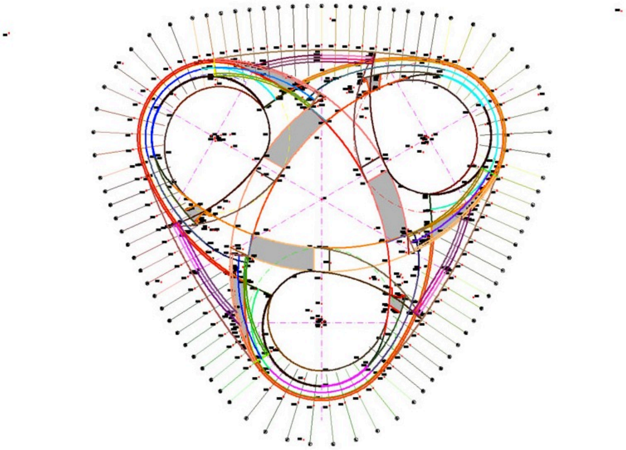


Figure 3.26 Parametric models of the Mercedes-Benz Museum by designtoproduction (Walz, 2012).

Figure 3.27 Zentrum Paul Klee (2004) in Bern, Switzerland, by Renzo Piano Building Workshop (Walz, 2012).

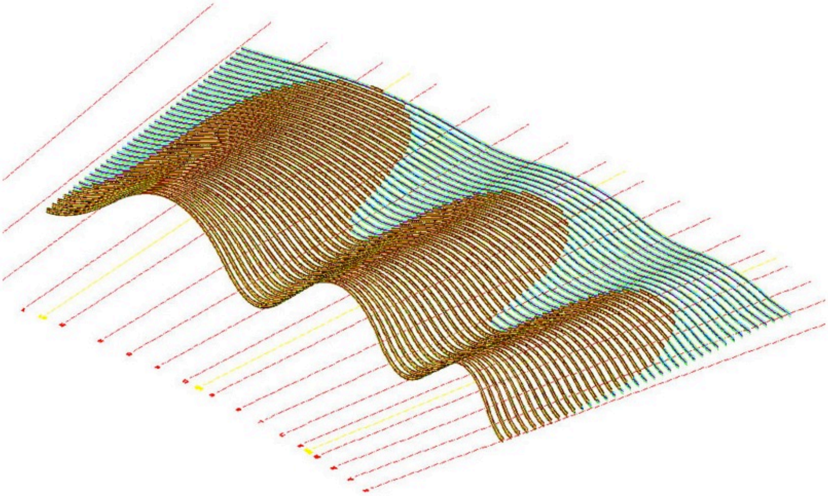


Figure 3.28 Parametric models of the Zentrum Paul Klee by designtoproduction (Walz, 2012).

While "designtoproduction" specializes mainly on large scale projects cooperating with well known offices, there is also growing demand for geometry consulting for smaller projects. Fostered by easily accessible 3D-modelling software together with advances in digital production, more complex shapes even in smaller scale projects become interesting and economically feasible to realize. The Vienna-based company "feasible geometry-consulting" supports architectural design and realization of geometrically challenging projects. feasible geometry-consulting offers support in digital design and production processes. Their approach makes not only complex architectural designs buildable, but feasible geometry-consulting develops custom designed software tools for architects. The company specializes in scripting customized plugins for the Rhino modelling software which are used by the architects themselves. The priority is to develop plugin tools while considering geometrical and productional issues. Example projects are shown in Fig. 3.29 to Fig. 3.34.

Figure 3.29 Lower Austria Regional Exhibition (2011) in Hainburg, Austria, pla.net architects (Reis & Schmiedhofer, 2012) © Klaus Pichler.

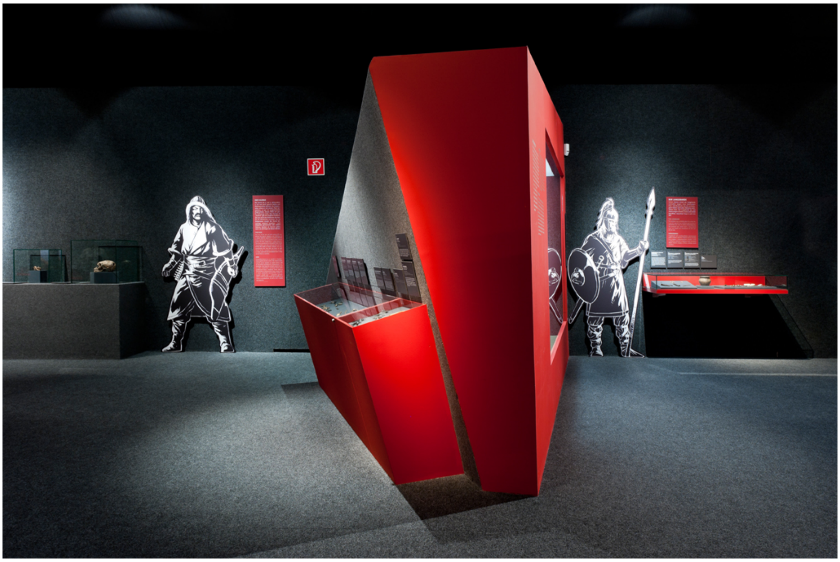


Figure 3.30 Lower Austria Regional Exhibition (2011) in Hainburg, Austria, pla.net architects © Klaus Pichler (Reis & Schmiedhofer, 2012).

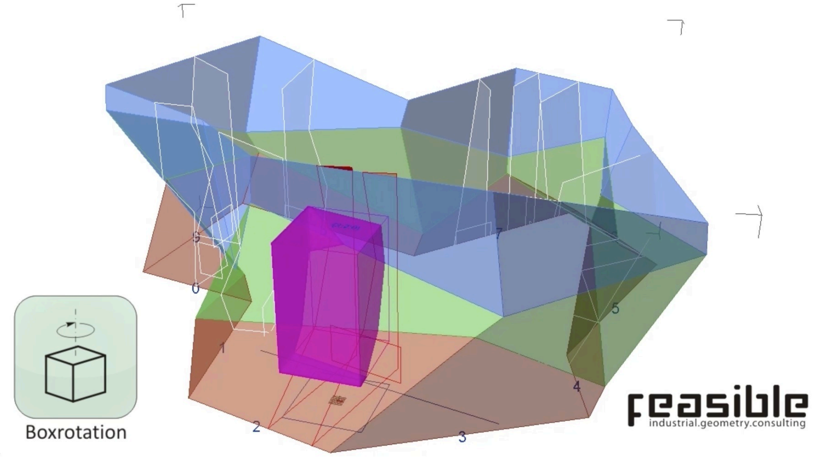


Figure 3.31 3D model of an exhibition showcase; design-tool by feasible geometry-consulting (Reis & Schmiedhofer, 2012).

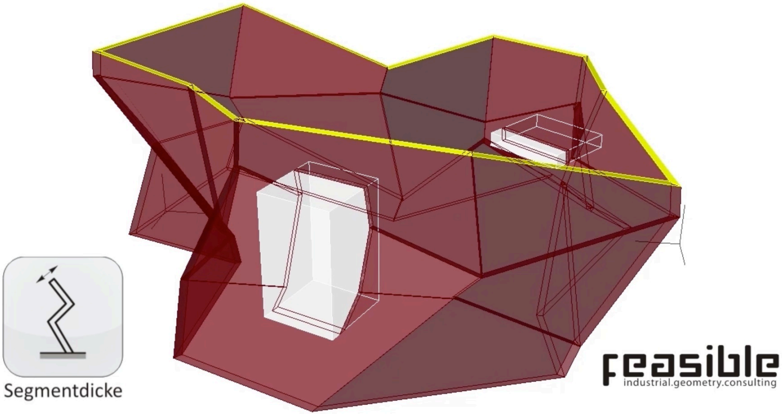


Figure 3.32 3D model of an exhibition showcase; design-tool by feasible geometry-consulting (Reis & Schmiedhofer, 2012).

Figure 3.33 Sportalm flagship store (2009) in Vienna, Austria, architect Baar-Baarenfels (Reis & Schmiedhofer, 2012).

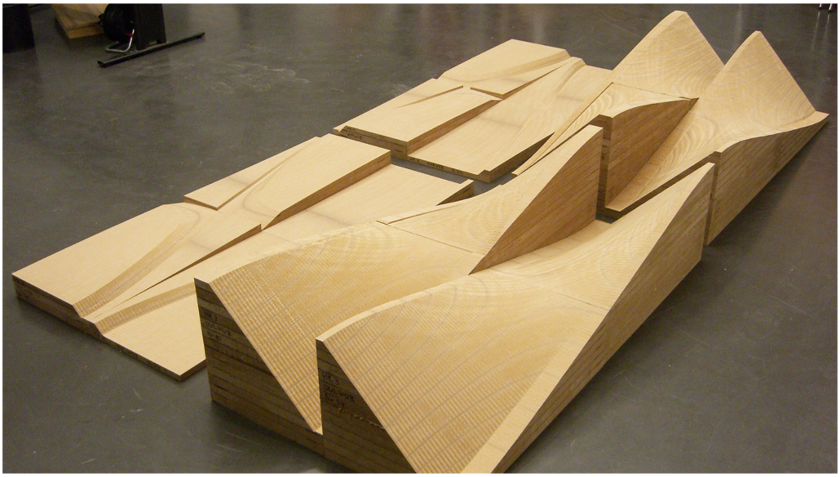


Figure 3.34 Wooden molds for wall elements; design-tool and molds by feasible geometry-consulting © Augustin Fischer (Reis & Schmiedhofer, 2012).

As a general principle, new technologies are first adapted by a few mostly larger pioneer offices. In most cases, only prestigious or large-scale projects can economically and technically afford to experiment with new technologies, whether it involves custom software development, specific production techniques, or new materials. The complexity and variety of different fields related to the architecture profession, creates a demand for technological know-how which does not yet exist in mainstream architecture offices. This leads to an opportunity for consultants specializing in digital technologies in various phases of architectural projects, varying from visualization, analysis, to production.

Experts in the field of digital design and production are mostly associated with leading architecture studios, universities, or research institutions. Students and new graduates are among the first exposed to new developments in digital design. The SmartGeometry Group is an example of an independent research institution whose goal is to advance education and research in the area of architecture and geometry, with a focus on applications for parametric modelling and generative scripting (Peters & DeKestellier, 2006, p. 11). Founded in 2001, the Smart-

Geometry Group includes experts from Foster + Partners, Arup Sport, Bentley and KPF. Annual workshops and conferences organized by the SmartGeometry Group bring together professionals and academics, creating an opportunity to exchange latest state of the art in digital design. The basis of most technological advances is established at universities and research institutions. Students and new graduates with an interest and education in digital technologies bring new knowledge and skills to architecture offices. Giving students an opportunity to participate in this field becomes an essential task in future architecture education.

4. Digital design process

This chapter analyses several digitally-based design methods using case study projects showing different approaches of digital media in the design process (Fig. 4.1). To summarize, the effects of digital tools on the design process are identified. The difference between digital and traditional (non-digital) design methods is not primarily visual representation (whether a plan or a digital 3D model), but how a design is developed. When using traditional design methods, the architect articulates a form; in a digital design method, the architect creates a generative logic of a design. Kolarevic describes this as "digital morphogenesis" in which "digitally generated forms are not designed or drawn as the conventional understanding of these terms would have it, but they are calculated by the chosen generative computational method" (Kolarevic, 2003a, p. 13). In a digitally driven design method, "designers articulate an internal generative logic, which then produces, in an automatic fashion, a range of possibilities from which the designer could choose an appropriate formal proposition for further development (Kolarevic, 2003a, p. 13). Examples for generative digital design methods are parametric design, datascape, and evolutionary design.

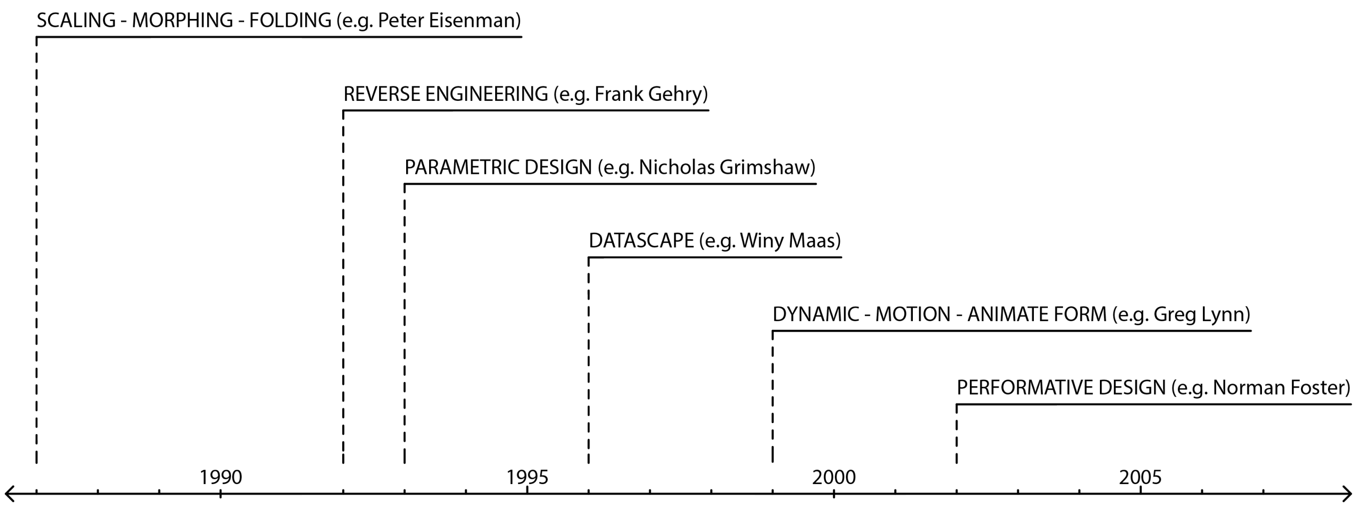


Figure 4.1 Timescale of digitally based design methods of case study projects (compilation based on various sources).

4.1. Case studies of digital design methods

Design methods are the general and underlying principles by which architects derive a design independent of a specific assignment. Architectural theory identifies a multitude of design methods, among others the use of natural, geometrical, mathematical or musical models; the use of precedents as a model (typology), rationalistic approaches, accidental, and surrealistic approaches, regionalism, contextualism as well as generative processes such as parametric design, datascape, evolutionary design, or morphing.

There are several prominent projects and buildings where architects and engineers exploited the generative potential of digital design. When commonly used technology was insufficient, some projects took advantage of software tools and know-how originally developed and used in other disciplines such as ship, aircraft, and automobile design. Historically, architects have always adapted processes, methods, and materials from other disciplines (Kolarevic, 2003c, p. 10). The transfer of know-how has challenged existing norms of practice and evoked innovation within architecture. Exemplifying the generative potential of digital technologies, the following case studies illustrate digitally supported design methods. It had been these and other innovative projects that pushed the development of digital tools in design and production. As a result, many of these technologies became commonplace in mainstream architecture today.

Reverse engineering

> *"... the principal story is that CAD/CAM saved the day..."*
> *(Glymph, 2003, p. 109)*

Figure 4.2 Model of the Walt Disney Concert Hall (2003), in Los Angeles, USA, architect Frank Gehry (Glymph, 2003, p. 111).

The Walt Disney Concert Hall (2003), Los Angeles, USA, by Frank Gehry is a prototypical example documenting the evolution of the digital design process. With the competition starting in 1988, it took 15 years to complete the building. Meanwhile several other prominent projects had been completed by the office, such as the Vila Olimpica (1992) in Barcelona, the Guggenheim Museum (1997) in Bilbao, and the Zollhof Towers (2000) in Düsseldorf. All of these projects contributed in one way or another to the realization of the Walt Disney Concert Hall such that they "created a digital design and manufacturing software environment that would make the complex geometry of the project not only describable, but also producible using digital means" (Kolarevic, 2003b, p. 31).

Figure 4.3 Vila Olimpica (1992) in Barcelona, Spain, architect Frank Gehry (Glymph, 2003, p. 107).

Figure 4.4 Zollhof Towers (2000) in Düsseldorf, Germany, architect Frank Gehry (Glymph, 2003, p. 108).

To handle the geometry in these projects, Gehry adopted a design strategy in his studio referred to as "reverse engineering". Reverse engineering is the process of extracting the knowledge or design blueprints from anything man-made in order to obtain missing knowledge, ideas, and design philosophy (Eilam, 2005, p. 3). In architecture, "reverse engineering" is commonly used to refer to the design process adopted by Frank Gehry. The design process involves digital technologies as a "translation" medium in order to create a digital representation of the physical design model, the reverse process of CAM. Digitization can be performed through various 3D scanning techniques, such as manually or automatically operated digitizing position probes (Fig. 4.6) which have largely been replaced by 3D laser scanners. The result of the scanning process is a point-cloud, which is further translated into a digital surface model (Fig. 4.5). An important issue in this process is to accurately capture the original form and to fit the curves and surfaces as closely as possible to the digitized points in order to preserve the important nuances and subtleties of the original model (Mitchell, 2001, p. 358). With the help of rapid prototyping devices, like 3D printers or multi-axis milling machines, a physical model is fabricated for further design iterations. The aid of digital scanning tools allows a precise match of the original design idea and sketches to the actual manufactured design.

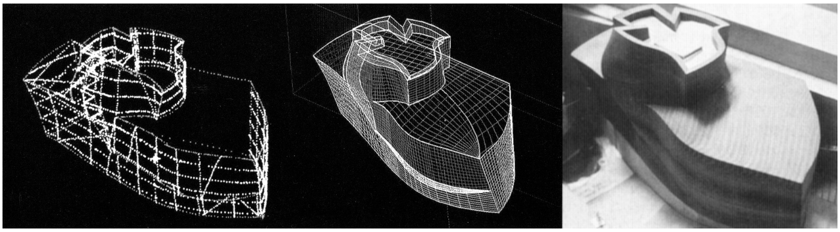


Figure 4.5 Translation process shown as digitized points (left), digital surface reconstruction (middle), CNC fabricated model (right) (Kolarevic, 2003b, p. 31).

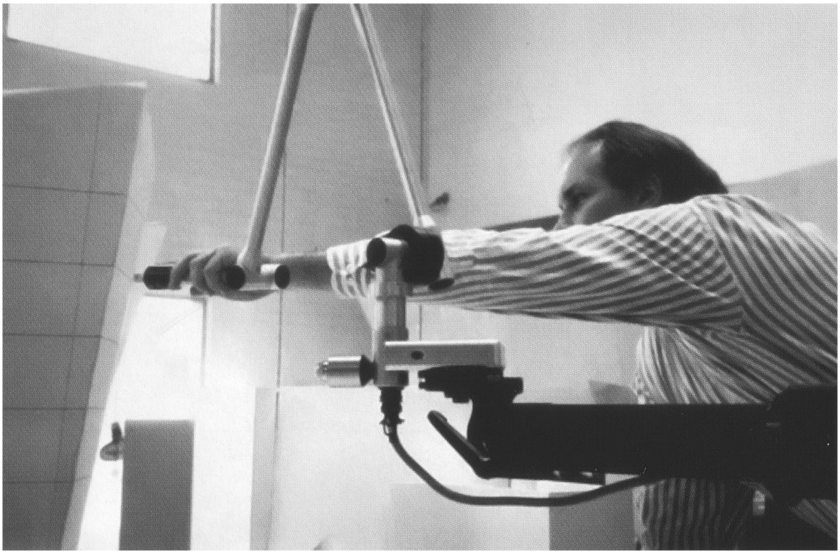


Figure 4.6 Digitizing a model of the Walt Disney Concert Hall (Glymph, 2003, p. 106).

The complex free-form geometry of the Walt Disney Concert Hall and other projects is heavily dependent upon the use of CAD software in all stages of design from the initial form finding, to structural analyses, up to digital fabrication (Szalapaj, 2005, p. 207). Due to the complexity of the geometry, Gehry's office was faced with a number of problems in design and construction processes. As a result, the project led to a notable change in the organizational structure within Gehry's studio as well as how the office worked together with other contractors. Prior to using CAD software, construction documentation was contracted out which led to errors and misunderstandings among the clients, which led to increased costs (Szalapaj, 2005). Consequently, Gehry changed his office structure and started to develop the whole project in-house, from the initial design to manufacturing and construction. This meant that the office had to gain the technical expertise of previously outsourced tasks. After running into problems with complex shapes, the studio referred to the French aerospace industry for help. As a result, the staff grew by several computer engineers and the office started working with the CATIA software (by Dassault

Systèmes), which at that time was used to design aircrafts, ships, and cars (Gehry, 1999, p. 49). CATIA software helped to transform the initial sketches, design ideas, and physical models into 3D CAD files for further design development and structural analysis, anticipating construction problems as well as calculating costs and quantities (Fig. 4.7).

"Reverse engineering" was used as an iterative design process with an exchange between physical and computer models. The physical design model was digitized, then further modified on the computer. From this digital model a physical model was again built using CAM for further design and technical tests such as acoustic performance (Fig. 4.9).

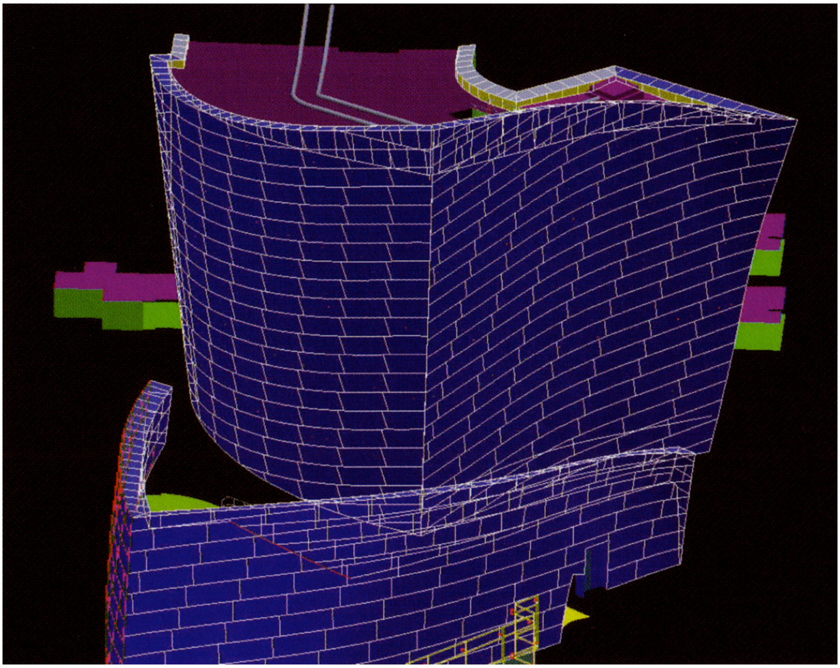


Figure 4.7 Surface pattern in CATIA of one part of the concert hall (Glymph, 2003, p. 118).

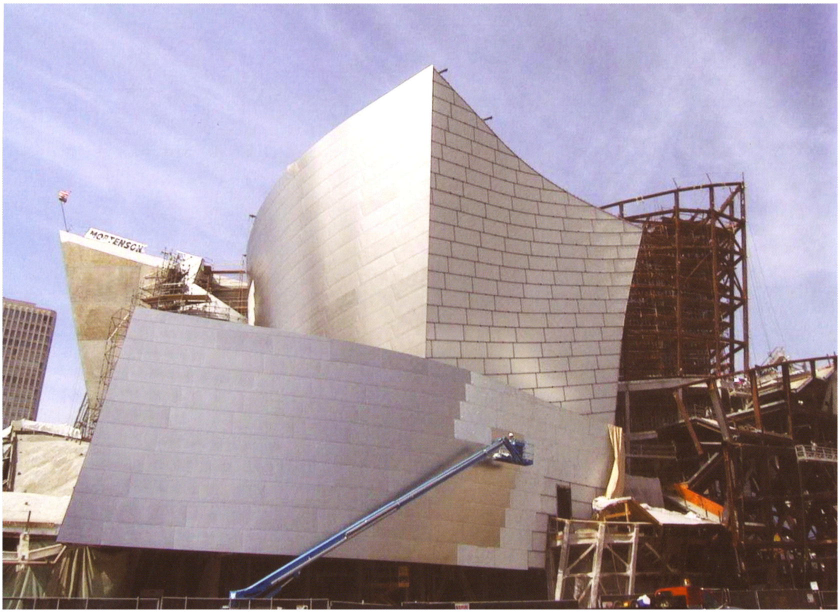


Figure 4.8 Installation of the cladding on the exterior of the concert hall (Glymph, 2003, p. 118).

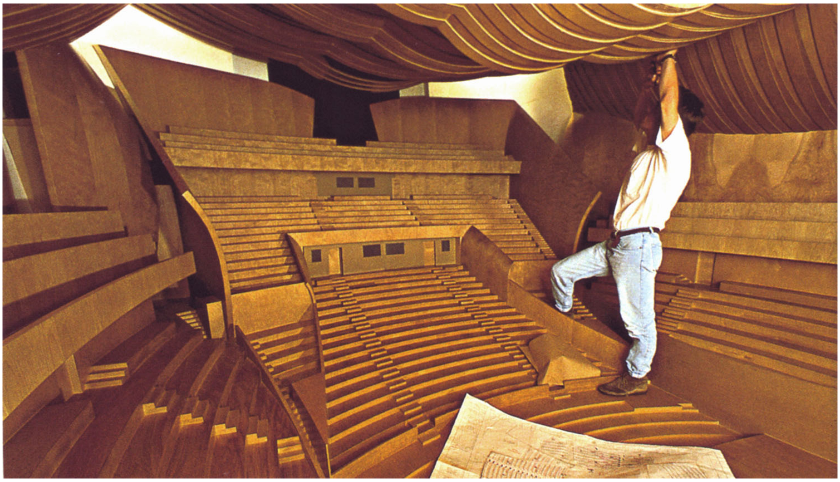


Figure 4.9 Acoustical study model of the Walt Disney Concert Hall, scale 1:10 (Gehry, 2001, p. 192).

One of the leading engineers in Gehry's office, Jim Glymph, reports that aesthetic modifications were all made using physical models, while the digital models was used for optimizing and patterning the surfaces and to make the system fit, e.g. with the steel structure model (Glymph, 2003, p. 106). The final digital surface model is then directly used to generate plans and sections for construction but more importantly also to drive the fabrication machine paths for the CAM process. What is revolutionary for that time, is that the whole design process was done in 3D, both physically and digitally. Jim Glymph explains that the success of Gehry's projects "had a lot to do with the way people used the computing tools, rather than the tools themselves, and the way people collaborated using the tools" (Glymph, 2003, p. 109). The implementation digital design tools in the design process can be seen as an enabler to realize the design ideas, which seemed to be impractical, unbuildable, and above all too expensive before.

The Walt Disney Concert Hall shows the influence of technological advances on the development of design and construction of architecture. Szalapaj projects, that "the way in which digital technologies are being used in Frank Gehry's office has immense significance for the future direction of architectural practice in general" (Szalapaj, 2005, p. 207). Gehry's projects also demonstrate the technological prevalence in a design process which almost exclusively works in 3D, both physical and virtual.

Scaling and morphing

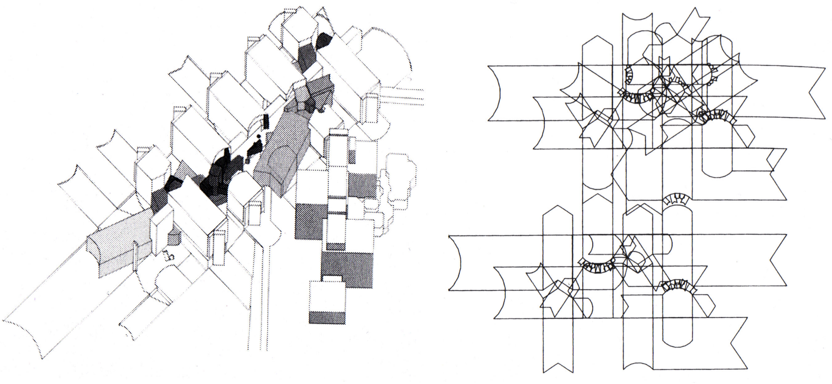


Figure 4.10 Biocenter (1987) University of Frankfurt, Germany, architect Peter Eisenman (Jormakka, Schürer, & Kuhlmann, 2008, p. 66).

In the mid-1980s, Peter Eisenman, a member of the architects group, New York five, experimented with a number of design techniques such as scaling and morphing. These methods can be described as image manipulation techniques which were facilitated by upcoming graphical digital design tools in the early 1980s: AutoCAD, Allplan, and ArchiCAD. Scaling for example, is the repetition of objects on various scales using graphical transformation techniques. These transformations can be easily performed using the basic geometric operations found in the first CAD systems: move, copy, rotate, and scale. The conceptual roots of scaling are argued to be found in fractal geometry which repeats similar figures independent of a specific scale. According to Eisenman, this notion of an independent scale can be compared to Jacques Derrida's (1930-2004) philosophical understanding that there is no originary source of meaning (Jormakka, et al., 2008, p. 66). Peter Eisenman applied the techniques of scaling in the Biocenter (1987) for the University of Frankfurt, Germany. The floor plan derives from overlaying the symbols of the bases of the DNA on a building's scale.

The technique of morphing originally described an image manipulation technique by which two or more images are gradually transformed into each other. This technique was traditionally used in the film industry and was immensely popularized with the release of the first morphing software for personal computers: Morph by Gryphon Software. Architects such as Peter Eisenman and Greg Lynn adopted this technique and applied it to buildings. In an architectural context, morphing operations are applied to 3D geometry and shapes. Offices like UN Studio, also refer to morphing on a more conceptual level. Morphing is used to express probabilities and uncertainty in the development of projects and thereby include the idea of motion and movement in architectural concepts. Technically, a morphing software computes a smooth, animated, and time-encoded transition between a "base" and a "target" object (Kolarevic, 2003a, p. 22). This morphing sequence generates different states of an object from which the designer could choose a state for further development. Examples of forms generated through morphogenesis are the Üstra Office Building (1999) in Hannover, Germany by Frank Gehry, or the competition entry for the Welsh National Opera House (1994) in Cardiff, Wales by Greg Lynn. Morphing addresses the idea of movement which becomes more explicit in design methods including dynamics and fields of force.

Figure 4.11 Üstra Office Building (1999) in Hannover, Germany, architects Frank Gehry (© thomas mayer_archive).

Dynamics and fields of force

One of the first architects using dynamic animation software as a tool to generate form was Greg Lynn. Lynn argues that animated design describes the evolution of a form and stores the motion and force at the moment of conception in its shape (1999). In that sense, architecture responds to internal as well as external forces based on a variable environmental and socio-economic context (Kolarevic, 2003a, p. 19). The Port Authority Bus Terminal competition project (1995) by Greg Lynn exemplifies the use of dynamic simulation software to generate the form of a protective roof and lighting scheme. Using particle systems, Lynn simulated the movement and flow of pedestrians, cars, and buses at different speeds and intensities (Fig. 4.12). The design tracks the gradient fields generated from these particle studies.

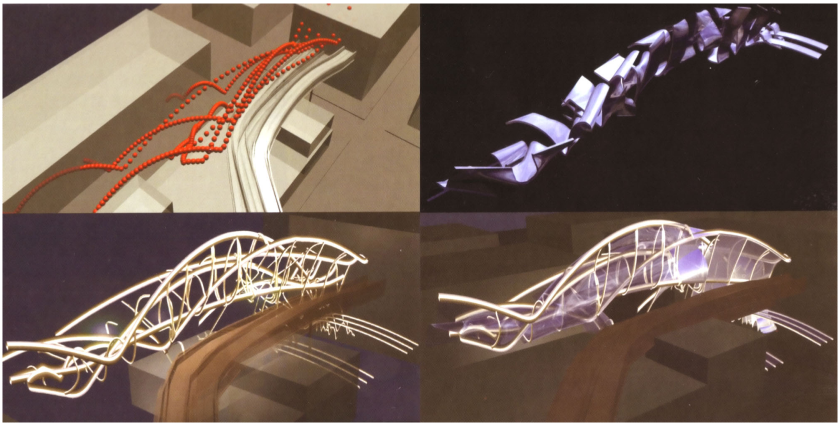


Figure 4.12 Competition for the Port Authority Bus Terminal (1995), New York, architect Greg Lynn (Kolarevic, 2003a, p. 20).

Another concept of dynamic form generation, isomorphic polysurfaces, is based upon parametric objects inheriting internal and reacting to external forces. Each object creates an interacting field of influence. Isomorphic polysurfaces are dynamically generated objects reacting to variations in their fields of influence. The resulting polysurface is computed where the composite field reaches the same intensity (Kolarevic, 2003a, p. 21). The design of the BMW Exhibition Pavilion (1999) at the IAA Auto Show in Frankfurt, Germany, by Bernhard Franken and ABB Architekten is based upon a digital model of isomorphic polysurfaces. Taking into account the brief by BMW, which was to express "clean energy", the architects generated the form of the pavilion by joining two drops of water. Following the physical behaviour of water, the forces of cohesion, gravitation, and surface tension are used to create the surface boundary of the pavilion (Fig. 4.14).

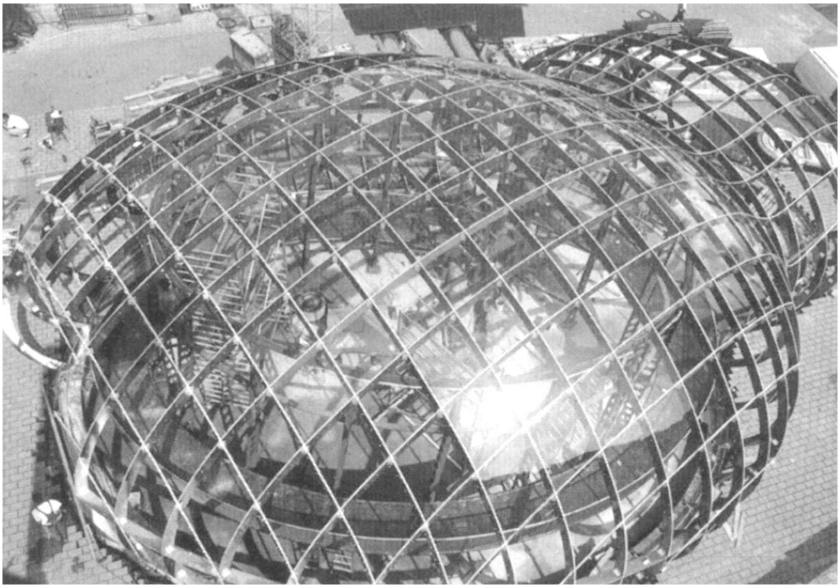
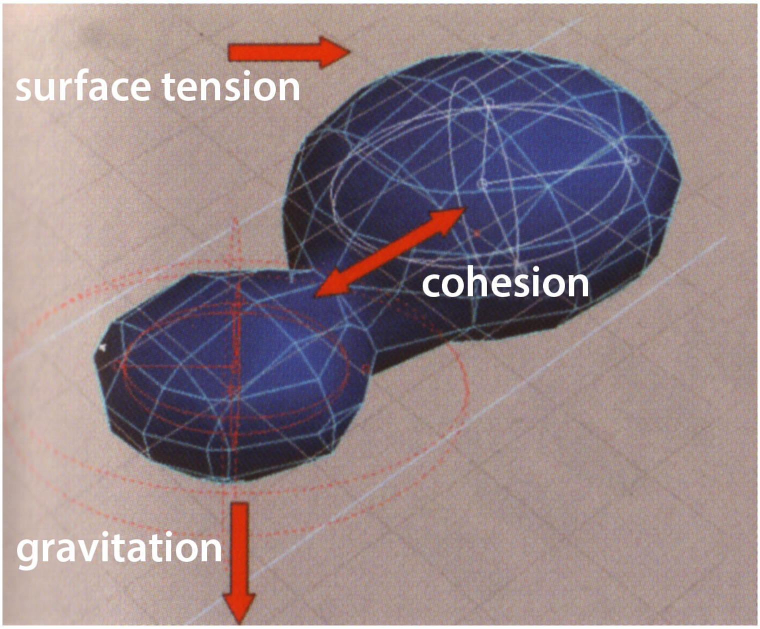


Figure 4.13 BMW Exhibition Pavilion (1999) at the IAA Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten (Franken, 2003, p. 134).



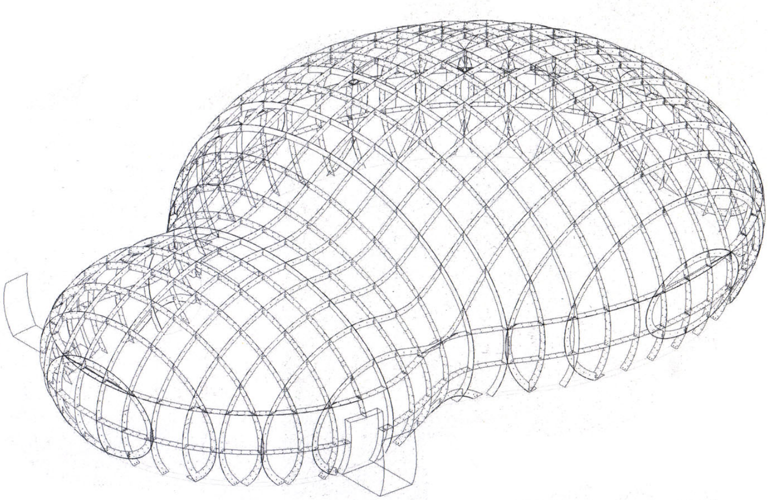


Figure 4.14 Interacting drops of water (top) (Kolarevic, 2003a, p. 21) and the translation into the three-dimensional model for the pavilion (bottom) (Franken, 2003, p. 132).

Parametric design

Parametric design[3], also referred to as algorithmic design or associative geometry, describes a design method using the manipulation of variables, parameters, or algorithms in order to generate formal compositions. This has led to various design methods, attempting "either to automate and enhance existing manual techniques or to explore new uncharted territories of formal behaviour" (Terzidis, 2003, p. 69). Compared to conventional (manual) design methods, it is usually the relations and dependencies of parameters which are declared by the architect, not the formal shape itself. Parametric design can be seen as an approach to selectively specify formal compositions on an abstract level. A schema consisting of dimensional, relational, or operative dependencies creates a variable geometrical representation (Kolarevic, 2003a, p. 17). The choice and interdependence of the parameters usually reflect the underlying architectural concept. As observed by Szalapaj, this manipulation of variables "leads to the generation of a range of formal possibilities, and is particularly useful in the systematic control of complex curved surfaces" (Szalapaj, 2005, p. 59). An important aspect is the ability to define, determine, and reconfigure the geometrical relationships (Kolarevic, 2003a, p. 18). Changes made to one variable are automatically applied to parts or the whole model depending on the underlying mathematical functions that define the dependencies of the geometry. However, to use parametric design in the early design stages, it is crucial that the outcomes are represented in visual form (Szalapaj, 2005, p. 59). Parametric design can be a very powerful and efficient modelling technique, as there is no need to manually redraw or remodel large parts when changes are made to the design. This design approach also allows to rapidly create various alternatives of a design and compare different results.

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[3] In digital architecture, the term "parametric design" is often overused and can be seen as redundant, given that probably all design is based on the evaluation of parameters during any given process. Grasping the sense of parametric design it is more accurately referred to as "associative geometry" (Burry, 2003, p. 149). However, for the purpose of this work the more common term parametric design will be used.

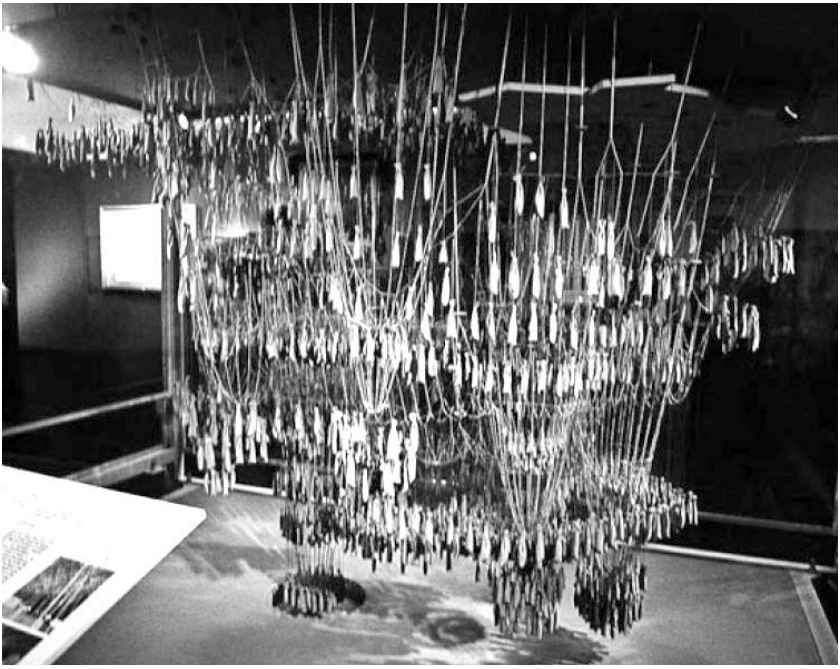

Figure 4.15 Catenary hanging model of the Cathedral Sagrada Familia, Barcelona by Antonio Gaudi (Gruber, 2010, p. 79).

Antonio Gaudi's (1852-1926) method of modelling catenary curves by suspending linked strings is often considered as an example of parametric design in a pre-digital era (Fig. 4.15). Gaudi's huge hanging models (4x6m) are based upon the principle, that a perfectly flexible and homogeneous string, suspended by its endpoints and affected by no other force than gravity, forms the shape of a perfect catenary curve (Gruber, 2010, p. 79). In theory, within a perfect hanging chain, only tension forces exist. Turning the shape upside down, creates a curve with optimal load transmission, as only compression forces appear. Having no lateral forces in a construction, allows to create a shape with a minimum of material and thereby allowing extremely fragile constructions. By varying the length of strings, their connection points, and applying weights, Gaudi created a system of interconnected or "parametric" strings whereas changes made to one element would automatically affect the shape of the whole system (Jormakka, et al., 2008, p. 77). Photographically documenting each configuration allowed Gaudi to compare and choose the final shape among multiple solutions. Similar experimental form-finding techniques had also been used by other architects like Frei Otto and Heinz Isler.

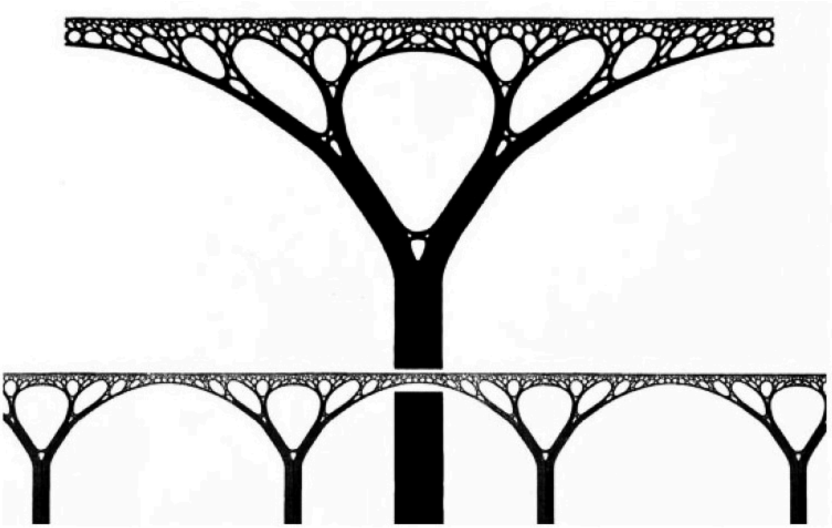

Figure 4.16 Soap film models by Frei Otto (Gruber, 2010, p. 80).

Architects also experimented with minimal and ruled surfaces long before computers arrived. The roof of the Catalano House (1954) in Raleigh, North Carolina, by Eduardo Catalano follows the geometrical principles of a ruled surface. The roof features the shape of a hyperbolic paraboloid constructed in wood using analog means (Fig. 4.17). The surface was generated by connecting two curves in space at regular intervals by straight lines (Mitchell, 2001, p. 355).

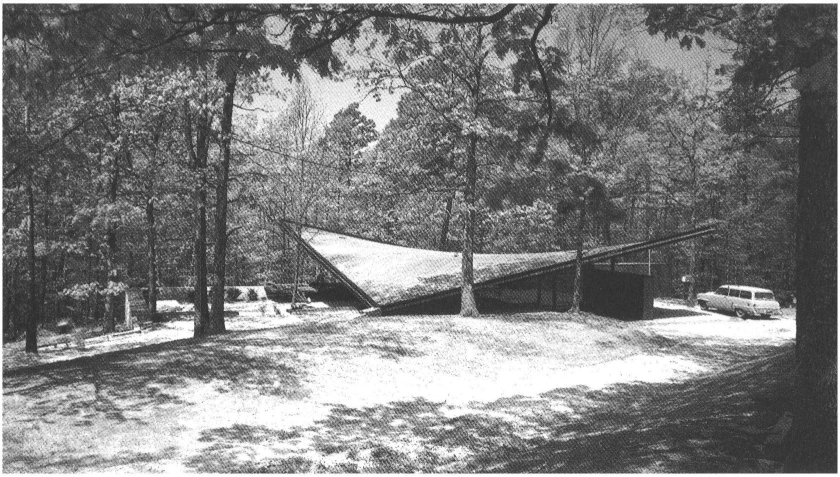

Figure 4.17 Catalano House (1954), Raleigh, North Carolina, architect Eduardo Catalano (Mitchell, 2001, p. 355).

The International Terminal (1993) at Waterloo Station, London by Nicholas Grimshaw and Partners exemplifies the concept of parametric design. The building is a 400 m long train shed with a glass roof supported by 36 three-pin bowstring arches. Due to the conditions of the site and the track layout, the shed shrinks from 50 to 35 m along the 400 m length of the building (Kolarevic, 2003a, p. 18). Each of the 36 arches distributed along the length of the shed is dimensionally different but topologically identical. All individual dimensions of the arches down to the connecting elements and cladding, are automatically created based on one generic parametric model, defining the relationship between the span and the curvature of the arches (Fig. 4.19).

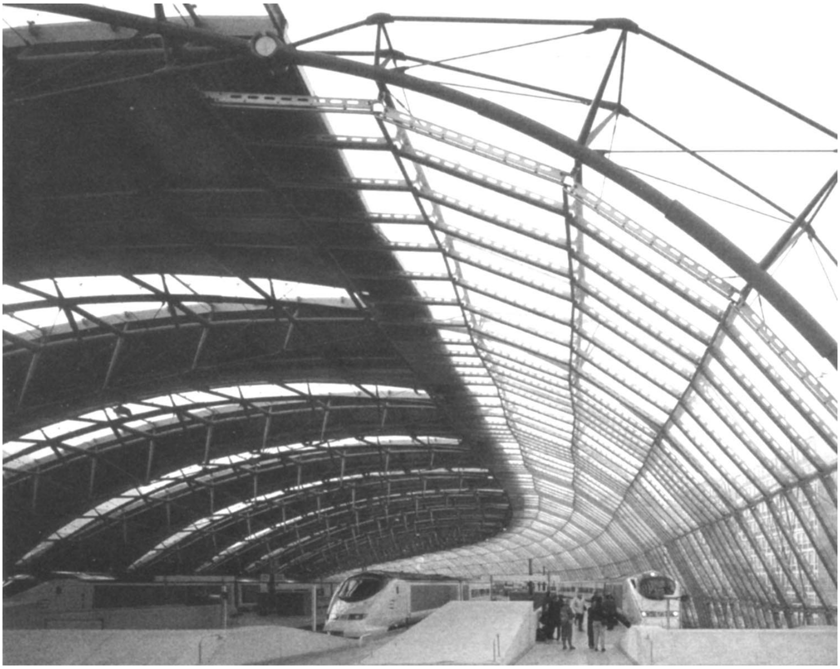

Figure 4.18 International Terminal at Waterloo Station (1993), London, architect Nicholas Grimshaw and Partners (Kolarevic, 2003a, p. 19).

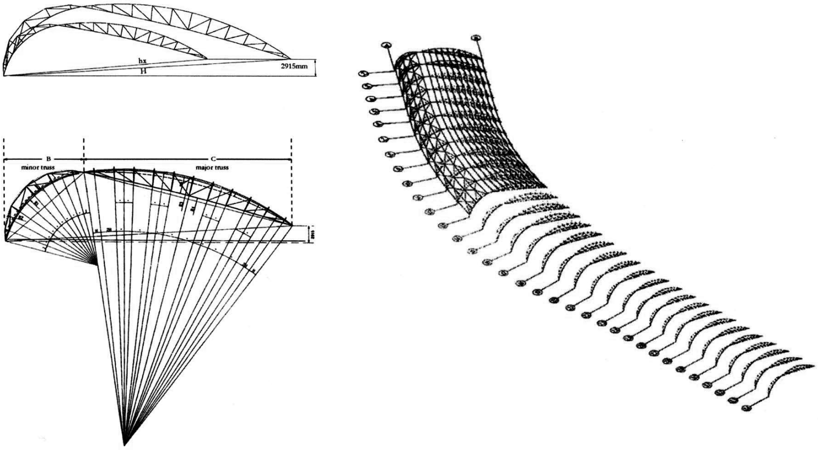

Figure 4.19 Parametric definition of the scaling factor for the truss geometry (Kolarevic, 2003a, p. 19).

The Swiss Re building (1998) in London by Foster + Partners is another example where a building is the result of a parametric design study. Relational geometry was used to describe the shape of the tower in a parametric model (Fig. 4.21). Changes made to the design allowed to flexibly redefine the complex curved shape along with its quadrilateral tiling throughout the design process.

Figure 4.20 Swiss Re (1998), London, England, architect Foster + Partners (Young, 2004).

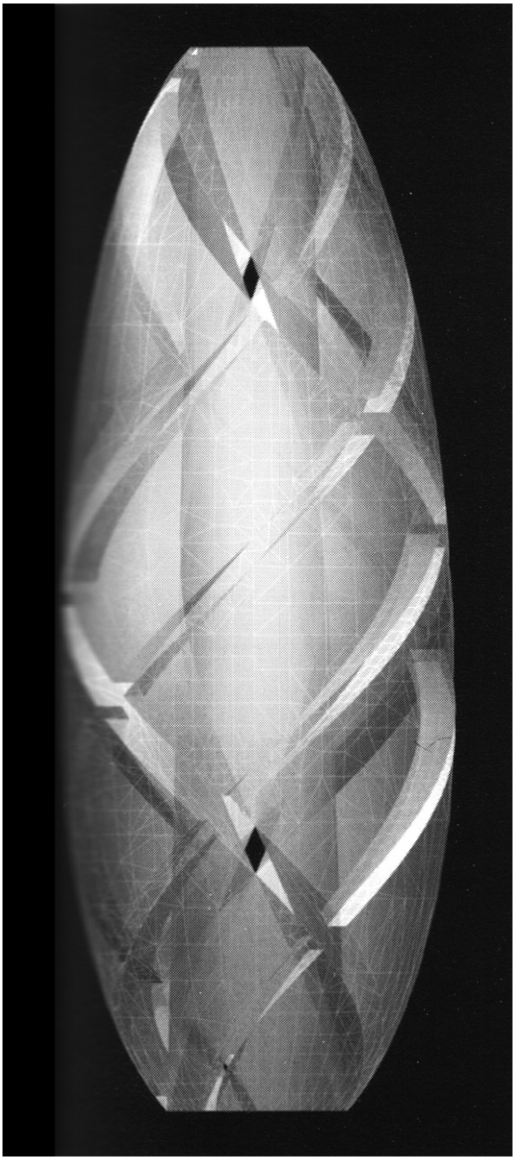

Figure 4.21 Parametric study for Foster + Partners, architect dECOi (Goulthorpe, 2003b, p. 173).

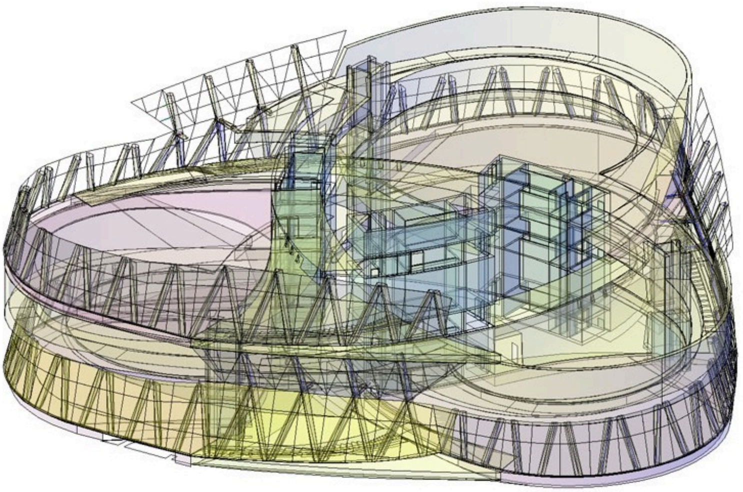

Figure 4.22 Parametric models of the Mercedes-Benz-Museum in Stuttgart by designtoproduction.

These examples show that a clear, coherent, and well-defined design strategy is crucial for the application of parametric design. According to Kolarevic, "for the first time in history, architects are designing not the specific shape of the building but also a set of principles encoded as a sequence of parametric equations by which specific instances of the design can be generated and varied in time as needed" (Kolarevic, 2003a, p. 18).

Another design method related to parametric design is datascape. This method, was coined and mainly developed by Winy Maas, a partner of the Dutch studio MVRDV. He uses existing rules and constraints such as regulations in the building code, fire escape routes, or natural site conditions like the sun and wind as a starting point for a design. Often, these rules are extrapolated ad absurdum like in the project Monuments Act 2 (1996) by MVRDV and used with a touch of irony (Jormakka, et al., 2008, p. 71). Maas' design investigates the possibilities of densification of an inner court of a 18th-century building block in Amsterdam. The resulting design purely represents geometrically one parameter of the building code, namely that the building should not be visible from the street (Fig. 4.23). Architectural considerations and all other regulations are deliberately ignored. Based on a complex and vast quantity of geometrical information, this kind of design can easily be realized using digital modelling tools. An initial starting volume is carved out based on the existing building geometries and the lines of sight from certain positions. Another emerging design strategy related to parametric design is performative design.

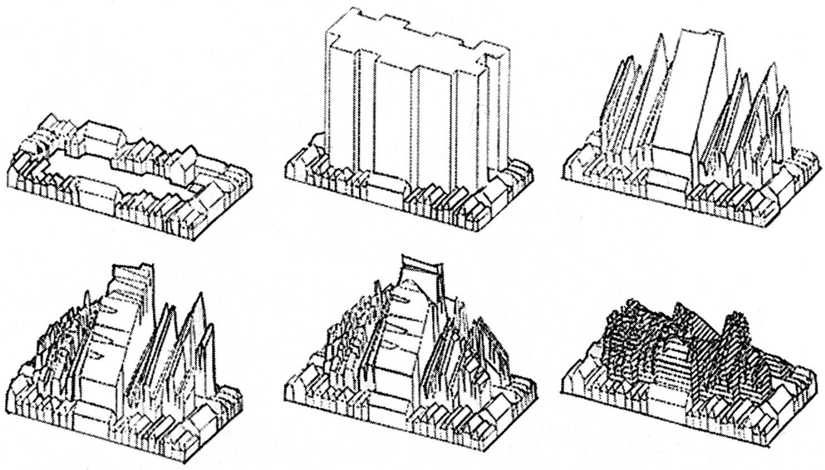

Figure 4.23 MVRDV, Monuments Act 2 (Jormakka, et al., 2008, p. 72).

Performative design

Performance-based design or performative design takes building performance criteria as guiding design principles. Performance characteristics of buildings can be the thermal, acoustical, or structural performance but also life safety, organizational, financial, or social aspects. The design of a building therefore reflects the chosen performance criteria. This simulation-based design approach is heavily dependent on digital technologies. Data intensive simulations are usually performed using digital 3D models and represented using visualization techniques. The goal of this design technique is to find the best fitting solution among various design alternatives and to optimize this solution according to the chosen performance criteria (Kolarevic, 2003a, p. 25). Although the analytical methods behind these quantitative simulations such like fluid dynamics or energetics are quite complex, a graphical output allows non-specialists in these fields to also interpret the results and make design decisions based upon the results. This design method is not limited to buildings but can also be applied to landscapes, infrastructures, and even whole cities.

Figure 4.24 City Hall (2002) London, UK, architect Foster + Partners (© Reza B. Assasi 2013).

An illustrative example of performance-based design is the City Hall (2002) in London, UK, by Foster + Partners (Fig. 4.24). The building is positioned on the River Thames next to the Tower Bridge and houses the headquarters of the Greater London Authority including the London Assembly and offices of the mayor. The iconic shape of the building reflects analytical studies of the energy and acoustical performance of the building. The outside shape follows the form of a contorted sphere as a sphere by itself already has a 25% smaller surface area than a cube of identical volume (Kolarevic, 2003a, p. 26). A smaller surface area results in reduced solar gains in summer as well as lower heat losses in winter. Hugh Whitehead, head of the modelling team at Foster + Partners, describes the chosen shape:

> "The inclined form allows maximum of sunlight to reach the riverfront walkway, the roof presents the minimum surface to the sun, and transparent glazing is restricted to the north-facing atrium, while the south facade is self-shading." (Whitehead, 2003, p. 88)

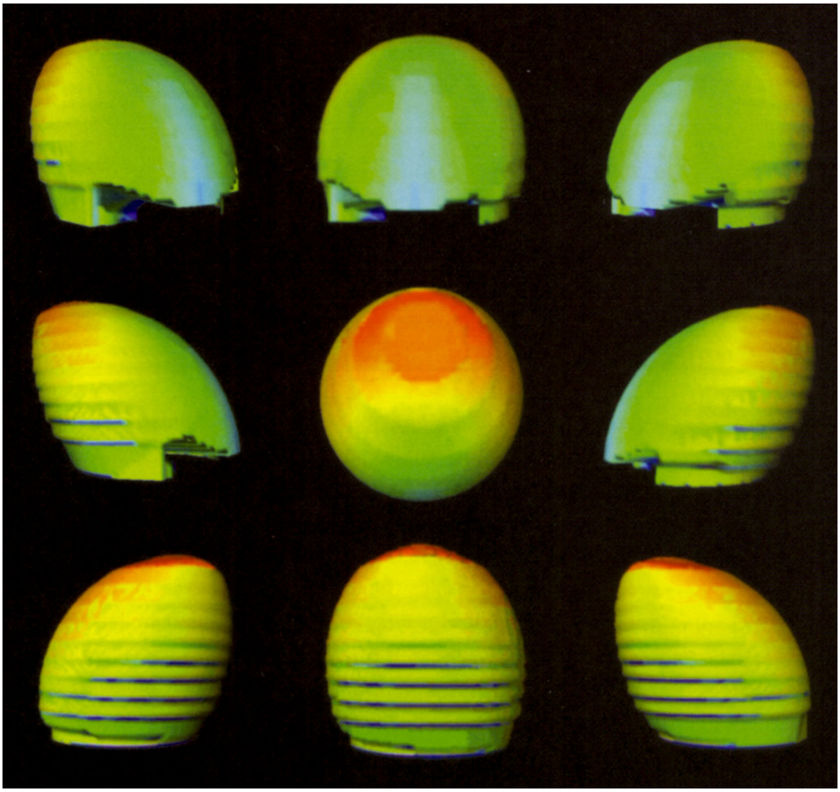

Figure 4.25 Solar studies for the City Hall building (Whitehead, 2003, p. 86).

The design team created a parametrically controlled model of the building which allowed the designers to relatively easily produce several alternative solutions for further test and design developments. Arup, an engineering consultant company produced an energy performance simulation of the building. The outcome of the study graphically showed the total amount of solar gain of each cladding panel (Fig. 4.25). A colour-coded digital model drove the glazing system to an optimal solution and indicated the ideal position of solar panels (Whitehead, 2003, p. 86). While the outside shape was defined by energy performance criteria, the interior, particularly the large debating chamber hall, was optimized according to acoustical properties (Fig. 4.26). These simulations led to an acoustically ideal glazing positioning. The resulting dynamic blob-like shape not only follows aesthetic design considerations but takes account of energetic and acoustic criteria.

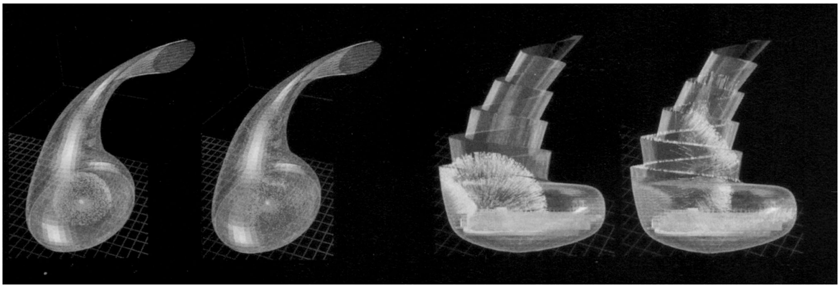

Figure 4.26 Acoustical analysis of alternatives for the City Hall debating chamber (Whitehead, 2003, p. 88).

An interesting detail of the project is the way how the design team communicated with the manufacturers. Opposite to Gehry's approach of only exchanging digital 3D geometry, Foster's design team chose to post-rationalize the complex geometry. For the manufacturing process, only arc-based curves were used to describe the building geometry (Fig. 4.27). While CAD systems can easily handle free-form surfaces and offsets created from complex curves, a geometrical simplification proved particularly useful for the manufacturing and construction process. The result was a significant reduction of data, especially for the cladding surface, and resulted in easier communication and accurate data exchange with the manufacturing companies (Whitehead, 2003, p. 87). An in-house developed software automatically produced a 2D plan of the glazing panels which was then given to the fabricators and contractors.

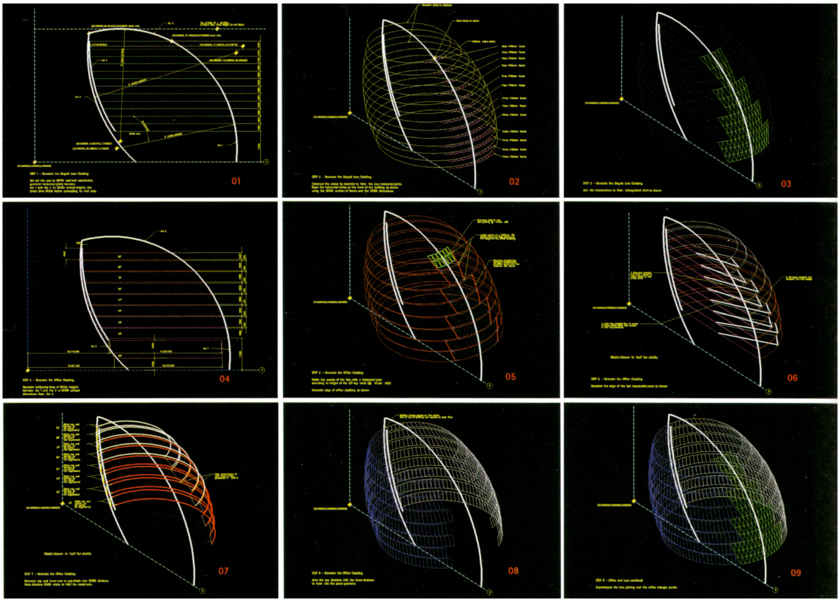

Figure 4.27 Post-rationalization of the geometry using only arc-based curves (Whitehead, 2003, p. 90).

The City Hall project illustrates a project which takes into account several different aspects - functional, spatial, sculptural, structural, and environmental (Whitehead, 2003, p. 88). This project also required to custom-built digital tools in order to be able to combine all these aspects in an optimal solution. Foster + Partners used a variety of digital and non-digital means in the design process. Besides digital simulations and modelling, the design process of the City Hall also involved rapid prototyping using CNC fabrication to produce prototypes and physical models. According to Whitehead, key decisions were still made based on physical models (Whitehead, 2003, p. 84).

While it is already very common to simulate the performance of a building after its design has been defined, the strength, but also the challenge of performative architecture, still lies in a dynamic computation of the performance targets. Instead of using simulation techniques after a certain building shape has been articulated, several solutions ranging from the most unoptimized to the optimal solution were produced. The target criteria could be dynamically visualized in a transformation of a defined generic shape while preserving the overall topology of the model (Kolarevic, 2003a, p. 26). In that way, the designer could also choose in-between solutions, when an optimal solution according to the defined parameters does not fulfill aesthetic or other non quantifiable criteria.

One may argue that many of the afore mentioned digitally supported design methods are primarily concerned with the generation of surfaces. However, these design approaches go beyond formal aesthetics and use the digital media not to generate "blobby" architecture but to support creating buildings which function and perform better within themselves and with their surroundings. Recent developments in design and production can also be seen as an approach, expression, and reaction of architecture to the zeitgeist of the digital age. This selection of design techniques and exemplary projects also shows that there are many different methods and starting points for using the digital medium as a generative tool at the conceptual stage of a design. According to Lynn, a paradigm shift has transformed a "passive space of static coordinates to an active space of interactions" (Lynn, 1999, p. 11). The integral part of this paradigm shift is the conceptual use of digital media as a generative design tool. In Gehry's early projects, aesthetic modifications were still made on physical models while the digital model was predominantly used for technical and structural optimization. More recent examples show that designers use the digital medium not only for technical simulations but also for making design decisions. CNC and CAM close the loop of a digital design process, where the physical and the virtual interconnect. Implementing know-how from other design disciplines has proven to be hugely useful where traditional architectural tools and methods were stretched to their limits. Projects by Gehry, Foster + Partners, and others show that the functionalities of existing software tools were sometimes not satisfying the conceptual requirements and had to be extended or even newly developed. It will be these projects that stimulate the architectural discourse and the development of architectural software. Thereby, the knowledge gained from these pioneer projects is brought to a wider architectural public.

4.2. Mediums of expression

> *"Every type of creation has constructed the proper means of expression and its own methodology."*
> *(Asanowicz, 2002, p. 36)*

Every medium or tool that is being used to express a design idea impinges in its generative process on the idea itself. Similar to a potter's wheel which inherently defines the underlying principle of the shape of the ceramic. The potter's wheel functions as a tool and defines what is possible and what is not, independent of the skills or creativity of the sculptor. Similar, digital tools can be seen as an enabling but at the same time limiting and restricting framework in which an idea is developed. In architecture today, CAD is used as an exploratory formal tool with an increasing dependency on computational methods (Terzidis, 2003, p. 69). Most CAD software uses analogies with physical devices. The following chapter looks at sketching and physical modelling as a medium of architectural expression.

Sketching and physical modelling

> *"For hundreds of years, sketches have been the link between ideas and reality of architecture."*
> *(Asanowicz, 2002, p. 36)*

The freehand sketch has always been the most intuitive medium for architects to express their ideas. Among all design tools, the freehand sketch symbolizes the architect's creative design process best. Freehand sketching allows for simple and immediate expression without fearing interruption of other media or digital distractions (Szalapaj, 2005, p. 37). This graphical way of communicating and documenting is deeply rooted in architecture and is linked to other fine arts. For many architects a sketch on a piece of paper is much more than a nostalgic memory of a pre-digital era. It is the medium through which and with which an idea comes to life. Just like every person has a different handwriting, each architect has a unique und distinguishable sketching technique. Examples of sketches by well known architects are shown in Fig. 4.28 - 4.31. If several architects were asked to sketch different objects, such as a chair, table, and lamp, and randomly shuffle the sketches, one would probably be able to group the sketches by person very easily (Marx, 2013). However, the same task given with 3D modelling instead of a pencil would make the versions less relatable. Often, it is this loss of personal expression and individuality which is argued to be lost when using CAD.

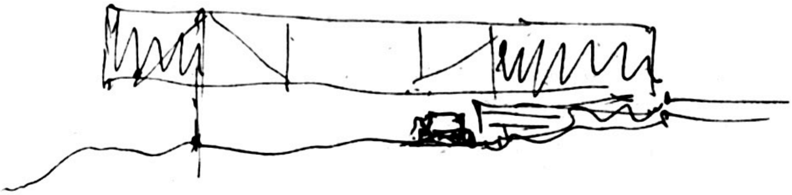

Figure 4.28 Mies van der Rohe's sketch of the "Glass House on a Hillside" (1934) © 2013 Artists Rights Society (ARS), New York / VG Bild-Kunst, Bonn.

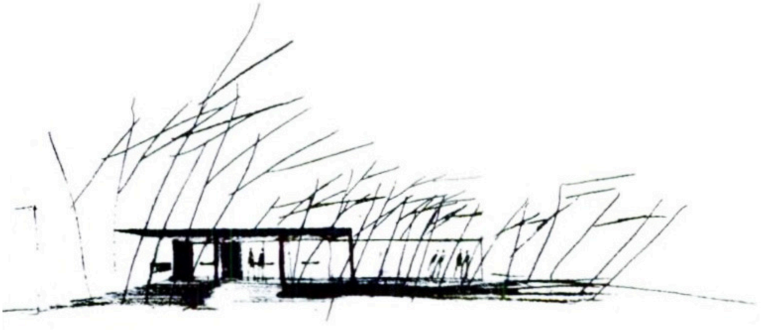

Figure 4.29 Glen Murcutt's sketch for the "Doug Murcutt house" (1972) in Belrose, Australia (Murcutt, 2002, p. 39).

Figure 4.30 Frank Gehry's sketch of the Ray and Maria Stata Center at MIT (Gehry, 2001, p. 267).

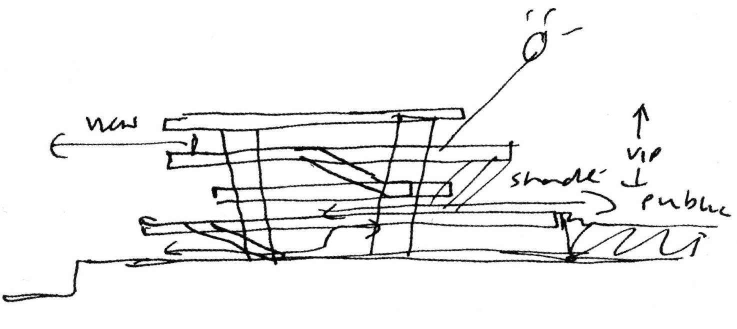

Figure 4.31 David Chipperfield's sketch of the "America's Cup Building" (2006) in Valenzia, Spain (Cecilia & Levene, 2010, p. 162).

Freehand sketching can be described as a circular and reflective process, including an externalization of an idea and a reexamination by the brain in a creative loop (Szalapaj, 2005, p. 37). Sketches are in a way the manifestation of the cognitive processes in the architect's brain. Graphical techniques in the creative process of design form an inseparable component of the whole design process itself (Asanowicz, 2002, p. 37). The Australian architect and winner of the 2002 Pritzker Prize, Glenn Murcutt, exclusively draws by hand, from the first sketch to the final construction plans. For Murcutt, manual drawing is entirely different compared to designing with computers. He argues that drawing become a way of thinking with which he arrives at a certain design before he realizes that he has arrived.

Sketches often combine plans, elevations, sections, perspectives, functional relationships of objects, or other references. Many architects describe sketching as a process, that helps them to formulate and specify a design idea. Usually, sketches are not drawn to scale whereas several sketches of varying size and levels of detail are drawn next to or on top of each other. As the design process continues, the initial sketches become gradually translated into more refined and detailed drawings. Even in the digital age, the sketch still remains the architect's most intuitive and direct way of expressing an idea. Freehand drawing skills form not only an essential part of the architectural education but pencil and tracing-paper are still part of today's highly digitally equipped design studios.

Besides sketching, physical modelling form an important part of the architectural design development. Physical model have "tactile qualities that can be matched neither by conventional drawings nor by digital models" (Szalapaj, 2005, p. 42). Different types of models varying in scale and level of complexity are used in different phases of the design: concept models, massing models, construction models, presentation models, and prototypes. Similar to the reflective process of sketching, physical modelling provides a direct and immediate way of expression and insight. In a digital environment rapid prototyping, that is the fabrication of physical models from digital data, becomes increasingly important. Rapid prototyping bridges the gap between virtual and real.

Especially when free-form geometry is involved, 3D printers and CNC machines allow to efficient production of precise models and prototypes from digital data (Fig. 4.32 and Fig. 4.33).

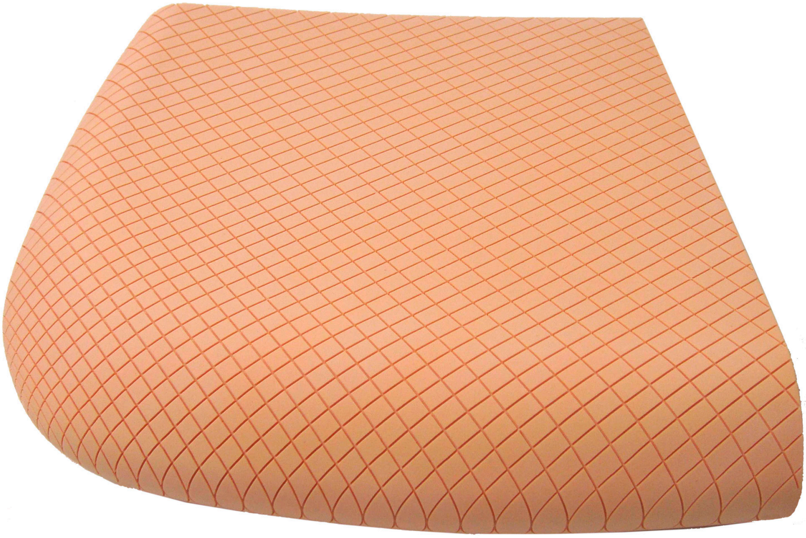

Figure 4.32 Feasibility study of a CNC milled model with lines produced by contour milling. Model by Ching-Hua Chen and Benjamin Stangl (2008).

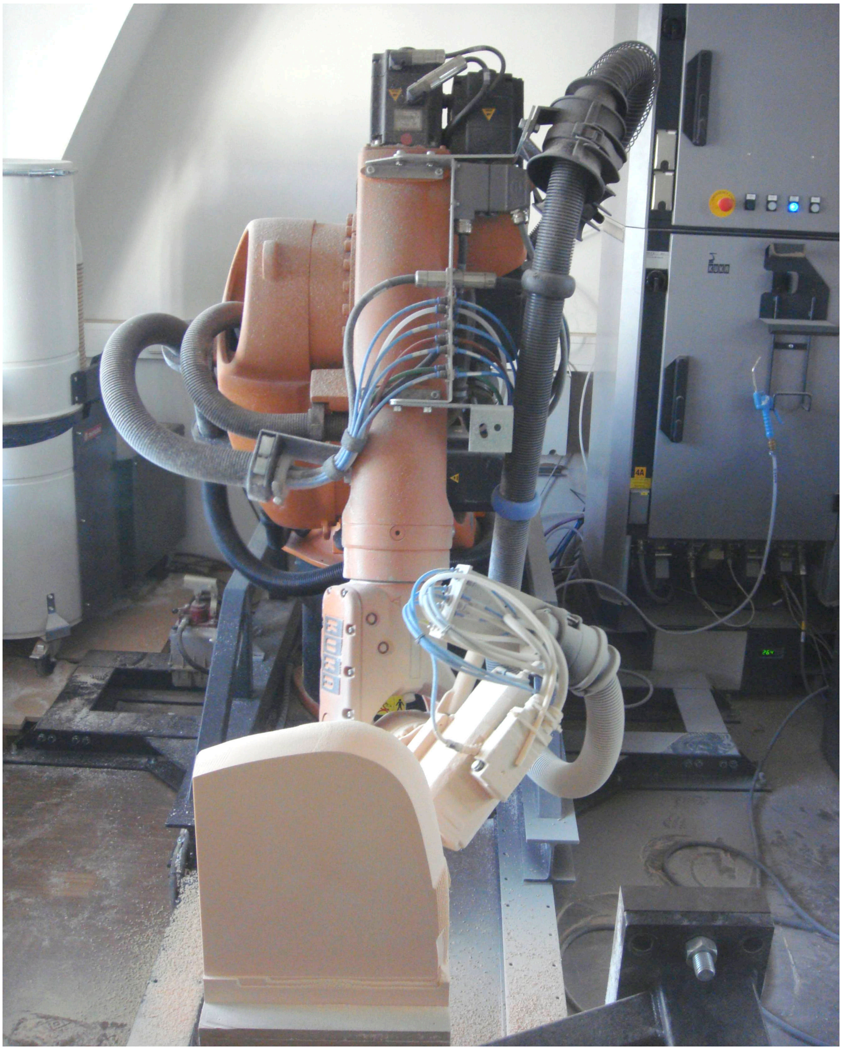

Figure 4.33 KUKA robot used as a milling machine at the Vienna University of Technology (2008).

Digital expression

Digital tools as a medium of expression goes beyond the benefits of efficiency, digital sketching, and BIM. Digital expression uses the computer as a medium to "sketch" ideas and develop architectural concepts. In architecture, digital media has a wide range of practical applications. In fact, digital tools can help to express ideas which are hard to communicate with conventional media. Generative design methods use these possibilities of digital expression to develop and specify a design concept. Concepts including transparency, movement, interactivity, optimization, or material elasticity are often easier to describe using digital means. Comparing traditional with digitally-based design methods, one can argue that there are similarities between the freedom of developing a design idea through sketches and generative digital methods.

Sketching on tracing-paper allows the architect a certain vagueness that is inherent in the tool (pen, pencil, or brush) and the way this tool is being used (freehand). Parametric design is a similar example, which allows the definition of an inner logic of a design without exact final shape. Similar to a sketch this allows an architect to stay on an abstract level of a design while still being flexible to define the exact final shape. Parametric models can immediately reflect changes made to an interlinked geometrical system. This up to realtime direct response is supported by CAD and allows a similar creative loop to sketching: an externalization of an idea and an immediate reexamination of the result.

Often, sketches show logical and functional relationships of spaces without defining the actual shape. Generative design methods support conceptual and functional design approaches, due to the approach of defining the logic behind a design rather than the actual shape itself,. While the capabilities and limitations of manual drawing and conventional CAD modelling tools are known and estimated in advance, it is not necessarily the case when using the computer to perform algorithmic procedures (Terzidis, 2003, p. 68). This often leads to results of which the designer does often not have the full control or prior knowledge. Digital technologies stimulates working in non-linear and cyclical creative ways (Goulthorpe, 2003a, p. 292).

The next chapter will take a closer look at how this shift towards digital technologies affects the design process.

4.3. Effects of digital tools on the design process

In today's offices, the architect works in a completely different setting and in a different framework than several decades ago. Conventional drawing boards have almost completely been replaced by computers, servers and printers. Constraints and logics of manufacturing and production have radically changed. Even since the beginning of CAD, the digital design tools themselves significantly evolved and rapidly increased over time. Besides the shift from 2D to 3D, the variety of the geometrical repertoire, such as splines and NURBS strongly increased over the last years. Beyond that, there is a growing trend towards design software providing computer scripting environments. Popular examples of applications integrating scripting interfaces in existing CAD packages are Grasshopper in Rhino, Maya Embedded Language (MEL) in Maya or MAXScript in 3ds Max.

Looking at the technological advances of the last decades, an important questions is: Has the architectural design vocabulary adapted the functionalities and opportunities offered by CAD and digital production, or has it been the reverse process? Keeping in mind the afore mentioned principle that "architects tend to draw what they can build, and build what they can draw", the reciprocity between representation and production raises crucial questions in the digital age (Mitchell, 2001, p. 354). The consequence of this correlating condition of designing and building is especially interesting, as both fields dramatically expanded and evolved around digital tools. As technologies developed, one could argue that architects became more adventurous in their designs experimenting with digitally supported forms of design and production as they became technologically and economically feasible.

Opposed to this thesis, Szalapaj argues that technology follows design demand rather than design adjusts to available technologies. Furthermore he argues that "most proprietary CAD software to date has been implemented in direct response to the needs of large architectural and engineering offices" (Szalapaj, 2005, p. 209). As mentioned, this holds true for avant-garde offices, like Frank Gehry or Foster + Partners.

These offices cooperate with software companies to develop applications suiting their needs for specific projects or develop customized software themselves by hiring computer programmers. However, the majority of architecture studios are smaller and have less advanced resources. Most architects depend upon available software products on the market or depend on their creative potential when needed. The architect is at risk that the options provided by the prepackaged digital tools are seen as the only possible solutions of a design problem (Füssler, 2008, p. 37). This raises questions like, how likely are architects to choose a predefined staircase from the object library rather than design one's own? To which extent do Boolean functions or NURBS surfaces invite the designer to experiment with the tool settings?

Looking beyond mainstream CAD software, one can see that many of the applications used in avant-garde projects were originally developed for other design professions and were only slowly incorporated into standard CAD. Other design disciplines already successfully demonstrated the adoption and incorporation of technological innovation in the design and production processes. Early examples include CATIA, a 3D modelling program that was originally developed for the aerospace industry, and dynamic simulation software such as Maya that was originally used in the film and video game industry. Popular generative modelling software requires both basic understanding of computer science and scripting skills which is at the same time considered as avant-garde architecture today.

In many ways, digital tools have shaped the architecture developed with these tools and the design process. The question arises, to what extent is the user of a software still a "designer" or has the user become merely an "implementer" of the formal ideas of the software developer (Füssler, 2008, p. 37)? This chapter identifies trends and directions how digital technologies and its tools changed the way architects design, based on the analysis of case study projects, interviews with experts in the field, observations, and the author's own experience.

Resource allocation

An interesting approach is to observe the design effort during different phases over a typical project, when studying the effects of digital tools on the design process. Mitchell conducted various studies in the U.S. and Britain between 1950 and 1970 which show that architects spend around 25% of their total project time on the production of construction documents (Mitchell, 1977, p. 85); only 15% is spent on design. Using CAD for drafting purposes has freed architects - at least to a good part - from time consuming drafting and document production.

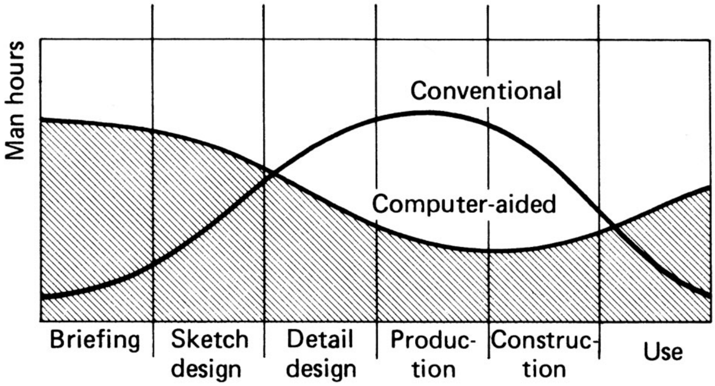

Figure 4.34 Redistribution of design effort with and without CAD during various design phases (Mitchell, 1977, p. 88).

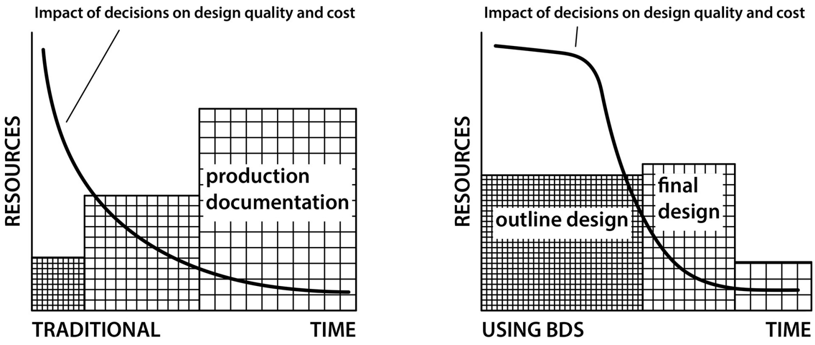

Figure 4.35 Distribution of resources during different design phases and decision impacts in the traditional and CAD design processes (Bijl, 1989, p. 84).

Based on case studies using early CAD systems, Mitchell also identified that CAD led to a significant redistribution of the time spent on various design phases. He compared traditional design techniques to computer-aided design processes by looking at the distribution of the design effort in different project phases. CAD has considerably reduced the design effort required for detailed design and the generation of construction documents. This can be explained by the fact that CAD techniques have made drafting tasks more efficient. Interestingly, Fig. 4.34 suggests that in a design project supported by CAD tools, more resources are allocated during early design phases. Similarly, Fig. 4.35 shows a redistribution of resources from the "production documentation" phase in a traditional design approach to the "outline design" phase in a design process using CAD. At the same time, the "outline design" phase claims a larger part of the overall project time and reduces both effort and overall project time of the "production documentation" phase.

Although Fig. 4.34 and Fig. 4.35 only reflect the digital tools available during the early use of CAD, it outlines an interesting phenomenon: When using CAD, there is increased emphasis on the early design phases, the concept of a design, and the problem definition. CAD software supports the automation of semi-skilled tasks, leading to a more specialized and expert-oriented work tasks. Due to this redistribution, the staffing requirements of a design team also change considerably (Mitchell, 1977, p. 88). In a broader sense, digital technologies have accelerated almost all aspects of designing. Fig. 4.36 shows that digital 3D modelling tools together with rendering software allow the creation of several perspectives and visualizations more efficiently.

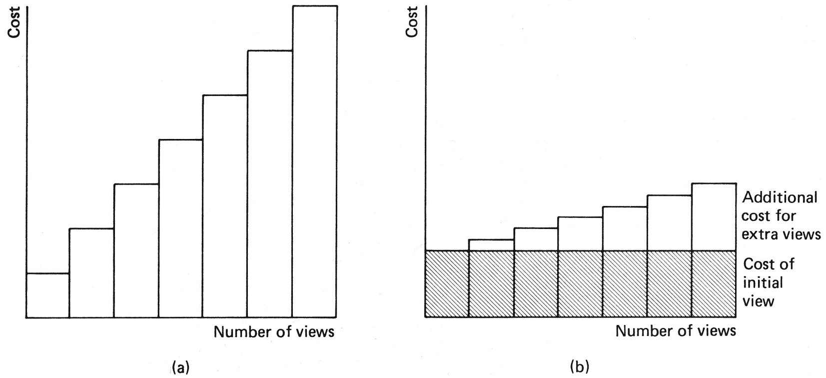

Figure 4.36 Typical comparative costs of manual and automated perspective production: (a) manual production, (b) computer production (Mitchell, 1977, p. 90).

The digital design process has also bridged the gap between design and manufacturing. In an ideal digital design process using BIM standards, the information required for manufacturing and construction is directly extracted from design information. CNC workshop machines and lately other CAM tools such as 3D printers or milling robots have enhanced and accelerated model building, prototyping, and construction.

The design and production processes require an exchange and information coordination between several professions and contractors. The capabilities of today's CAD software could potentially push the emphasis even more on early design stages. At the same time, digitally exchanging plans, models and construction documents considerably reduces printing and delivery time compared to shipping documents physically by mail. The possibilities of CAD together with faster communication media have also raised expectations in quality and time. Due to general advances in the field of telecommunication technology, both clients and contractors expect rapid decisions and adjustments. Digital tools shifted the design workload to earlier design stages, and simultaneously significantly increased the expectations of what can be completed in a short period of time compared to the pre-digital era. Global net-working allows almost instant access to project documents anywhere in the world, however certain decisions in the design process are "immune" to time compression; especially those tasks which are not (yet) delegated and formulated in a language understood by computers. These decisions especially include aspects like brainstorming, design concept development, and decisions related to taste such as the aesthetic comparison of alternative solutions. It is however questionable to what extent the idealized resource distribution in CAD design processes suggested in Fig. 4.34 and Fig. 4.35 corresponds to reality. In a professional environment where "time is money", the luxury to consider options for a day, week, or a month is questioned and often reduced to minutes and hours (Luebkeman, 2003b, p. 279). Cutting time on these tasks arguably affects the quality of the outcome of the design process. On an organizational level, architecture studios also have to adapt to a changing marketplace in order to survive. Digital tools also challenge standardized fee structures which need to take into account new patterns of resource allocation in the architectural design process.

Design in scale 1:x

The scale of a physical drawing, plan, or model is an essential characteristic of the representation itself. The scale usually defines the level of detail, which is limited by the physical properties of the representation (e.g. size, line width, or material) and visual cognitive abilities, i.e. what can be seen by the human eye. Scale is also often used by architects to challenge common conventions of forms. Designing in a digital environment in both 2D and 3D creates a potentially infinite space where the usual conventions of scale are rescinded. In digital modelling, objects are usually drawn on a scale of 1:1. Digital drawing and modelling allows to work and examine a design simultaneously on different scales. Scale becomes a matter of the definition of units which is flexible before and after a shape is defined. Compared to a physical drawing in a fixed scale, the ability to zoom in and out adds another level of perspective to the design process. The static representation in a certain scale is replaced by a dynamic view of changing scales. With the aid of the scroll wheel or a few mouse clicks, CAD allows the architect to jump from the scale of a site plan to a detailed plan. It is obvious that this has an effect on the design process. However, these effects should neither be seen as only positive or negative. As an example, the traditional and linear approach of working from a bigger scale towards a smaller scale in the design process is fragmented. Dynamic scales allow architects to work on different scales simultaneously and to immediately see design decisions in a bigger context. However, working in a fixed scale could allow for more focus on, e.g. the functional organization and the formal composition of the scale at hand. A dynamic scale not only changes the representation of the geometry itself, which is automatically supported by the CAD software, but also challenges the organizational aspect of space (Franck, 2013). Yet, support for solving organizational problems is still missing in common CAD software. By modifying the scale of a drawing, the functional connections of spaces vary. A new scale requires the designer to continuously adapt to the organizational problems of the new scale at hand. Yet, the cognitive abilities to overview elements at the same time is limited. Considering several organizational problems at the same time is especially crucial on larger scale projects, such as airports or hospitals where a large number of different organizational, functional, and aesthetic problems appear simultaneously.

2D to 3D

The concept of drawing to scale gets even more blurred in 3D modelling. In a CAD environment which is increasingly dominated by 3D modelling, the plan becomes more the role of being one representation of a form, than actually generating the form itself. Floor plans, sections, and renderings are generated from a 3D model. Using 3D parametric objects for modelling often includes more information about objects than their 2D representation. The concept of BIM is that a digital building model comprises all information related to a building in a single project database. Again, it is obvious that this affects the framework of the design process as such. The option to dynamically switch between 2D and 3D views and to edit in both dimensions creates a more direct way of interacting with objects, shapes, and buildings. Designing in digital 3D not only has consequences for the design process, but also gains importance in the fabrication process. Increasingly, the geometrical design information is directly used as the basis to drive the digital fabrication machines (Kolarevic, 2003b, p. 33). As described earlier, Gehry was one the first architects who used digital 3D modelling throughout the design process. 3D scanning tools, CNC, and rapid prototyping closed the loop of digital and analogue.

Figure 4.37 Weltstadthaus for Peek & Cloppenburg (2005), Cologne, Germany, architect Renzo Piano Building Workshop (Walz, 2012).

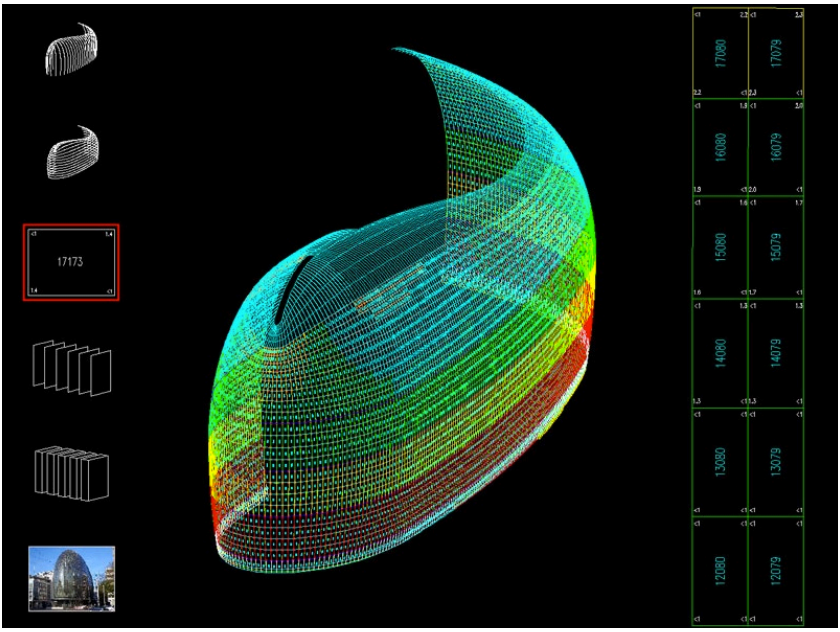

Figure 4.38 Parametric models of the Weltstadthaus for Peek & Cloppenburg by designtoproduction (Walz, 2012). The façade is covered with 6,500 glass panels.

New architectural geometry

For the most part, the computer is merely used as a more efficient and precise drafting instrument. As a matter of fact, offices using CAD systems became less labor and more capital intensive. This allowed architects to either produce designs on a shorter schedule, or to explore more options within the same resource constraints (Mitchell, 2003b, p. viii). However, the shape universe was still within straight lines, arcs, planes, spheres, cylinders, and the like. This changed when CAD software provided the means to represent NURBS and other free-form curves using mathematical functions. As a result, the architect's shape universe expanded. Spectacular projects like the Guggenheim Museum in Bilbao reinforced the aspiration for free-forms.

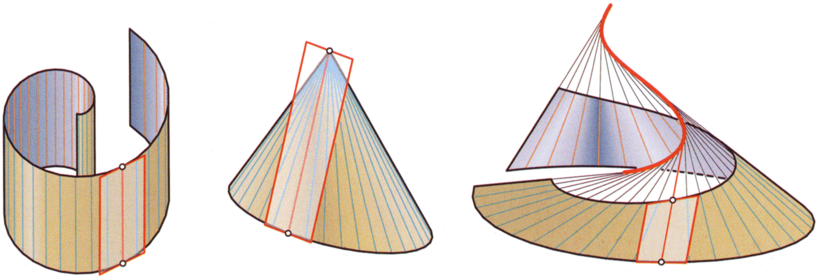

Figure 4.39 The three types of developable surfaces: cylinders, cones, and tangent surfaces of space curves. More general developable surfaces are composed of such developable ruled surfaces (Pottmann, et al., 2007, p. 535).

Figure 4.40 Implications of the geometric properties of developable surfaces on the aesthetics and construction of a design at the Guggenheim Museum (1997), Bilbao, Spain, architect Frank Gehry (Gehry, 2001, p. 170).

However, the ease of digital modelling not at all holds true on the production side. The realization of geometrically complex forms requires knowledge in areas exceeding the prevalent architect's expertise. Advanced mathematical understanding of geometrical principles and its application in architectural geometry is necessary in order to efficiently handle and operate with complex geometry. As a result, there is a knowledge transfer of geometry and mathematics into architecture, going beyond elementary geometrical principles such as linear transformations or the Golden Section.

The scope and relevance of geometry in architecture dramatically shifted and increased. While the architecture curriculum in many universities offer only basic knowledge in architectural geometry, today's 3D modelling tools allow to quickly generate almost any geometrical shape. When it comes to analyzing and manufacturing free-form shapes, not only structural and material considerations comes into play but issues such as surface types, curvature, subdivision, optimization, and mapping need to be considered. This knowledge gap led to an interdisciplinary research area often referred to as Architectural Geometry, involving designers, architects, engineers, computer scientists and mathematicians. Pottmann from the Vienna University of Technology, was one of the first researchers bringing mathematical knowledge to the area of architectural geometry and construction. Beyond applied geometrical problems, building complex shapes also requires an understanding of material properties and fabrication techniques. Bridging the gap between visualization and production requires a strong geometrical grounding based on mathematical principles for handling complex shapes. Digital technologies have also created a new form of aesthetics deriving from geometric or fabrication implications (Pottmann, et al., 2007, p. 592). As most of these design projects feature very specific and unique characteristics, often no standard solution from commercial software and construction techniques is applicable. Professionals from different disciplines collaborate to find project-specific solutions for challenging architecture projects.

'Making of form' to 'finding of form'

Looking at today's generative CAD systems, there is a shift from designing the form of a design as such to defining rules or choosing relevant parameters according to which a form is generated. This tend is clearly visible in generative design methods like parametric or performative design. Similar to the concept of topology[4] in mathematics and geometry, generative design processes put more effort on defining a certain set of rules from which a design or several alternatives of possible design solutions are generated. This leads to a shift from the "making of form" to the "finding of form", where the generative design process focuses more on the emergent properties of form than the form itself (Kolarevic, 2003a, p. 13). It is the relations and interdependencies that become the structure of the form. The resulting design or design solutions follow the predefined set of rules, parameters, or transformations. This shifts away emphasis from particular forms to the internal logics and external relations that exist between and within an existing site and the proposed program (Kolarevic, 2003a, p. 13). Consequently, digital tools considerably increased the speed at which different design options can be represented and explored. CAD allows changes made to parametrically defined forms to be geometrically reflected in up to realtime. Love points out that shifting from finding an acceptable solution to weighing alternatives means a change in approach from "how to?" to "what if?" (Love, 1985, p. 5). This enables an interactive design process where the architect is able to reiterate the design parameters and immediately see the resulting changes. A generative digital design process can be described as a more conceptually-oriented way of designing compared to conventional methods.

Examples are recent projects in London by Foster + Partners, such as the City Hall or the Swiss Re Headquarters. As observed by Peters and DeKestellier, both members of the Specialist Modelling Group (SMG) at Foster + Partners, these projects were realized using para-

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[4] Roughly speaking, geometric topology deals with the description of the way geometric objects are connected, independent of the actual shape of the object (Pottmann, at al., 2007, p. 517).

metric models, controlling the geometry in response to variable parameters and relationships (Peters & DeKestellier, 2006, p. 2). This dynamic and interactive relationship between parameters and geometry allowed to rapidly create several comparative design solutions. Conventional CAD already took a big step towards more efficient ways of drafting and designing. However, generative tools allows for greater consideration of alternatives in the early design stages (Love, 1985, p. 4). Technologies such as real-time rendering, 3D printing, and rapid prototyping support this exploratory approach which allows side-by-side comparisons of several design alternatives (Stocking, 2009). A parametrically defined and interlinked geometry also allows to see the effects of changes immediately in relation to other parts of the design. This allows more flexibility in later design phases.

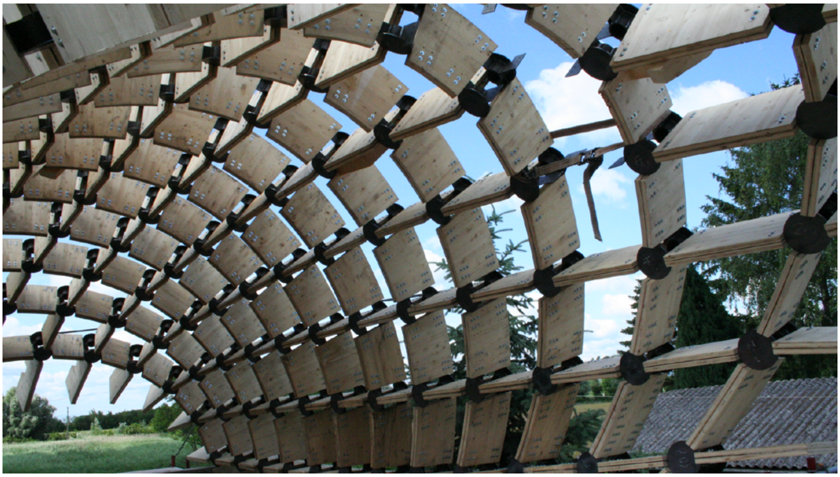

Figure 4.41 Roof construction (2010) Leopoldsdorf, Austria, architect EXIKON arc & dev © Bernhard Sommer (Reis & Schmiedhofer, 2012).

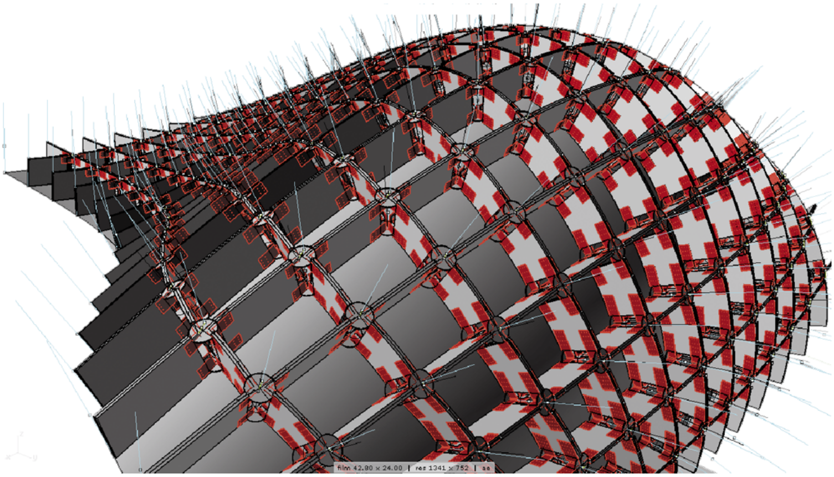

Figure 4.42 3D model of a roof construction realized with a design-tool by feasible geometry-consulting (Reis & Schmiedhofer, 2012).

Design for production

The principles of industrial mass-production and standardization imposed an economy of shapes to architecture. Mitchell argues, that "throughout the twentieth century, the straightforward logic of industrial standardized production seemed to provide an unassailable justification for the spare geometries of architectural Modernism" (Mitchell, 2001, p. 359). In pre-digital industrial production, regular and standardized construction elements had been easier and therefore cheaper to fabricate than more complex customized elements. Restricting oneself as a designer to a limited number of different parts had been usually a safe strategy to cut down costs. However, these implications of standardized production do not necessarily hold true for digitally controlled production. In a digital fabrication environment, using mass-produced parts might not be as important as before. The designer has more creative freedom liberated from the constraint of repeating the same elements for economy. The boundary condition of an obliged uniformity can be replaced by similarity and individuality in the production process.

As buildings have a tendency to be unique rather than mass-market products, it is often difficult to achieve long production runs (Mitchell, 2001, p. 360). CAM allows for easier variation of elements and helps mass-customization becomes an affordable option to mass-production. In digitally supported design and fabrication, the architect is less restricted to use as few varying elements as possible. Using repeating parts for economical reasons has been a restrictive corset for creative thinking for a long time. CAD/CAM supports individuality and allows for non-repeating parts. For example, the exterior glazing of the City Hall in London by Foster + Partners consists of individually shaped panels (Fig. 4.43). Frank Gehry excessively used CNC prototyping and manufacturing. The facade of the Experience Music Project in Seattle consists of more than 21,000 individually cut stainless-steal shingles (Gehry, 2001, p. 228). Thus, every digital fabrication technique has again its own constraints and has to be considered in the choice of material and the design and construction process.

Architects also take advantage of custom "designed" materials, featuring specific physical or aesthetic properties and functions. However, a crucial aspect of effectively using the opportunities offered by CAD/CAM systems, is to be familiar with the capabilities of materials and fabrication facilities offered by various vendors (Mitchell, 2001, p. 363). Building free form shapes requires knowledge about the specific properties and limitations of materials and their fabrication. As a consequence, the architect becomes more directly involved in the fabrication and construction process.

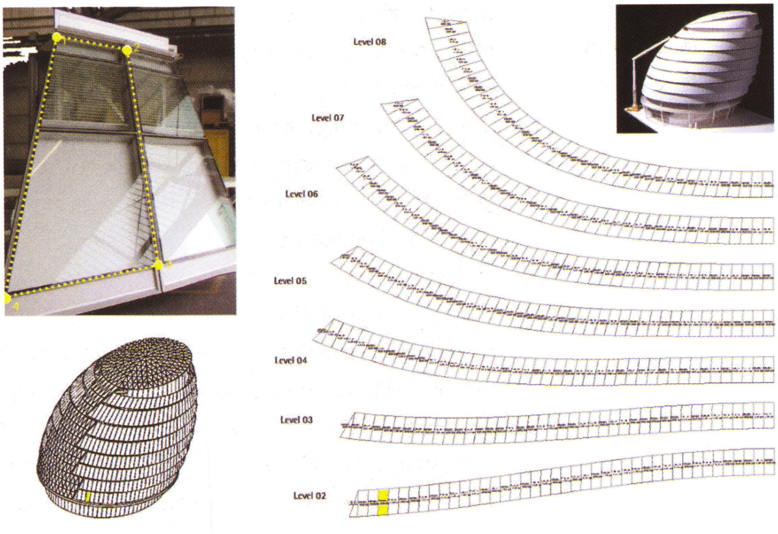

Figure 4.43 Flat-patterned drawing of the glazing for the London City Hall (Whitehead, 2003, p. 87).

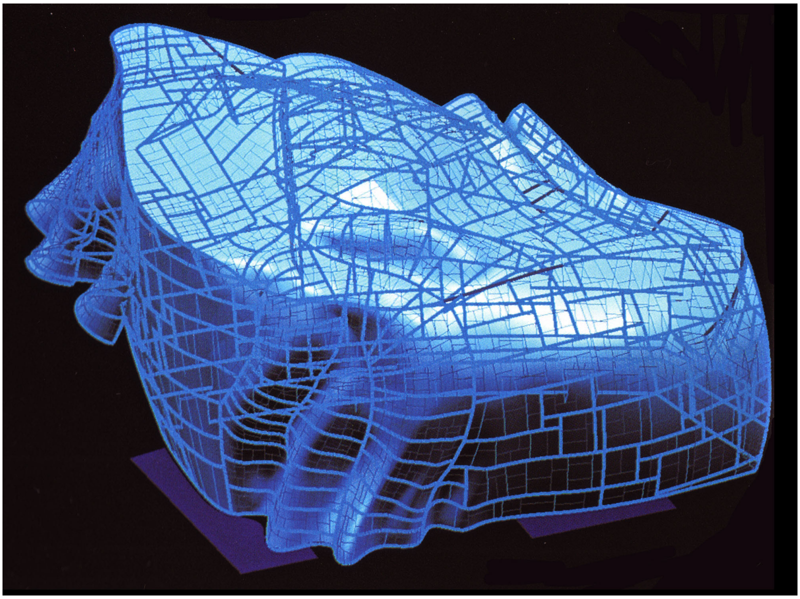

Figure 4.44 CATIA model of the individual shingles of the Experience Music Project (2000) Seattle, architect Frank Gehry (Gehry, 2001, p. 228).

5. Conclusion and outlook

Digital tools are a part of the central workplace in almost all architecture practices today and strongly shape all phases of the architectural design process. Many design tools and methods used in architecture today have primarily been developed in other disciplines such as car manufacturing, aerospace, computer science or the film industry. CAD software first replaced traditional drafting instruments by mimicking physical equipment and drawing techniques. The generative use of digital media supports the design process as a genuine medium of expression, and thereby becomes part of the design process itself. It allows architects to arrive at design concepts which had not been able to be developed, controlled, or grasped with conventional means. Architects and engineers exploited the generative potential of digital design in projects like the Walt Disney Concert Hall in Los Angeles by Frank Gehry, the BMW Exhibition Pavilion in Frankfurt by Bernhard Franken and ABB Architekten, the London City Hall by Foster + Partners, and the Mercedes-Benz-Museum in Stuttgart by UN-Studio.

Digital technologies in both representation and fabrication extends the design vocabulary. The aspiration of curvilinear forms is also tied to a broader cultural and design discourse responding to the cultural zeitgeist of the Digital Age. Implementing NURBS and other free form curves forms to CAD software opened a new shape universe, which due to technical and economic constraints was for a long time defined by straight lines, arcs, planes, spheres, cylinders, and other conventional geometry. Operating with complex geometry requires applied knowledge of architectural geometry, material properties, and fabrication techniques. Using standard application software, especially common BIM software, the architect is again at risk of being dictated by the language-tools these applications use and see the options provided as the only possible solutions of a design problem. CAD makes the design process faster, more efficient, and enables the architect to perform new operations. However, the effects on the design process vary due to the diversity of CAD software and the architects individual usage of digital design tools. The degree of technological involvement in the design process is different for each architect and project. The interviews showed that each architect develops his or her unique way of applying CAD in the design process. Table 4.1 summarizes the observed general effects of digital tools on the design process by comparing characteristics of a conventional with an idealized computer-aided design process.

Table 4.1 General characteristics of a conventional (manual) versus an idealized computer-aided design process.

conventional	**computer-aided**
manual	digital
pencil, paper …	software, hardware
defined scale	dynamic scale (1:x)
resources in later design phases	resources in early design phases
design in 2D or 3D	design in 2D = 3D
making of form	finding of form
representation of object	object itself
plan generates design	plan derived from design
low semantic level	higher semantic level (BIM)
labour intensive	capital intensive

While digital tools have entered all aspects of architectural practice, it remains open whether it has improved the "quality" of architecture. Even within architectural theory, it is notoriously difficult to define architectural quality (Franck & Franck, 2008). Digital design tools do not automatically guarantee better architectural quality. However, it considerably changed the framework conditions under which architecture is produced today. For example, CAD software makes it easier for architect to iterate and evaluate design alternatives which can improve the quality of a design. Building modelling and simulation tools combined with new building materials and precise manufacturing techniques give architects more control of the construction process and potentially facilitate better performing buildings. Yet, digital tools expand the field of architecture and challenge existing conventions in architectural practice. Higher expectations of productivity, increasing complexity of the construction process, and growing information volume set a challenging framework for architects.

5.1. Challenges ahead

Design by tool design

In a digitally supported design process, an increasing dependency of the architect on the capabilities of the used tool is seen. In the early days of CAD development, software developers stayed in close touch with the professional architects using their software. Often times it was architects themselves who developed software tools they needed. Today, and this has led to the axiom that there can never be a digital system capable of making everybody equally happy (Yessios, 2011, p. 10). Increasingly, CAD software allows not only computer scientists but also digitally literate architects to customize and extend their software environment. The role of the digital tool as an integral part of the design process itself is so essential that architects are forced to search for design ideas in a wider field outside the finite world of application software (Füssler, 2008, p. 39). Programming skills diffused into architecture, which allows smaller offices to customize and extend their software tools. A logical solution would be not to rely on pre-made software tools but to create one's own tool. Füssler calls this "design by tool design" (Füssler, 2008). Leading architecture practices have developed project specific tools for a long time. It is important to understand, that the design of one's own design tools is considered a substantial part of the design process and therefore a genuine matter of architecture (Füssler, 2008, p. 39). Design by tool design introduces a meta level as it explicitly incorporates the thinking about the process of design ideas. The field of tool design broadens the role of a classical architect. However, in order to give architects the chance to enter this world, it is necessary to teach programming skills alongside of design skills (Aish, 2003a, p. 294). The implementation of architecture friendly programming tools and scripting environments in 3D modelling software is an option for designers to create a broader and task-specific repertoire of design tools beyond common application software.

Changing tools

The development of future CAD tools needs close collaboration between software developers and architects. The option to implement scripting environments within existing CAD applications will gain currency and contribute to more flexible and customized tools. At the same time, we will see a multitude of different tools in the design process. Especially, free or low-cost CAD software, in combination with specific plug-ins or add-ons, invites digital generation by architects to naturally experiment with different tools. Today's architecture students belong to a digitally native generation, who naturally operate with digital tools. Graphical programming bridges the gap between design and automation. It is also likely to see more generative algorithmic tools similar to Grasshopper in Rhino.

At the same time, performance-based analysis tools within CAD software will become more important. As a result of higher expectations, the performance of a design, may it be acoustical, structural, energetic, or even functional, will take on greater significance. Therefore, it is crucial to create the link between generative codes, that control the geometry, and performance analysis (Luebkeman, 2003b, p. 282). That leads to the question how the core functions of CAD software will develop. Beyond the before mentioned performative analysis functions, there are other "candidates" which could be interesting for architectural design. Concepts, such as fractal geometry or genetic algorithms are since long integrated in specialized software outside of architecture, however, they have not been implemented in the toolbox of common architecture CAD software. This might be due to the more complex background of these concepts and techniques. Though, the mathematics behind NURBS surfaces or geometric deformations is rather complex, these functions are taken for granted in most CAD software today. An explanation why fractal geometry or genetic algorithms are not (yet) used in mainstream CAD could be that these concepts have hardly any tradition in architecture. The concept of splines digitally resemble bending wood or metal stripes. In fact, software is a deeply conservative force, as typically, almost all software begins with the observation of some existing practice, with maybe some incremental transformations of it in mind (Mitchell, 2003a, p. 294). The lack of a physical equivalent tool to evolutionary problem solving makes the practical application dependent on the processing power of computers. Also, the fear of ceding control of the design process to a "black box" software might come into play.

Which technological developments will inspire future architecture software? Gehry was looking at the aircraft industry to find the appropriate design tool. Technologies from the video game industry brings visualization in form of immersive real time rendering or augmented reality to architecture. Potentially, innovation in every field could be inspiring and interesting to architecture.

User interaction

The interaction of the architect with the digital design tool will develop towards a more intuitive, efficient, and at the same time functionally rich design environment. For the most part, user input is still dominated by mouse and keyboard. 3D mice and multi-touch screens are a step towards more functionality and intuitive user experience. Science fiction films often proved to be a good source of inspiration of how technology could one day be used. It is likely to see user interaction develop towards sensors tracking the designer's gestures and blurring the boundaries between real and virtual by using augmented reality visualization for design interaction.

'Code libraries'

Exchange among each other and support of the community is highly important in the area of software development, programming, and coding. However, opened collaboration and the dependence on support in online libraries or wikis is opposed to the traditional understanding of design work in architecture offices. When code enables or supports the generation of forms, it also raises issues such as copyright and intellectual property. Writing code from scratch is not only time-consuming but also requires profound programming skills. The reuse and adaption of code goes beyond the reuse of geometry or object libraries. "Code libraries" will be essential for designers who want customized tools but do not want to spend most of their efforts on coding.

Architecture education

The majority of interview partners agreed that the architecture education plays a crucial factor for the integration of new technology to architecture practice. Education needs to provide an environment where students learn basic knowledge of digital design and develop practical skills to utilize technology for their needs. Besides an understanding of programming skills, a theoretical framework is needed, as is a critical view on technology itself. A crucial skill for students is also to learn how to analyze, develop, and express design ideas in parametric models in order to take full advantage of digital technologies. This requires a way of thinking in defining rules and interdependencies that become the structure of the design.

In the future, there will hopefully be a vital discussion in academia and beyond about the possibilities and challenges of a digital design process that goes beyond formal aesthetics.

Abbreviations

BIM	Building Information Modelling
CAD	Computer-Aided Design
CAAD	Computer-Aided Architectural Design
CAM	Computer-Aided Manufacturing
CATIA	Computer Aided Three-Dimensional Interactive Application
CNC	Computerized Numerical Control
GUI	Graphical User Interface
NURBS	Non-Uniform Rational B-Spline
SMG	Specialist Modelling Group

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