Architecture Meets Computation: an Overview of the Evolution of Computational Design Approaches in Architecture

Architecture has always embraced innovative ideas, materials, and techniques. Contemporary architecture is no exception. The emerging computation-based design approaches, known as Computational Design (CD), differ significantly from the previous ones since, instead of grounding the design representation in its geometric aspects, they base it on its computational logic. CD is causing considerable changes in both design theory and practice, but most architects are not yet aware of its impact. To promote a more critical view, while further improving its future application, this paper analyses the course of CD from its origin until today by (1) explaining its evolution since the early 60s, (2) discussing the advancements in CD tools during that period, (3) presenting architectural projects and events that explored CD, and (4) providing a chronology of the literature on CD. It concludes that, as it happened in the past, technological developments continue to shape architectural theory and practice and, at the same time, are guided by their needs and aspirations.

Keywords: computation-based design; design evolution; design theory; design research; computational design thinking.

1. Introduction

Throughout time, architecture, as a creative practice, has strived to embrace innovative techniques, materials, and concepts. Contemporary architecture is no exception and, thus, it has been exploring the latest technological advances, particularly, the new computational means of conception and production, which offer new possibilities for design and manufacturing, translating virtual design representations into their physical realizations. These emerging computational-based design approaches have been addressed by several authors and applied in several design studios to extend the aesthetical and constructive possibilities of the projects developed. This paper provides an extensive literature review on Computational Design (CD) approaches, organized chronologically along different dimensions.

2. Methodology and structure

The goal of this review is to promote a more conscientious and critical view on the evolution of CD technologies within the architectural theory and practice. To this end, we followed a methodology based on four main phases:

1. The first one focused on studying the state-of-the-art on the use of CD in architecture, from the 60s until today. From this literature review, we selected works that had a major contribution to the integration of CD approaches in the field. Simultaneously, we analysed the main international conferences and journals responsible for publishing much of the literature studied.
2. The second stage addressed the contextualization of the technological evolution of the same period. We identified the emergent tools that better suited the architectural design process, along with the technical innovations carried out by them.
3. The third stage concentrated on making a parallelism between the theoretical evolution, the technologies available throughout time, and the implementation of CD techniques in real case scenarios.
4. The last stage focused on tracing two timelines on CD evolution: one structuring the events and technological innovations that we consider important and the other organizing relevant theoretical works on CD. Concurrently, we conducted a critical reflexion on the evolution of CD and its influence in architecture, evaluating not only its role in

architectural practice and theory, but also its advantages and disadvantages.

The paper is organized in two main parts: one presenting the literature review on CD and the other discussing it and presenting relevant considerations. The first part structures the state-of-the-art in three main categories:

- one introducing the technological background that contributed to the emergence of CD methods and to their integration in architecture;
- another focusing on the research background, discussing scientific events that were important for debating (1) theoretical issues and social concerns, (2) emergent tools and techniques, (3) the latest research, and (4) the existing environmental problems;
- a last one addressing the theoretical background, dividing it into three generations of thought: (1) the embryonic-generation, from the early 60s to the early 90s; (2) the first-generation, or the "Post-folding Period", from the early 90s to the early 00s; and (3) the second-generation, from the early 00s until today.

The second part presents two timelines, one containing important events and technological innovations and the other organizing relevant theoretical works on CD. We conclude the paper with a critical discussion on both the state-of-the-art and the timelines presented.

3. Literature review on CD

3.1 Technological background

CD is a design process that takes advantage of the design tools' computational capabilities. In this section, we contextualize it by presenting (1) the evolution of CD tools, and (2) the CD design techniques mostly used by architects.

3.1.1 Evolution of design tools

In the 21st century, the use of digital technologies is already part of the architectural design practice. For Rocker (2006), CD processes have become a means of design exploration, extending the capacity of traditional processes, while challenging and, therefore, changing the design conventions and praxis. In this scenario, the development of CD tools for architectural design, namely Computer-Aided Design (CAD), Building Information Modelling (BIM), analysis, and simulation tools, played an important role.

Regarding CAD tools, in 1982 *Autodesk* released *AutoCAD*, a 2D digital drafting tool suitable for architecture, project management, and engineering. In 1985, it was extended to integrate a 3D kernel. In 1985, *BentleySystems* launched *Microstation*, an application similar to *AutoCAD,* with a limited interface supporting only basic 2D drawings. A decade later, 3D modelling was incorporated.

Another step forward occurred in 1987, with *Pro/ENGINEER*, a tool developed by Samuel Geisberg for mechanical engineering that allowed users to associate 3D parametric components, which not only reduced the cost of design changes, but also overcame the rigid constraints of 3D modelling at the time (Tedeschi 2014).

In 1998, *Robert McNeel & Associates* launched *Rhinoceros 3D*, a commercial 3D CAD tool based on the NURBS (non-uniform rational basis spline) mathematical model (Rogers and Adams 1990) that focused on producing a mathematically precise representation of curves and freeform surfaces.

In 2000, *@Last Software* developed the 3D modelling software *SketchUP*, an easy-to-use tool that gave architects more design freedom. In 2006, *Google* acquired the company, extending the tool under the name of *Google Sketchup*. In 2012, *Trimble Navigation* (currently *Trimble Inc.*) purchased the tool to continue its development.

Programming environments to automate and extend the modelling tools were also proposed early on. *Autodesk* released *AutoLISP* in 1986, promoting the use of algorithmic-based approaches. In 2007, *Bentley* announced *GenerativeComponents*, allowing the user to manipulate geometry by applying rules/relationships between elements or by using algorithms. In 2008, the visual programming tool *Grasshopper* was added to *Rhinoceros 3D*, which became very popular among architects due to its ease of use and ability to create complex parametric models.

Regarding BIM tools, Graphisoft started developing BIM in 1982 and made it available to architects when it launched ArchiCAD in 1987: it produced 3D models whose elements were parametrically/associatively connected, while including the corresponding construction information. Following earlier experiments regarding the use of the aeronautics design software CATIA in architecture (Brown 1986), in the mid-90s, Gehry Technologies adapted it, originating Digital Project. In 2000, Revit Technology Corporation released Revit, which supported the design and documentation of buildings by creating parametric models containing both geometry and construction information. In 2002, *Autodesk* purchased the company and enriched the tool, creating *Revit Structure* (2005), *Revit MEP* (2006), and the visual programming tool *Dynamo* (2011). Further BIM tools include *BentleySystems*' *AECOsim* and *Tekla Corporation*'s *Tekla Structures.*

Alongside CAD and BIM tools, it has also been noticeable the use of (1) simulation tools, to model the behaviour of buildings, (2) analysis tools, to evaluate their performance, and (3) optimization tools, to search for the best values of the design parameters. *EnergyPlus* (for energy consumption simulation), *Ecotec* (for daylight analysis), *Robot* (for structural analysis), *Radiance* (for lighting simulation), and *Galapagos* (for optimization) constitute some examples.

3.1.2 Design Techniques Generations

For Aish and Bredella (2017), the CD evolution is a progression from 2D drawing to 3D BIM and, then, to design computation. Ironically, after several years developing tools suitable for non-coders, the design field increasingly felt the need to integrate programming environments into such tools, because the latter did not satisfy all the design practice needs.

The evolution of computational tools went through different generations, reflecting their capabilities and the way these were used by architects. For Dorst and Dijkhuis (1995), the first generation (60s-80s) was influenced by technical systems theories, therefore reducing the design process to a system. The resulting CAD software had many shortcomings, including a deterministic and linear design approach, a limited scope to solve functional problems, and the lack of a Graphical User Interface (GUI) (Reffat 2006). These limitations, along with a steep learning curve and large cost, demotivated architects from using such tools.

Later, with the spread of personal computers and the improvements in GUIs, CAD software became accessible to a larger architectural community. The resulting association between computation-based and design processes rapidly matured as a design medium and, for the first time, most computer users were non-coders (McCullough 2006). For Asanowicz (1999), this originated the second CD generation that, according to Reffat (2006), was marked by the improvement of the designers' communication with the computer, since software packages already enabled them to draw on computer screens without any programming knowledge. Some authors named this generation as *2D Drafting Era* (Aish and Bredella 2017), *Electronic Drawing*

Board Era and *first generation in the architectural offices* (Achten 2009), since it used advanced technology to emulate the traditional 2D design process. In fact, it replaced traditional drawing tools with more efficient and precise ones but without taking advantage of the available computational power (Terzidis 2006); a scenario where the use of CAD tools was mostly associated with the idea of *Computer Aided Drafting* (Asanowicz 1999; Burry 2011). Nevertheless, Reffat (2006) recognized that the use of computational approaches was positive for architectural design in facilitating the exploration and documentation of more complex forms.

In the 21st century, the advancements in 3D modelling tools enriched the design exploration, visualization, and documentation processes. This evolution first culminated in the BIM era, in which, according to Aish and Bredella (2017), architects already created and extracted drawings from 3D models but still resorting to limited construction processes. Then, it reached the Algorithmic Design (AD) and generative levels, enabling architects to overcome the limitations of their design tools and to directly connect their design representations with the construction phases.

For Achten (2009), the architectural design process is now "beyond the first round of imitating and supporting traditional practices", as the use of computers has prompted several changes in the architectural design workflow. This originated another generation in which the computer acts as a device fully integrated in the design process (Asanowicz 1999). For Leach (2009), the nature of the architect has evolved from the restricted 'form-giver' to the controller of generative processes, where the final design results from the combination of the architect's imagination with the generative capabilities of computer tools.

3.2 Research background

The scientific events of the last decades promoted important debates on (1) theoretical and practical issues, e.g., the architectural practice state, the impact of emerging tools and techniques, and the applicability of scientific research, and (2) social concerns, e.g., current environmental problems and emerging living needs. These discussions contributed to guide the application of CD.

3.2.1 Academic and scientific events

We can evaluate the theoretical relevance of CD by the number of scientific events over time. Therefore, we present a timeline (Figure 1) of the international scientific events on CD that, somehow, influenced the architectural design theory.

The *Conference on Design Methods* in 1962 is considered the field's embryonic conference, having as main goals (1) designing better by understanding the design process, (2) externalizing the design process to allow collaborative work from early to later and more complex stages, and (3) using the computer to automate repetitive design tasks. According to Celani and Veloso (2015), the 60's *Design Methods* movement is closely related to CAD origins.

In 1972, the *1st International Congress on Performance* brought a new design perspective resulting from the computer scientists' interest in both systematic design methods and design science, concepts based on which they evaluated buildings performance as a means to scientifically justify design decisions.

During the 80s, the number of international conferences greatly increased: in 1981, Mitchell, Eastman, and Yessios founded the north-American *Association for Computer-Aided Design in Architecture* (*ACADIA*) conference to discuss the role of computation in Architecture, while encouraging innovation in the architectural design practice (Celani and Veloso 2015). In 1983, the conference *Education and Research in Computer Aided Architectural Design in Europe* (*eCAADe)* was first held, introducing education as a new research focus. Established in 1985, the *CAADFutures* conference embraced all continents aiming at fomenting CAD advancements envisioning the quality of the built environment; the conference *Artificial Intelligence in Design* (renamed as *Design Computing and Cognition* in 2004) focused on using Artificial Intelligence techniques in design; and the bi-annual *International IBPSA Building Simulation* conference aimed at improving the design, construction, operation, and maintenance of both new and existing buildings. In 1989, the *International Conference on Computational and Cognitive Models of Creative Design* explored the advancement of designers' understanding of computational and cognitive models of creative design.

During the 90s, the *Association for Computer-Aided Architectural Design Research in Asia* (*CAADRIA*) conference was founded (1996) to promote teaching and research in CAD in Asia. Settled in 1997, the *Sociedad Iberoamericana de Gráfica Digital* (*SIGraDi*) aimed at debating the application and potentialities of the new digital technologies.

Already in 2001, the *Arab Society for Computer Aided Architectural Design* (*ASCAAD*) conference was founded, as were, two years later, the *Smart Geometry Conference*, focusing on capturing CD to architecture (Peters and Peters 2014), and the *Performative Architecture Symposium*, investigating the gap between geometry and analysis and the influence of performance in architectural design. In 2008, the *Advances in Architectural Geometry Conference* was organized to address the new geometrical developments in architecture and engineering, and, in 2009, the *Digital Architecture London Conference* was held to discuss the role of technology in society. Settled in 2010, the *Symposium on Simulation for Architecture and Urban Design* (*SimAUD*) aimed at building a collaborative simulation framework to support sustainability, and, in 2013 the *BIM Conference* focused on evidencing the benefits of BIM in design and construction.

Likewise, scientific journals were critical for the dissemination of CD approaches. Some journals, such as *Design Studies* (1979) and *Architectural Design* (AD), started exploring the role of CD in architecture and manufacturing in the mid-80s (Carpo 2012). Other journals were created specifically to address CD, e.g., *Automation in Construction* (1992), *Journal of Architectural Engineering* (1995), *Nexus Network Journal* (1999), *Construction Innovation Journal (2001), International Journal of Architectural Computing* (2003), *Journal of Building Performance Simulation* (2008), *Building Simulation: An International Journal* (2008), and *Frontiers of Architectural Research Journal* (2012). Finally, journals with a high impact factor on building science and technology fields often incorporate articles exploring CD techniques, especially those on building simulation, e.g., *Solar Energy* (1957), *LEUKOS: The Journal of the Illuminating Engineering Society* (1972), *Building and Environment* (1976), and *Energy and Buildings* (1977).

Figure 1 temporally organizes both the conferences and journals previously presented. Its analysis reveals a tendency to establish new conferences/journals with the emergence of new terms or design approaches.

3.2.2 Architectural production

The role of architectural practice is critical in design paradigm changes. This section presents a set of architectural projects that took advantage of CD methods at a representational, modelling, or construction level, constituting therefore important milestones due to their aesthetical rupture or level of innovation. The selected projects were, therefore, pioneers in integrating (1) new design methods and tools, (2) original aesthetical discourses, and (3) never before used design/construction strategies.

The *Sydney Opera House,* by Jørn Utzon, challenged the means of architectural production of its time, justifying the long period between its design (1959) and its actual construction (1973). It was a pioneer project in resorting to computers to execute structural analysis to understand the loads over the roof shells and the assembly of the arches.

Jean Nouvel's *Institute du Monde Arabe* (1987) is considered the first building with a kinetic façade composed of several mechanical light-sensitive units that control the amount of light entering the building. Although kinetic design approaches were little explored during the following decade, this project paved the way for several other buildings to take advantage of *kinetics* potentialities.

The *International Terminal* at *Waterloo Station* by Nicholas Grimshaw and Partners (1993) was one of the first projects to technically apply parametric design: the roof structure was composed of 36 dimensionally different but identically configured arches placed along the tracks. Instead of modelling each arch separately, the architects created a parametric model based on the project's underlying design rules (Kolarevic 2003), proving the applicability of a parametric approach in a real context, evidencing its advantages for architectural practice.

In 1995, Future Systems's *Project ZED* was one of the first buildings resulting from a Computational Fluid Dynamic (CFD) analysis: it incorporated photovoltaic cells and a wind turbine to become self-sufficient regarding its energy needs. Resorting to CFD analysis, the architects could determine the optimal performance of the building envelope by channelling the wind towards the turbine (Kolarevic 2003). This project demonstrated that, using CD methods, it was possible to combine the creative process with the search for a better performing solution.

One of the greatest catalysts in theorizing new design directions and in postulating novel design, materialization, and manufacturing methods, was Frank Gehry's *Guggenheim Museum Bilbao* (1997). The architects used aerospace modelling software to model and guide the fabrication of the double curved surface panels. Actually, Gehry's office had been exploring digital technologies in architecture since the late 80s: with the *Walt Disney Concert Hall* project (1989) and the *Fish project* for Barcelona (1991).

Lastly, the design of the *Southern Cross Railway Station* roof (Grimshaw and Partners, 2002) used performance to guide the definition of its final shape. The roof had to, simultaneously, act as an umbrella/sunshade, be visually interesting, and extract stale air from the diesel trains. Its final design resulted from wind analysis, promoting the natural extraction of stale air, while shaping the roof in an organic way.

More recently, we find numerous other examples that heavily use CD, such as *Museo Soumaya* (2011) by FR-EE, *Huangzhou Tennis Center* (2015) by NBBJ and CCDI, *Raffles City Hangzhou* (2017) by UNStudio, *Louvre Abu Dhabi* (2017) by Jean Nouvel, and *Morpheus Hotel* (2018) by Zaha Hadid Architects, among others.

These examples demonstrated the advantages of using CD methods in architectural design. Moreover, due to their different aesthetic expressiveness, they became urban landmarks, representing important turning points in architecture that not only inspired future projects, but also encouraged the architectural practice shift. On the other hand, the intake of CD processes meant several changes in design studios, specially the adoption of collaborative design processes involving differently skilled professionals, which, for Hensel and Nilsson (2016), constitute a recent research focus within several design studios, like *Perkins+Will*, *White Architects*, *Woods Bagot*, *UNStudio*, and *SHoP*.

3.3 Theoretical background

CD methods changed the architectural design practice. Lately, such techniques became important subjects of architectural design theory.

To evaluate its theoretical evolution, we present a timeline (Figure 2) with CD literature organized into three generations of thought (the last two proposed by Oxman and Oxman [2014]): the *embryonic-generation,* embracing works until the early 90s; the *first-generation,* also known as the "Post-folding Period", i.e., the decade after *Folding in Architecture* (Lynn 1993); and the *second-generation*, starting at the 00s.

In the next sections, we contextualize the reader with the historical background of each generation, while presenting the scientific corpus that best characterizes each one.

3.3.1 Embryonic-generation (the 60s – early 90s)

Since the early integration of computation-based methods in architecture, the design theory has undergone several transformations. For Koutamanis (2005), the first steps happened in the 60s, a period in which the literature had as inspiration the modernist thinking, the occurring technological explorations, and other scientific fields theories, namely, artificial intelligence and mathematics. The resulting theory viewed architectural design as a rational activity, or as *thinking before acting* (Papamichael and Protzen 1993), that handled the design problems in an argumentative way. This theoretical shift was encouraged by works like *Theory and Design in the first Machine Age* (Banham 1960), Christopher Alexander's writings on design processes (1964), *Towards a Humanism Through Machines* (Negroponte 1969), and Ivan Sutherland's ideas on design variation methods, design constraints, and parametric instances (Ahlquist and Menges 2011).

The following decades witnessed an increase in the number of scientific publications and in the popularity of certain generative systems, such as Space Allocation techniques (Dietz 1974) and Shape Grammars (Stiny 1980). The 70s were marked by works like *Computer-Aided Architectural Design* (Mitchell 1977) and *A*

Pattern Language (Alexander et al. 1977), the publication of the first Ph.D. theses on CD (Yessios 1973; Akin 1979), and overviews on the CD ambitions of the time (March and Steadman 1971; Eastman 1975; Mitchell 1977).

In the 80s, CD gained recognition in the architectural field due to the convergence of the different approaches/techniques used, allowing it to evolve more coherently and to cover both the architectural and construction domains. Outstanding works of this decade include *Introduction to Shape Grammars* (Stiny 1980), *How Designers Think* (Lawson 1980), and *Computational Compositions* (Novak 1988).

The early 90s brought an increase in the popularity of computers among students and practitioners, which resulted from the design efficiency improvements of the new tools available. Also, an explosion of conferences, journals, and theoretical works on CD occurred during this decade, from which stand out *The Electronic Design Studio* (McCullough, Mitchell, and Purcell 1990), *Logic of Architecture* (Mitchell 1990), *Digital Design Media* (Mitchell and McCullough 1991), and *Visions Unfolding* (Eisenman 1992).

3.3.2 First-generation (early 90s – the 00s)

This generation is characterized by (1) a discursive interrelationship with philosophy and mathematics, (2) an attempt to characterize the new architecture being produced, and (3) a concern to correctly apply CD techniques in architecture while stimulating its use.

Starting with Lynn's *Folding in Architecture* (1993), a new paradigm based on "smooth transformations" was proposed, aiming at replacing Post-modernism and Deconstructivism in a visual and mathematical sense. In *Evolutionary Architecture* (1995), Frazer extends the *Anticipatory Architecture* of Cedric Price (Fox and Kemp 2009), defending an architecture that acts as a living evolving system. With *Animate*

Form (1999), Lynn proposes the use of animation software as a medium for form generation. Lastly, in *Architecture in the Digital Age* (2003) Kolarevic explores the impact that CD had in both architecture and construction fields, presenting some of the new terms resulting from it, like performance-based design and morphogenetic design.

3.3.3 Second-generation (the 00s – today)

In this generation, the paradigm shift became more accentuated. Previously, formulating new design theories required the understanding and reinterpretation of prior concepts, however, the emerging design paradigms of this period had no precedent (Terzidis 2004). The rapid evolution of design tools triggered a revolution in architectural theory, which considered the new perspective of design as research (Oxman and Oxman 2014), enabling architects to view design as a medium for knowledge production, promoting a theoretical shift following a more scientific, computation-based direction. In this scenario, human intuition becomes the starting point of design exploration, augmented by CD, which gives the means for exploring and experimenting in an alternative realm, potentiating human creativity instead of replacing it (Terzidis 2004).

For R. Oxman (2017), the use of CD in architecture is increasingly embracing more processes and techniques, e.g., scripting, optimization algorithms, and digital fabrication, which, in turn, originate new related terms, such as Parametric Design (Woodbury 2010), Generative Design (McCormack, Dorin, and Innocent 2004), Performative Design (Kolarevic and Malkawi 2005), Performance-based Design (Oxman 2008a), and Biomimetic Design (Oxman and Oxman 2014), among others. The result is an increase in the ramification of CD into multiple research perspectives and specializations; a variety of thoughts quite evident in the literature of this period, which we will describe in the following sections.

3.3.3.1 Intelligence in design. The idea that intelligence can inform and guide the design process emerged in the early 00s. Speaks (2002a) presented the *after theory* idea in which intelligence had replaced theory as a guiding architectural concept. Although in the past "theory changed the practice of architecture", according to Speaks, it "no longer has any consequences for the practice of architecture" (2002b). Works sharing a similar perspective include Oxman's *Digital Architecture as a Challenge for Design Pedagogy* (2008b), Picon's *Digital Architecture* (2010), and Carpo's *The Digital Turn in Architecture 1992-2012* (2012).

3.3.3.2 Performance in design. The notion of *performance* became quite popular in the early 00s. This notion emerged during the 40s-50s with the *performative turn* movement, which aimed at theorising *performance* as a social and cultural element (Hensel 2013), and reached its peak in the early 00s: resorting to simulation, optimization, form-finding, and evolutionary methods, authors such as Whitehead, Bollinger, Kolarevic (2005), Tschumi (1996), Kronenburg (2007), Oxman (2008a), Leatherbarrow (2009), and Picon (2012) studied the engagement of analysis processes with architectural design to understand how the environmental context can inform the design process.

3.3.3.3 Morphogenesis/evolutionary designs. In the past decade, the design paradigm *natural morphogenesis* emerged, focusing on applying the biological principles behind the development of organisms (Ahlquist and Menges 2011) and biological structures. The notion of *morphology* was introduced by Goethe (1790) in distinguishing *form* from *formation*, while focusing on form-guiding processes inspired by natural processes. Thompson (1961) continued studying this idea by focusing on the geometric laws behind organic structures and transformations. Recently, similar methods were explored and integrated in architecture as *morphogenetic* or even *evolutionary design* paradigms: e.g., Migayrou (2003) explored design processes in which geometry and production occurred simultaneously (naming it as *mutations of form*) and applied principles of *natural morphogenesis* to integrate differentiation processes in architecture; Hensel, Menges, and Weinstock (2004) analysed the differences between emergent properties in life and computation and the gap between nature and machinic production; Menges (2006) studied material systems performing through deformation or that self-organize to resist external forces. Still, for Ahlquist and Menges (2011), the full knowledge on biological formation was achieved only with the consolidation of genetics, thereby originating a third paradigm, *biomimetics,* using the principles of biological organisms to guide the design process (Oxman and Oxman 2014).

3.3.3.4 Algorithmic strategies. Architecture has also embraced methods from the computer science field, especially algorithmic techniques. The design paradigm *algorithmic architecture* was proposed by Terzidis (2006)*,* who believed that the use of algorithms in architectural design should be further explored due to the advantages it entailed in automating tedious tasks and exploring generative processes, among others. Similarly, Burry (2011) introduced the idea of *programming as a culture* and identified three scripting cultures in architecture, one for productivity, another for research, and yet another for creative exploration. Still within this perspective, we highlight the works of Woodbury (2010), Jabi (2013), and Schumacher (2009; 2012).

3.3.3.5 Material tectonics. The field of *tectonics* also gained prominence in architecture, with several authors studying the *design-tectonics* relationship, i.e., the relation between the structure of materials and architectural forms, e.g., *Architecture and the Virtual/Towards a New Materiality?* (Picon 2004), *Materialising Complexity* (Scheurer

2010), *Design Robotics: A new Paradigm in Process-Based Design* (Bechthold 2014), *Informed tectonics in material-based design* (R. Oxman 2012), and *Made by Robots* (Gramazio and Kohler 2014). Another example is the *AD Magazine Versioning* issue (SHoP 2002), which anticipated the agenda of the BIM software being developed at the time.

3.3.3.6 Material fabrication processes. The universe of material fabrication constitutes another research topic studied by authors who focused on linking CD methods to the growing sophistication of both materialization and fabrication technologies: e.g., Lisa Iwamoto (2009), Willmann et al. (2012), and N. Oxman (2015; 2012; 2017). This connection is also evident in the latest buildings resulting from advanced fabrication processes, whose application differs from studio to studio, e.g., *Design to Production*, *Gehry Systems,* and *Zaha Hadid Architects*,

3.3.3.7 Interactive design. The idea of a design capable of interacting with both the users and the environment is the basis of *responsive*, *interactive*, or *dynamic design* approaches. This notion was already addressed in the mid-20th century by Chareau and Bijvoet with *Maison de Verre* (1932), by Fuller with his *Dymaxion houses* (1930 and 1945), and by *Archigram* with their utopian projects (1964); and later by Rogers and Piano with the *Centre Pompidou* (1977), by Nouvel with the *Institute du Monde Arabe* (1988), and by Toyo Ito with the *Tower of Wind* (1991). Current works on this design perspective are authored by, for example, Beesley, Hirosue, and Ruxton (2006) and Oosterhuis (2011), not only enhancing the behaviour of responsive materials by resorting to parametric control mechanisms, but also exploring new related terms, e.g., “smart surfaces”, “intelligent facades”, “hybrid materiality”, etc.

3.3.3.8 Patterns of knowledge. Although mathematics has always been a part of architecture, only recently did architects recognized the importance of studying mathematics, geometry, and computer science. Pottmann (2010) evidenced the importance of architectural geometry and CD in creating design knowledge, claiming that architects are now more engaged with design research. Lately, the design field has been witnessing the application of more mathematical methods, resulting from the increasingly complex requirements of both architectural design and construction. An example is the use of rationalization processes to adjust a geometrically complex design towards a feasible and affordable solution, a research area addressed by Andrade, Harada, and Shimada (2017), Eigensatz et al. (2010; 2010), Flöry and Pottmann (2010), Fu and Cohen-or (2010), and Son et al. (2017), among others. Another example is the development of architectural design patterns, i.e., the reuse of known strategies or solutions in solving design problems (Qian, Chen, and Woodbury 2008), a subject explored by authors such as Woodbury, Aish, and Kilian (2007), Qian (2009), Woodbury (2010), Hudson (2010), Larson (2012), Chien, Su, and Huang (2015), Yu and Gero (2015), and Su and Chien (2016), who aimed at facilitating the programming task by promoting the reuse of knowledge in the search of new design solutions; a scenario that not only avoided repeated reinvention, but also reduced the development time of algorithmic solutions.

4. Final considerations and conclusion

The growth of architectural theory is closely linked to both social and technological issues. These have been constantly evolving and, at the same time, influencing the design field. The 00's brought new social and environmental concerns, to which architects have become quite sensitive, motivating the need for performance analysis and optimization. At the same time, the design field has been increasingly embracing methods and approaches from other fields, namely biology, mathematics, mechanics, physics, and, more frequently, computer science, enriching both the design practice and theory.

To promote a more critical view on the evolution of CD within architecture, we summarized its evolution over the last decades, organizing it into three main perspectives: the technological, the research, and the theoretical. We also presented two timelines, one based on CD technological and scientific events, and the other on CD publications. Finally, from the analysis of these timelines, we now draw considerations on the CD evolution in the architectural field.

Firstly, we note the profound impact that technology can have on architecture. The advances in the digital computer made *Sketchpad* possible and this, in turn, caused a revolution in the architectural practice. Secondly, it is also the case that the design limitations felt by the architectural community end up causing the development of new technologies and design paradigms that address them. With time, these technologies become commercially viable and are embraced by the architectural practice. This cycle has been recurrent and, on each iteration, many related research directions are pursued, as is visible in the scientific publications and international conferences associated with the technologies of the time.

As a case in point, consider BIM, which was developed to overcome the limitations of 2D technical drawings, incorporating additional dimensions for improving the coordination between the different specialties. Similarly, programming was a frequent request that motivated CAD vendors to develop dedicated programming languages, such as *AutoLisp* and, later, *Generative Components*, for visual programming. Still, it was the release of *Grasshopper* that made the interest in AD techniques intensify among the architectural community, mostly because it provided an attractive, more intuitive, and, most importantly, economically accessible solution.

As another example, the development of simulation and analysis tools made performance analysis possible and triggered the interest of architects, particularly, due to the growing concerns regarding the environmental impact of architecture. The combination between AD and analysis then made optimization desirable and promoted the emergence of tools that considerably simplified its exploration (e.g., the combination *Rhinoceros*/*Grasshopper*/*Galapagos*). This led to a vast research on design approaches (e.g., evolutionary, performative, morphogenetic, responsive, and embryologic, among others) that seek for solutions with good performance regarding different criteria, such as, energy, daylight, and thermal.

The interdependency between CD and technology will continue in the future and, thus, we should expect new developments in architecture caused by the current technological advances. Robotics deeply changed the automotive and aerospace industries and, despite its application in architecture being still in the embryonic research phases, when the technology becomes more accessible, it will become widespread (Gramazio and Kohler 2014). Similarly, machine learning is starting to have a large impact in many different areas and activities, from medicine to driving, and we preview that it will also affect the architectural field (Tamke, Nicholas, and Zwierzycki 2018; Belém, Santos, and Leitão 2019). At the very least, it will force architects to adapt to new design techniques, as it happened with the introduction of CAD (Ebel and Ulrich 1987).

Despite initial fears that CD methods would replace the architect's role, we verify that, instead, they address and support his creative needs. In fact, their use in architecture has proven to empower architects with further design knowledge, a wider range of design possibilities, more advanced design and construction methods, and a higher conscience and control over the design conception.

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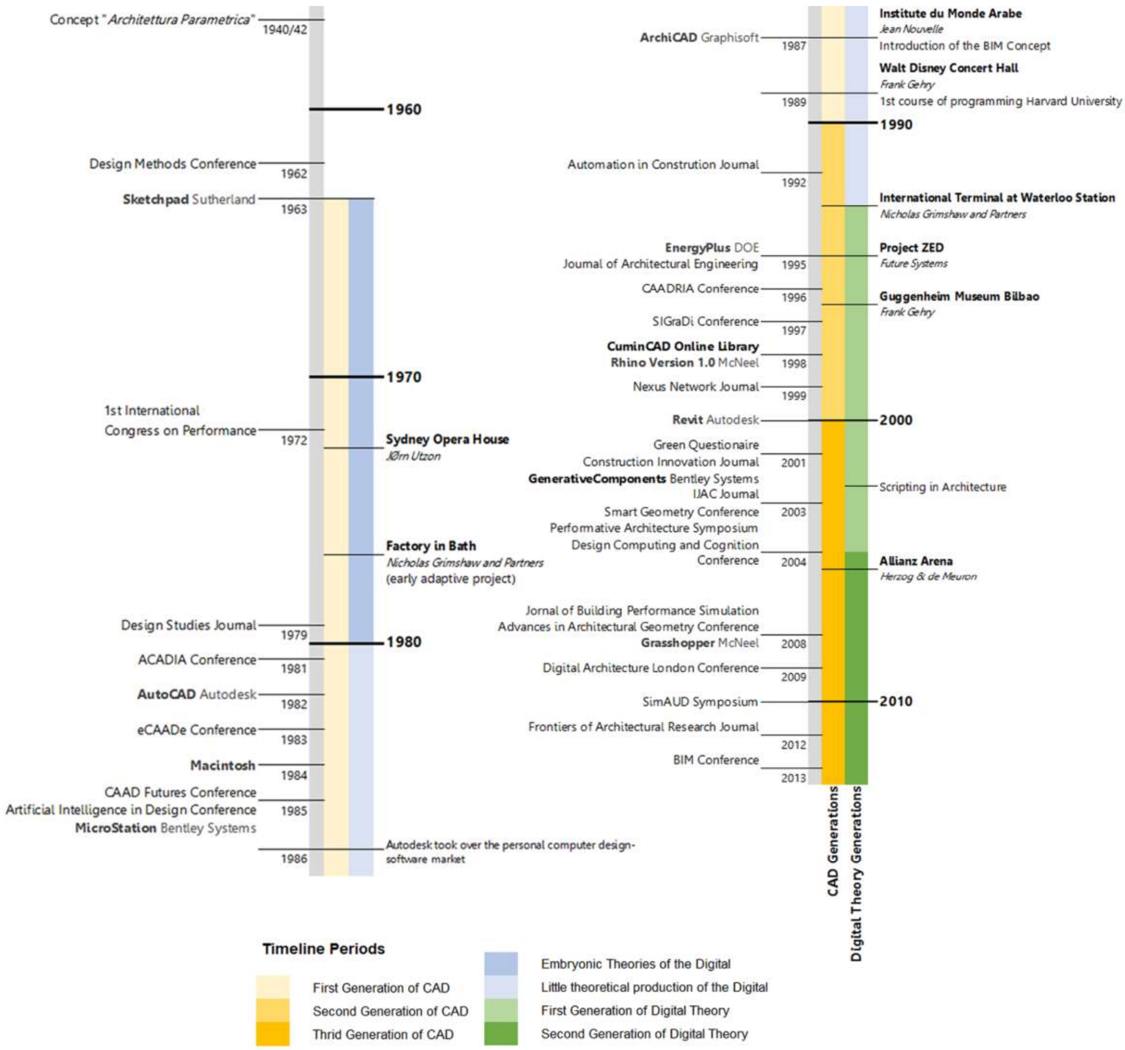

Figure 1. Timeline on CD technological and scientific events.

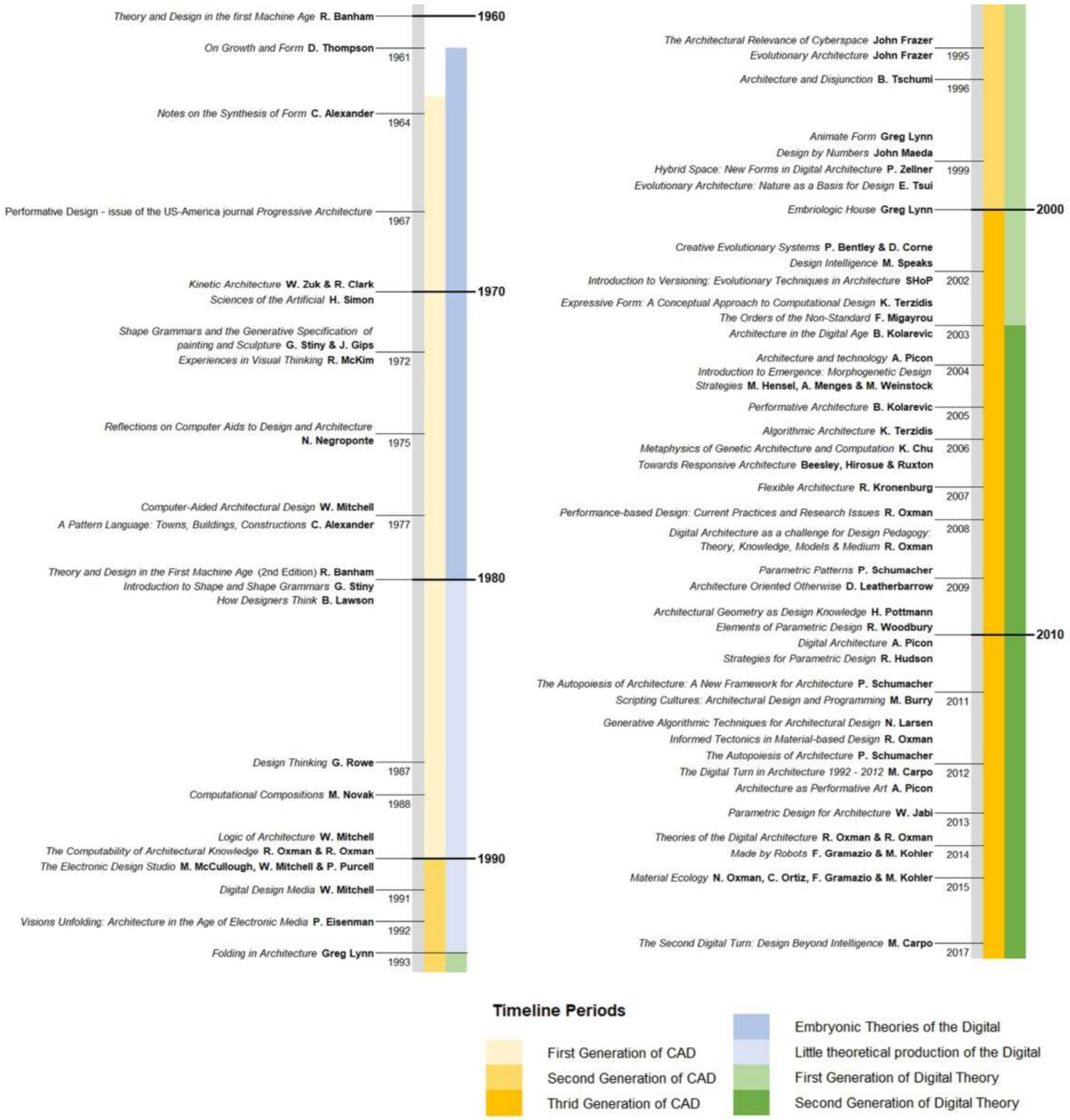

Figure 2. Timeline on CD literature.