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ARCHITECTURAL DISRUPTION IN THE AGE OF COMPUTATION: A CRITICAL REVIEW ON DIGITAL ARCHITECTURE

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INTRODUCTION

This paper investigates whether digital architecture qualifies as disruptive innovation comparable to modernity's transformative impact. It contextualizes digitality by analyzing exemplary digitally designed projects across structure, form, and materiality. The goal is to define what architectural disruption looks like in the age of computation, focusing on the mentioned threefold conceptual framework.

According to Kenneth Frampton (1995), structural logic and construction techniques are central to the poetics and aesthetics of architecture across history. Similarly, Mario Carpo (2013) has noted that digitally-enabled variability in geometrical form constitutes a key innovation, differentiating digital architecture from rigid modernism. Greg Lynn (2013) highlighted the parametric derivation of complex surfaces as a departure from rectangular modernist orthodoxy. Zeynep Mennan (2008) revealed that formalist methodologies used in computational design broaden architecture from a standardized to a non-standardized realm. By synthesizing these insights, this paper addresses this triad of structure, form, and materiality through a systematic critical analysis.

The research questions guiding this study are:

1. What are the conditions for architecture to be considered disruptive in the age of computation?
2. How does digital architecture challenge the standards set by modernism or postmodernism in terms of structure, form, and materiality?
3. What are the conceptual reorientations and possibilities that computation opens up for the future of architectural design and practice?

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To conduct this research, the authors have critically analyzed the so-called digital architecture, trying to identify features and characteristics that make it a differentiated niche within contemporary architectural trends. Even though current architectural production is facilitated through the use of computers, not every contemporary practice can be regarded as either disruptive or digitally conscious. The latter could be defined as digitally designed architecture whose output would be impossible to achieve without the tool itself, benefiting from different forms of computational design. However, the purpose should not be confused with the means. Although the tool may be a determining factor, it is the design itself what should concern architectural criticism, not the fact of its accomplishment through the tool.

This research tries to identify the transformative changes that information technologies, computation and digital culture have introduced in architectural practice, challenging the standard set by modernism or postmodernism. An increasingly wide array of software tools contributed to advancing architecture in the first decades of their irruption. However, it is the computational logic of the design that allows the creation of conscious forms for optimized environmental and structural behavior within a new computational design paradigm.

The research methodology involves an in-depth literature review of over 50 sources, papers, and books. Additionally, the case selection has been mostly made by searching for keywords and disruptive practices in the threefold conceptual framework of structure, form, and matter. Consequently, these examples are critically addressed to establish the conditions of disruption in the age of computation. As Carpo (2013) suggests, digital architecture requires being assessed on its conceptual reorientations more profoundly than on its superficial stylistic features enabled by new tools. Accordingly, the authors have observed the effect of these tools on architectural language and the changes introduced in the way we think, design, and build architecture. What began as a mere optimization of the design processes with the use of computers has now achieved a truly disruptive advancement in the design and production of architecture, genuinely affecting architectural language itself. Thus, part of the aim is to provide a critical historiographical contextualization for this architecture.

A thorough reflection on the term disruption itself and the conditions necessary for architecture to be considered disruptive is followed by a dialectical discussion comparing the disruptive qualities of modern architecture as well as the parallels and divergences with contemporary digitally conscious architecture. The review dwells on well-known examples, and the original contribution of the paper lies in the critical analysis and synthesis of these examples across the triad of structure, form, and materiality, establishing the conditions of disruption in the age of computation.

Going beyond just analyzing current digital practices, the paper reflects on how computation enables new ways of conceiving and fabricating buildings by managing complexity, simulating building behavior, and integrating design and manufacturing. This study argues for a digitally conscious architecture that harnesses the generative and optimizing potential of computational tools while still engaging architecture's humanistic foundations. The paper maps out an open-ended trajectory for the ongoing developments on digital disruption.

The paper is structured as follows: Section 2 discusses the concept of disruption and its relation to modern architecture. Section 3 examines the conditions for digital disruptive architecture. Sections 4, 5, and 6 analyze disruptive tectonics, aesthetics, and materiality, respectively, through case studies. Finally, Section 7 concludes by synthesizing the findings and outlining future research directions.

DISRUPTION

Apparently, there is a certain contradiction between the terms discipline and disruption. The problem relies on considering tradition as an established standard of any creative discipline while obviating the course of history with regard to a time perspective. Of course, even well-established styles are not a perfect set of unchanged rules during a precise time span. Changes appear as language evolves and settles through repeated practice in leading figures of the period which are then spread by others. Yet, the style is always impersonal as it is referred to a collective disciplinary practice. Architecture has its own history and, therefore, its own creative tradition, a sort of "accumulated knowledge of all previous architectures", in the words of Eisenman (1999, 37), who refers to it as architecture's anteriority.

As aforementioned, classical language in architecture was reinterpreted for almost five centuries. Benevolo (1978) defines the span of Renaissance architecture from the onset of this historic period to 1750, when a group of artists decided to work inspired by the remains of Roman architecture, while Frampton (1985) dates neoclassical architecture in a time span comprised between 1750 and 1900. However, it is obvious that Renaissance architecture differs from Roman architecture; in fact, it was quite different from Mannerism or Baroque (Wölfflin, 1964). Yet not every change is certainly disruptive; not even a change of style is necessarily disruptive. That is the reason for Benevolo or Summerson referring to "Renaissance architecture" or to "the classical language of architecture", respectively, although the time span of their analysis runs through several centuries and different styles. The question to be posed should then be: to what extent can any change be considered genuinely disruptive?

The term disruption was originally used in academic circles within the field of business management regarding innovative practices and business models. It was used to point out situations of rapid intense change in previous business models and focuses on the emergence of new ones indebted to accelerated processes of development, commercialization as well as to the use of innovative products or services. Christensen and Bower (1995) coined the term "disruptive technology", a concept that was later analyzed more in depth in the book *The Innovator's dilemma* (Christensen, 1997), where it was redefined as "disruptive innovation". The concept of disruptive innovation began in this way a process of accelerated diffusion in all fields related to creative innovation although frequently misunderstood, as the authors themselves stated in a more recent article (Christensen and McDonald, 2015).

According to the original framing of disruption and extrapolating it to architecture, it could be stated that it involves a rapid transformation due to emerging technologically innovative changes displacing existing models. Thus, the evolution of architectural language is produced slowly throughout history based on successive variations introduced through disciplinary practice and only, on few occasions, a sudden significant innovative alteration occurs involving not only a change in architectural language itself, but the replacement of a well-established tradition. According to this, Gothic revival in the nineteenth century could not be regarded as disruptive. It wasn't then innovative as Gothic surely was in relation to Romanesque when it first emerged as a truly disruptive style in the twelfth century.

Disruption involves change, but not any kind of transformation. It implies substantial innovation which does not only affect the stylistic appearance, the ornamentation repertoire and the like. Disruptive innovation is a "mindset" rather than "a tactic in itself" (Williams, 2016). In architecture, disruption implies a transformation in tectonics influenced by a novel conceptual framing which altogether introduces a significant alteration of architectural language itself.

The most significant disruptive changes in the history of architecture are indebted to the alterations of the topological relationships established between the supported and the supports, allowing different kinds of spatial possibilities and architectural form. Giedion (1971) refers to three stages in the conception of architectural space throughout history. The first two can be exemplified by the architecture of Greece and Rome, respectively, while the third emerges with the dismembering of structure and enclosure once the tectonics of steel and reinforced concrete freed walls from their loadbearing function. Frampton (1995, 365) has reflected extensively about the major importance of tectonics in his consideration of architecture as the "poetics of construction" and on the significance of the construction technology in the conformation of architectural modernity. The early stages of digital architectural design and the solely formalistic approach characterizing the so-called blobitecture initially received harsh criticism esteeming it as unrealistic or counter-tectonic (Picon, 2004).

Summarizing, disruption involves innovation and radical transformations in architectural syntax, changes that can embody a new *zeitgeist* while setting a novel framework that eventually displaces the existing. Although the most genuinely disruptive changes in architecture are indebted to tectonics, as these greatly affect its syntax, topology and materiality, alternative possibilities to address disruption are also possible regarding other disciplinary aspects that refer not only to structure, but also to aesthetics, ideation, materiality, utility and optimization.

Digital architecture can claim to be disciplinary disruptive in many ways and has proven to be a genuine avant-garde within architectural practice at least over the last three decades. We must also bear in mind that not all disruptions necessarily come hand in hand through technological innovations. Ideas can be more disruptive than digital tools; eventually, the embracing of these may recall previous periods, such as the so-called digital crafting.

The term disruptive is increasingly trendy in the field of digitally designed architecture. The influence of a series of new paradigms in the design process could also be considered disruptive within an innovative architectural context characterized by the emergence of new formal sensibilities, the crisis of the concept of stability and the challenging of Vitruvian categories (Picon, 2010).

Figure 1. Source: (Zaha Hadid Architects, 2013). Zaha Hadid Architects, Morpheus hotel (digital rendering), Macao, 2013-2018.

DISRUPTION AND MODERN ARCHITECTURE

Giedion (1964) addressed the idea of constancy and change in his famous sequel of *The Eternal Present* dedicated to architecture. He studied the architecture of Egypt and Sumer identifying the basic elements that define architecture and the principles that have inspired architectural production ever since. Egyptian architecture with its colossal proportions set the basis for permanence as a disciplinary attribute. Architecture evolved enriching the scope of functions although this genuine attribute remained. Thus, architecture has been "conventionally conceived in a dimensional space of idealized stasis, defined by Cartesian fixed-point coordinates" (Lynn, 1999, 10).

Despite this idea of permanence, architecture is subject to changes, interpretations, and variations. All of these, produced in the course of time, progressively generate a history, a practice based on a recorded tradition which combines strategies of difference and repetition (Deleuze, 1994) along the dialectic course of history (Hegel, 1977).

Classical architecture was typologically driven: models were repeated and reinterpreted thus contributing to set a style. An architectural style is a collectively agreed way of designing during a given period of time. This remained so until the crisis of the styles in the nineteenth century debating itself between eclecticism and revivalisms (certainly not disruptive) trying to find in the past the justification for architectural practice. In part, these were the genuine intentions of Renaissance architects, endeavoring to vivify a classical glorious past: a language to be preserved. This illusion proved to be so successful that for a period of no less than five centuries classical language was reinterpreted relentlessly (Summerson, 1966, 7).

Traditionally, art historians have dealt with formal changes, especially focusing on ornamentation and the articulation of the physical limits themselves rather than the space confined by them (Zevi 1974). They have underestimated the relationship between matter and space and the way in which this is achieved through tectonics. Thus, the Romans were classical because they kept using the ornamental repertoire of the Greeks, but they were, in fact, disruptive in the way they substituted post and lintel architecture for vaulted construction, certainly not because they added Tuscan and Composite orders. Remarkably as it may seem, Vitruvius never “mentions arches or vaults, which were already a major achievement of Roman engineering” in his treatise (Carpo, 2017, 1). It was the relationship between matter and space, between exterior, enclosures and interior what clearly implied a breakthrough in the course of architecture. Only, thereafter, did architectural space achieve an effective leading role within the discipline. Surprisingly, it was not until the nineteenth century when Schmarsow (cit. Van de Ven, 1978) began to consider space a key aspect in architectural theory.

The polarity between tradition and modernity is the driving force of progress in any creative discipline; every artist is bound to position his work with regard to valuable precedents in order to defy them, to imitate them or, simply, to produce variations over them. Innovation does not magically appear by chance nor is it a mere product of inspiration. Paul Ricoeur (2003, 23) wrote to this regard: “In the same way that each writer writes ‘after’, ‘according’ or ‘against’ something, each architect determines himself in his relation with an established tradition”. Creativity sparks out of a critical reading of disciplinary precedents, on the one side, and a conscious positioning with regard to them, on the other. It is the poet who affirms the difference “overturning all orders and representations” instead of repeating what he has been taught or uncritically following the pre-existent models within the discipline (Deleuze, 1994, 53).

The architectural controversy of the *querelle des anciens et des modernes* probably transcended the circle where it was held, *l'Académie royale d'architecture*, because it is a good example of the tension between tradition, personified by Blondel, and disruption, on the side of Perrault, magnified by subsequent criticism (Gerbino, 2010).

Perrault's modernity relies on his questioning of the absolute and permanent embodied in the classical orders uncritically reinterpreted for centuries and on the value given to materiality, functionality and comfort. His approach served as an inspiration for Cordemoy, Laugier or Milizia as the brave innovators in architectural theory with the emergence of rationalism, contributing to set the basis of modern principles and the constructive logic of tectonics.

Modernity, in a broader sense, could be identified with disruption provided it is opposed to tradition and driven by a progressive spirit of innovation. Modernist architecture should be, accordingly, considered a brilliant moment of disciplinary disruption even if it ended up establishing its own architectural canon (Miranda, 2005).

Considering all of the above, disruption in the context of architecture can be considered so provided several conditions are observed. Thus, it could be defined as a major change rapidly driven by innovative practices affecting both tectonics and the conceptual framing of the discipline itself, merged to embody what could be referred to as a new practice that succeeds to displace a preceding established tradition. If digital architecture is to be considered truly disruptive, all these conditions have to be met.

A question then naturally arises: which architectural style if any, should digital architecture challenge?

CONDITIONS FOR A DIGITAL DISRUPTIVE ARCHITECTURE

Although visionary Cedric Price's Fun Palace 1964 project and the collaboration of Gordon Pask in the design is regarded as one of the first noteworthy steps in the integration of architecture and cybernetics (Mathews 2005). It is probably the 1980s the decade when we may consider that digital architecture's foundations truly began (Lynn 2013). At the time, rampant pseudo-classical historicist postmodernism was living its glorious moment, boldly confronting modernist principles. Probably, the least disruptive change in the history of the discipline as it superficially repeated a formal repertoire taken from classicism (only in a literal ornamental sense), however building with reinforced concrete and steel. Thus, it completely undermined the tectonic sense and its relationship with geometry and structural types; moreover, it was certainly not innovative. Historicism is a "mode of operating" based on repetition strategies rather than a stylistic problem as Somol (1999, 10) has wittily noted regarding the pretended modernity of the late works by Richard Meier: his repetitive design strategies have undermined the modern to become historicist itself.

In 1931, Henry Russell Hitchcock and Philip Johnson were commissioned by the MoMA to curate an exhibition on the incipient architectural modernism which exhibited early works of the main figures (Wright, Le Corbusier, Mies van der Rohe, Aalto, Gropius, Oud). The title of the catalogue, *The International Style*, proved to be so successful that it eventually coined the name for the emerging architecture (Hitchcock and Johnson, 1966). Wright's organic architecture did not fit in the rigid canon set by both curators and was, therefore, censored in the catalogue. The canon, greatly indebted to Le Corbusier's five points of architecture, as admitted by Hitchcock (1951) years later, identified three principles. The first, "architecture as volume", actually meaning the dismembering of architecture in skeleton and skin (consistent with Corbusean first point: construction on pilotis, from which the rest of them basically stem). The second, "regularity", is in part an aesthetical feature somewhat derived from the repetition at regular distances of the supports. This feature displayed architecture's order while also ensured "that strains may be equalized" presenting characteristic gridded façades (Hitchcock and Johnson, 1966, 56). The third was dictated as the "avoidance of applied ornament" and was the very metaphor of constructive sincerity, thus evidencing the tectonic logic while avoiding false impressions. Architecture's materiality ought to appear bluntly, as it represented the truthfulness of the constructive system. If we were to categorize the three principles the first would deal with tectonics, the second with aesthetics and the third with materiality: structure, form, and matter.

In 1988 the MoMA held another exhibition titled *Deconstructivist Architecture,* curated by Philip Johnson again and Mark Wigley. A relatively heterogeneous group of architects, most of which were later to become world famous (Eisenman, Tschumi, Libeskind, Coop. Himmelblau, Zaha Hadid, Koolhaas and Gehry), exhibited their production at the time which, according to the exhibition catalogue's claims, shared "striking formal similarities" (Johnson and Wigley, 1988), even if the exhibited works were rather diverse and the claim too bold. Although some of them have been relatively critical with the digitally driven shift in architecture, others have, in fact, pioneered it, as may be the case of Gehry, Eisenman or Zaha Hadid.

Furthermore, it is necessary to note that many other noteworthy architects took different paths that lead to alternative interpretations and positionings with regard to modernity. Architects such as Foster, Piano or Rogers relied on technology while others such as Mendes da Rocha, Vilanova Artigas, Niemeyer or Candela further exploited the expressive possibilities of reinforced concrete to a larger scale in their architectural production. The Smithsons, Stirling, Neutra, Saarinen, Holl, Nouvel, Siza, de la Sota, and many others would further extend modernity with different nuances. However, neither of them could be considered part of the historicist postmodern trend nor did they use digital tools to consciously follow a digital disruptive approach.

According to this time-frame, digital architecture commenced its disruptive road map through the work of a few. From this perspective, deconstruction in architecture (if there was ever any such a common program as Tschumi (2012) himself has admitted) could not be part of the displaced style but the first manifestation of the new. Genuine disruption may only be achieved if digital architecture manages to effectively challenge modernist architecture (the only valid and valuable established canon at the emergence of the digital turn), something that implies looking innovatively into the future and working on a digitally conscious design basis (Carpo 2013, 10).

In 2003 another exhibition took place curated by Frédéric Migayrou and Zeynep Mennan titled *Architectures non standard* at the Centre Pompidou. It showcased a series of architectural practices(Asymptote, dECOi Architects, DR_D, Greg Lynn, KOL/MAC Studio, Kovac Architecture, NOX, Objectile, Oosterhuis, R&Sie, Servo, UN Studio) that addressed the shift of paradigm introduced by customized mass production through CAD-CAM tools replacing the industrial and modern ideals of serial production for non-standard modes of production (Carpo, 2005). This exhibition delved into multiple references that included mathematics, physics, philosophy, architecture and art alike, setting up the stage for a rich intellectual background of the digital realm (Migayrou, 2003). It is therefore worth analyzing the hallmarks of digital architecture with regard to structure, form and matter to gauge the sort of disruption that it has brought.

The introduction of CAD, digital 3D modeling, visual programming languages (VPL), and BIM, along with the concept of digital twins, has undoubtedly improved architectural representation. However, these advancements primarily focus on representation and do not extend beyond it. It is the integration of a computational logic into architectural design over the past fifteen years that has profoundly revolutionized the discipline in the realm of digital architecture.

Traditional graphic representation's role is not only questioned but also completely transformed. The use of code as a means to generate instructions, prototype forms subjected to performance criteria through generative design approaches, genetic algorithms, and iterative methods that mimic nature's evolutionary model, have fostered a new mindset. Instead of solely focusing on form-making, architects now emphasize form-finding, or as Carpo (2017) aptly puts it, "form searching." Architectural geometry, now deemed advanced or intelligent, has been rethought to explore the interplay between form, material, and computer tools, employing a wide array of approaches that showcase the generative potential of digital techniques (Pottmann, 2014).

This newfound integration with the digital realm is reshaping tectonics through material and form simulation and optimization, thereby introducing structural considerations (Oxman and Oxman, 2014). The emergence of digital tectonics has shifted priorities between architectural and structural elements, giving rise to novel representation and generation methods through strategies like "digital morphogenesis," which emulate the evolutionary capabilities of natural systems (Leach, 2009). These generative processes are digitally interconnected, spanning from conception to materialization, and seamlessly integrated into the logic of material manufacturing. This seamless integration of processes (generation, materialization, and manufacturing) defines the core characteristic of the new digital design/information paradigm in architecture.

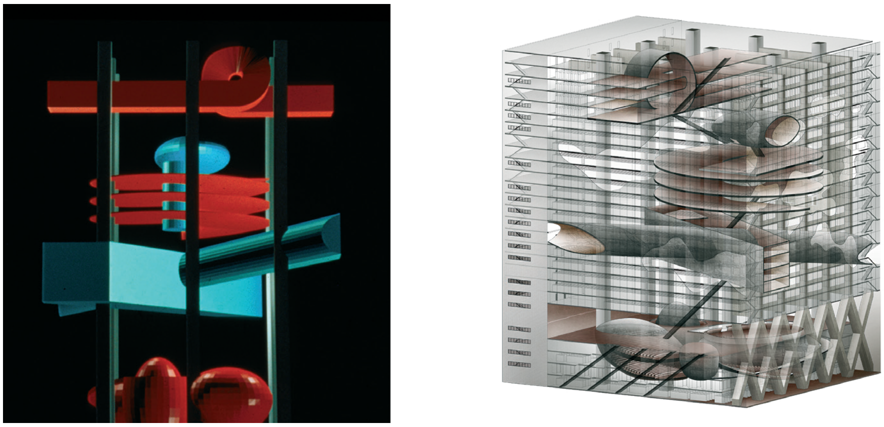
These new tools offer architects the ability to mediate with tectonics, bridging the gap between information and matter. Form-finding processes are guided by three principles (Oxman and Oxman, 2014): the differentiation processes inherent in natural systems, informed or integrated tectonics, and continuity from design to production by incorporating material logic into the parametric approach.

The concept of open form, parametrization in designs, algorithmic possibilities, and form-finding strategies aimed at optimization along with the convergence of construction and manufacturing processes, represent a significant disruptive leap in architectural practice. Through computational logic, architects can now enhance and improve their designs with a focus on optimization rather than form. Architectural geometry is no longer dictated by a top-down approach but, instead, follows a bottom-up logic based on form-finding strategies (Leach, 2009, 34).

DISRUPTIVE TECTONICS. STRUCTURAL RELEVANCE

An extraordinary competition entry for the French National Library designed and submitted by OMA in 1989 (**Figures 2a, 2c**) was discarded not without polemics as the decision was finally taken by president Mitterrand himself (Sudjic, 2006). As for most architectural practices at the time, digital tools were only timidly used, although they were in this case. Most of the models made for this project were, however, physical, something which has been a standard of OMA's design process ever since they commenced their practice. Although it cannot be regarded as a digitally conscious design, it could be ventured that the subtractive strategies typical of Boolean 3D modeling set the conceptual disruptive framing of the building's overall conception: "the major public spaces are defined as absences of building, voids carved out of the information solid" (Koolhaas and Mau, 1997, 616) (**Figure 2a**).

Cecil Balmond, a former Ove Arup structural engineer, collaborated in the conception of one of the most disruptive building structures in the century: enormous deep-beams (walls 100 meters high), spanning 70 meters within the cube, capable of supporting gigantic perforations to host five thematic libraries inside the information solid (Koolhaas and Mau, 1997, 673). In fact, Balmond has significantly contributed in other OMA projects but has also collaborated with other well-known architects such as Stirling, Libeskind, Toyo Ito, Moneo, Siza, UNStudio, to mention a few. In the past decades, he has been working at the intersection of architecture and



Figures 2a. OMA's proposal for B.F.N., Paris, 1989. Sources: (OMA, 1989) Digital Visualizations. Original conceptual 3D model. **2b**. (Oscar Rubio, 2015) Axonometric view by showing in transparency the structure and the five thematic libraries.

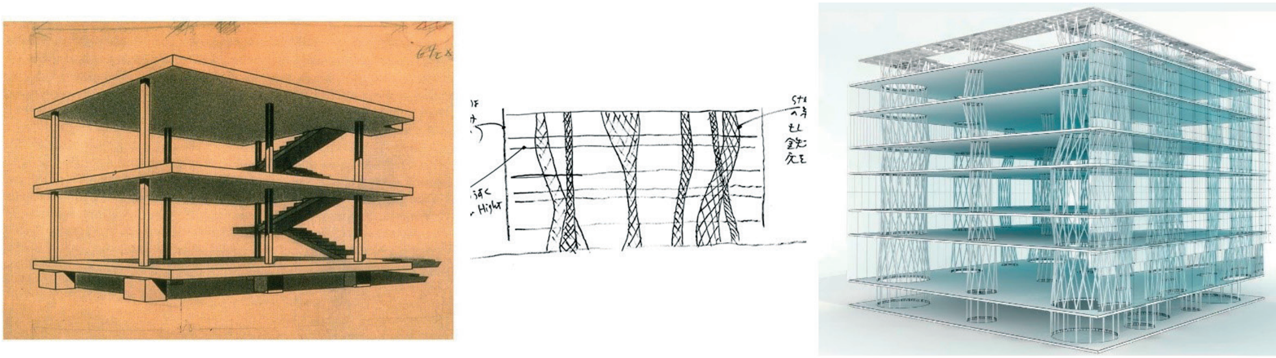
structural engineering. His mastery in the field of tectonics has contributed to the development of complex geometries and the feasibility of their construction, an initial limitation during the 90s of blobitecture and the emerging folding architecture (Mallgrave and Goodman, 2011, 170).

Sendai Mediatheque (**Figures 3b, 3c**) designed by Toyo Ito is an example of truly digital tectonic disruption. It is apparently similar in conception to Le Corbusier's Domino (**Figure 3a**) structural scheme of slabs and columns. However, instead of regularly placing the latter in accordance with a fixed grid, the columns here are concentrated around circular openings in the slabs with different diameters slightly misaligned, so that the characteristic verticality indebted to guarantee the necessary continuity in the transmission of stresses is stepped over thanks to this new topological relationship (Ferré and Sakamoto, 2003).

What was originated as a metaphor of seaweeds in Toyo Ito's conceptual design (**Figure 3b**) proved to be even more relevant from a structural design point of view. This geometric disruptive approach has a significant tectonic influence in the structural behavior of the whole building as its resistance to horizontal stresses is greatly enhanced due to the increased rigidity of the composed vertical supports (the light-wells made-up with the columns irregularly skewed). This design feature proved to be providential during the earthquake that Sendai underwent in 2011, leaving the building relatively unscathed despite the 9.0 magnitude of the seismic catastrophe resulting in the Fukushima's nuclear accident.

The National Stadium designed by Herzog & de Meuron for the 2008 Olympic Games (**Figures 4a, 4b**) could well be considered another example of tectonic differentiation and relevance regarding modern precedents

Figures 3a. Le Corbusier, Domino houses structural scheme, 1914. **3b, 3c**. Toyo Ito, Sendai Mediatheque, 1995-2001. Inception drawing and structural scheme. Sources: (Le Corbusier Foundation, 1914; Desigboom, 2012; Shaowen Wang, 2011, respectively).



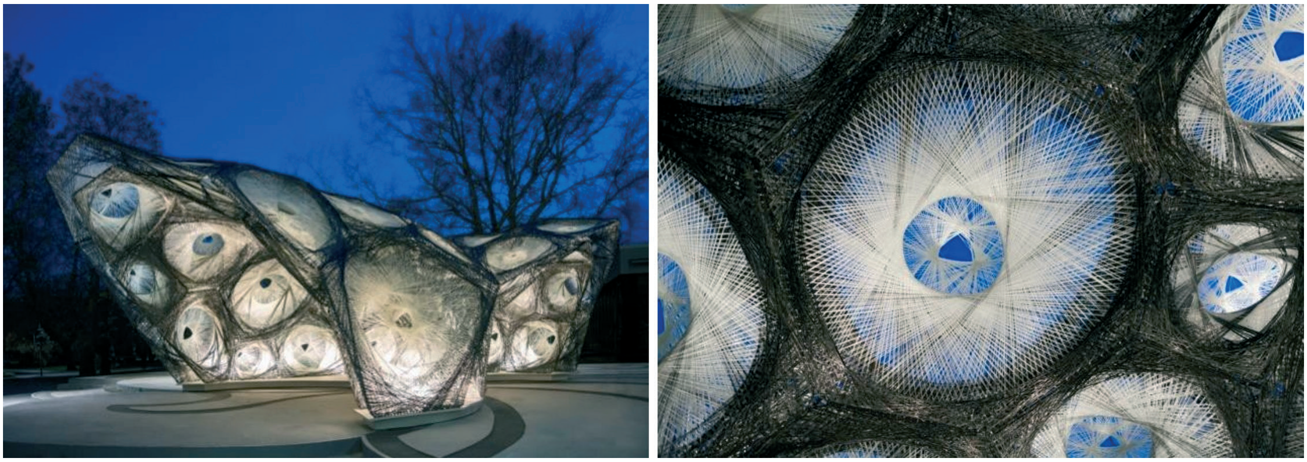

Figures 4a, 4b. Herzog & de Meuron, Beijing's Olympic Stadium, 2003-2008, Source: (Herzog&de Meuron, 2011).

in which the structure is typically an undifferentiated grid of pillars and beams. The extraordinary geometrical complexity of the hyper-static nested structure of the stadium would have been impossible to calculate without the computerization potential of digital tools and finite elements calculation methods, something for which computers greatly surpass human capacity. From its inception to its construction, the stadium could have not been conceived or built without computerizational aid.

A significant number of projects digitally developed make use of a conspicuous relevance of structure of which exoskeletons are notably some of the most evident. Projects such as Zaha's Morpheus in Macao (**Figure 1**) is a good example of this design strategy which, in this case, is also part of an improved design feature to counteract the climatic particularities of the location (the recurrent typhoon exposure). The building's exoskeleton was designed to support the extraordinary strong winds produced by the endemic typhoons, something which could be considered as a contemporary digital reading of critical regionalism.

Digital tectonics defines a new relationship between structure and materiality balancing the focus between space and structure (Oxman and Oxman, 2014). Structure recovers the prominence it used to have in Gothic architecture, thus contributing to the configuration of architectural space in some of these buildings. Although there is no material equivalent to reinforced concrete or steel which contributed to shape architectural modernism, disruptive tectonics have also explored the use of alternative materials such as carbon fibers as Achim Menges has been able to achieve "at the juncture of structural design, design and digital production" (Picon, 2022, 67).

Some research projects are delving into the prospect of applying the principles found in biological fiber systems to architecture, offering a fresh perspective on reinforced fiber structures to which Achim Menges refers to as "fibrous tectonics". The various proposals for the ICD/ITKE Research Pavilion exemplify a comprehensive approach to biomimetics (Pawlyn, 2016, 62–5), computational design, digital simulation, and robotic manufacturing, all aimed at creating structures of exceptional lightness and optimal material efficiency (**Figure 5**). Drawing inspiration from the morphological principles observed in arthropod exoskeletons, this pavilion serves as a platform for exploring innovative spatial designs through diverse textile methodologies, filtering various biomimetic design principles to establish a new tectonic repertoire. The digital fabrication



Figures 5a, 5b. Institute for Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart, ICD-ITKE Research Pavilion 2013–14, Stuttgart. Source: (Archdaily, 2014)

process relied on robots tasked with executing the "coreless robotic filament winding process," enabling the construction of "construction-scale composite structures on a simple linear framework" (Menges, 2015, 45). These remarkably lightweight tensile structures explore geometries and techniques that transcend traditional architectural practices, drawing from a range of disciplines and trades.

DISRUPTIVE AESTHETICS. IRREGULARITY AND COMPLEXITY

The possibility to deal with complexity in unprecedented ways thanks to information technologies has allowed architects to displace the modern canon of regularity, based as it was on simplicity, to that of irregularity, something to which Balmond has referred to as the informal. It is characterized by three main features: "local, hybrid and juxtaposition", characteristics that may be considered as "active ingredients of an animate geometry that embraces the linear and non-linear" (Balmond, 2002, 217-27).

After its construction, Gehry's Guggenheim (**Figure 6a**) soon became the icon of digital architecture (despite it is only half digital). At the time of its completion no other building similar in size or shape had ever been built. The irregularity characteristic to its complex surfaces made of it an extraordinary novel design imbued by the new aesthetics of complexity and irregularity. It could probably be regarded as the first sound attempt to build large scale complex surfaces within the archaeology of the digital. Although Gehry's architecture has often been criticized for the use of irrational forms (not without reason), he has also explored the use of

Figure 6a. Frank O. Gehry, Bilbao Guggenheim Museum, 1992-1997, Source: (Bilbao Guggenheim Museum, 2024). **6b**. FOA Architects. Yokohama Port Terminal, Yokohama, 2000-2002 Source: (Archdaily, 2014).

ruled surfaces in some of his projects (Lawrence, 2011). Gehry's firm has enormously contributed to the expansion of digital culture in architecture developing its own software (Gehry Technologies) to be able to deal with a level of formal complexity that conventional software was incapable of addressing (Iwamoto, 2009, 6). Unfortunately, probably inebriated by their early success in Bilbao, their repetitive design imaginaries have somewhat been disappointing.

FOA's Yokohama Port Terminal (**Figure 6b**), for instance, is another example of this aesthetics of irregularity dealing with unparalleled geometries within the history of the discipline which clearly differs from modern simplicity and regularity. In this case, it is unmistakably indebted to software commands such as 'sweep' or 'loft' for the generation of surfaces. The geometric control derived by the assistance of CAD tools has proved to be decisive in the achievement of this kind of architecture; the building's own conception as a topography to walk on is disruptive too.

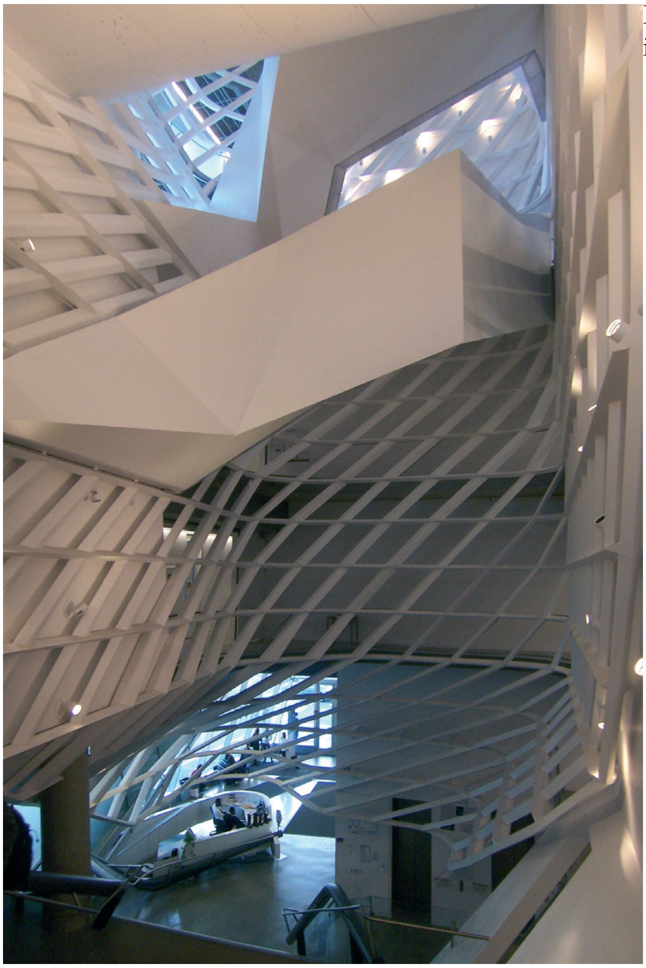
The increased performance of these tools together with an ever-growing variety of tasks carried out by software applications have made sceptics doubt regarding the real value of architecture developed with these tools. Greg Lynn has analyzed some early digital practices by Eisenman, Gehry, Hoberman or Yoh in the *Archaeology of the Digital*, in which their pioneering is indebted to their "treating the digital not merely as a tool but as a new creative medium that is integral to and an extension of their design process" (Lynn, 2013, 12). The tools are just that, instruments that help us to perform different tasks. Nevertheless, the tool is not innocent; it has an effect in the outcome; beyond its instrumentality, it is a medium in itself. The way to conceive architecture and the consistency of the approach is what truly counts. Digital tools can be regarded as the bearers of a new creative media that some architects have managed to deal with, achieving results which would not have been possible to attain without the computers' assistance (Jencks, 2013).

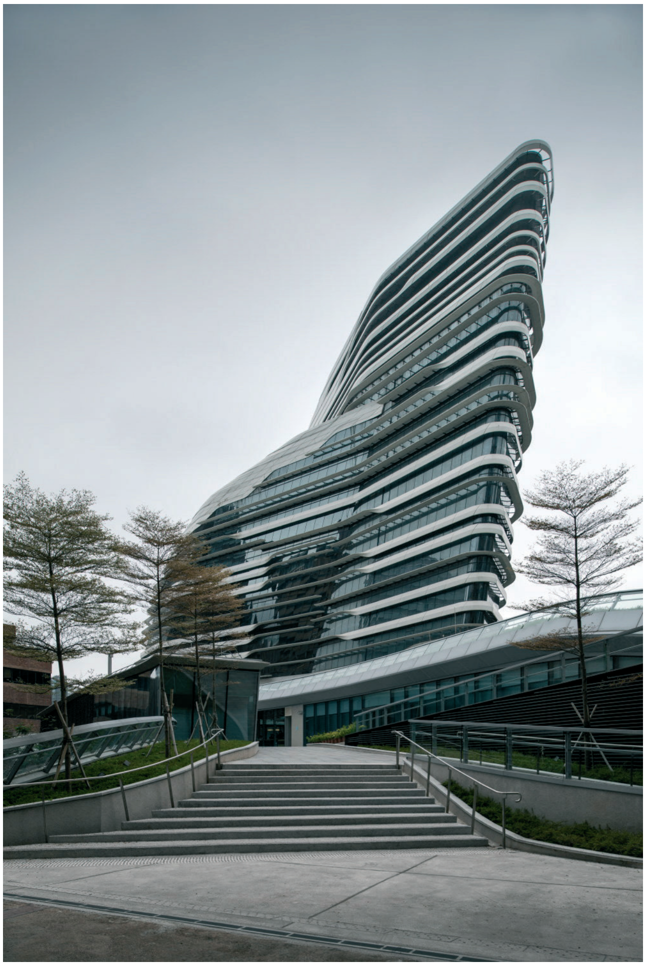
These tools have enhanced architectural ideation in unique ways, from the emergence of the virtual three-dimensional space (changing the relationship of architecture and its representation) to the unlimited possibilities derived from scripting languages applied to architectural design. That is: the codification of geometry replacing forms by parametrized formal structures or to what could be referred to as open forms.

The spatial conception, for instance, is no longer static or perspectival. This irregularity and complexity of architectural space is, undoubtedly, one of the hallmarks of digital architecture as can be seen, for example, in Morphosis' design for the Cooper Union's enlargement in New York (**Figure 7a**).

Open form addresses architectural configuration of space in a totally novel way, allowing architects to experiment with form-finding strategies dependent on the variability of the parameters introduced in the design in what could be referred to as digital typologies. Parametric design has allowed to produce extraordinarily complex architectures geometrically codified. The characteristic volume and façade work in Zaha Hadid's Jockey Club Innovation Tower (**Figure 7b**), is a good example of the complex geometries achievable through parametric design that go beyond the over-abused Voronoi patterns. This design shows how to conceive and deal with complexity in uncharted paths until the advent of IT.

It is





Figures 7a. Morphosis, Cooper Union new academic building (lobby), New York, 2004-2009, (Source: Carlos L. Marcos, 2010). **7b** Zaha Hadid Architects, Jockey Club Innovation Tower, Hong Kong, 2007-2014, (Source: Zaha Hadid Architects, 2014).

true that expressionist architecture (i.e., Hans Scharoun, Frederick Kiesler) could also be considered a realm of complexity in architecture and a formal precedent (Mennan, 2008). Deconstructivism is certainly more closely related to this 'expressionist' trend of the modern that it is to the international style. However, the level of complexity differs from non-standard modes of architectural production and the inner logic of irregularity characteristic of digital architecture.

Digital tools enable the modeling of geometry and inform design decisions based on spatial, social, cultural, and technological information. Computational design can incorporate data abstraction to optimize the final form, thereby altering the architect's role in defining geometry while digitally exploring relationships between material, structure, and form. This genuinely computational design can incorporate data abstraction to improve the performance of the final form, significantly altering the architect's role in defining geometry while digitally exploring existing relationships between such triad.

One example of this optimized design is found in the projects of Marc Fornes/THEVERYMANY, which blur the line between art installation and architecture. For instance, the structure "Under Magnitude" at the Convention Center in Orlando, Florida, continues the "Structural Stripes" series, aiming to integrate surface, structure, and space to create a distinctly three-dimensional and complex architectural topology (Fornes, 2016a).

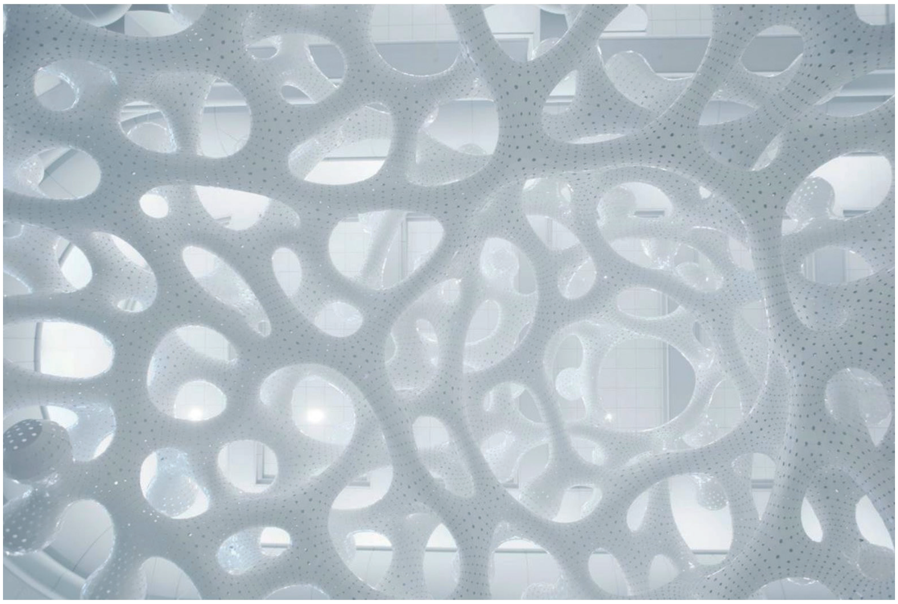


Figure 8. Marc Fornes/THEVERYMANY, Under Magnitude, Orange County Convention Center, Orlando (Florida), 2016 Source: (Marc Fornes/THEVERYMANY, 2017).

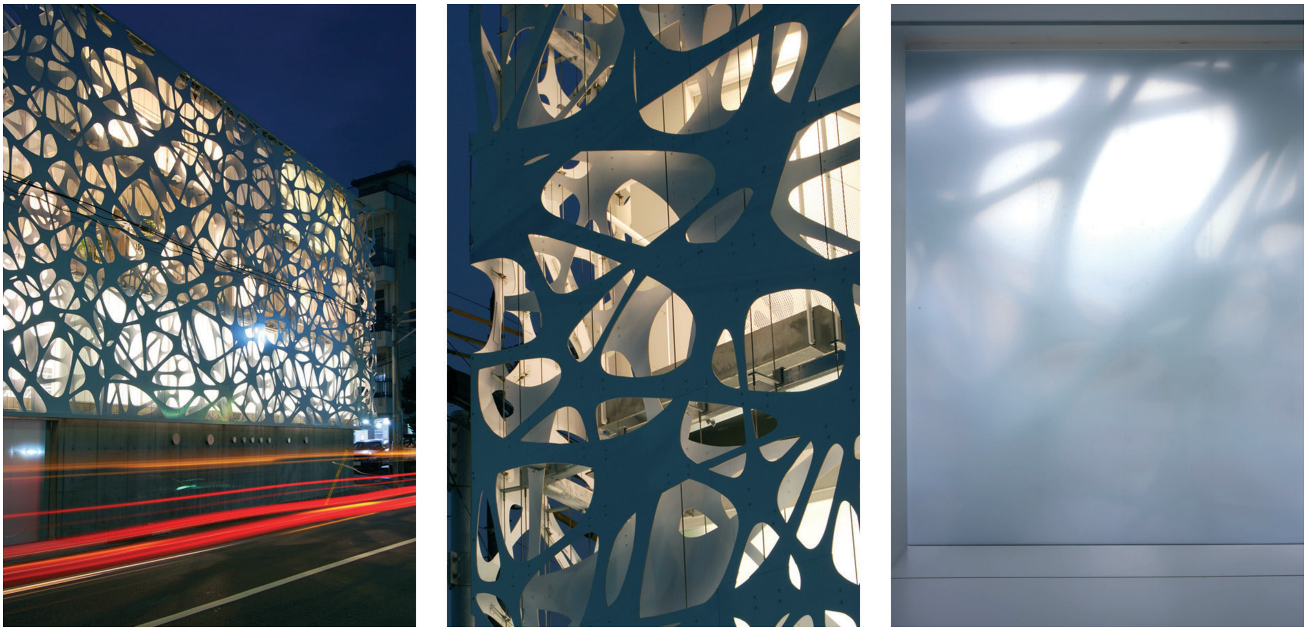
This design relies on extensive curvature and Frei Otto's bubble patterns to achieve resistance through intense curvature, resulting in characteristic coral-like structures of tubular curved branches obtained by very precise laser-cutting of an ultra-thin 1 mm thick aluminum sheet (**Figure 8**). Here, data serves as a constraint imposed on the geometry to maximize structural integrity and minimize weight (Fornes, 2016a). This formal strategy makes it possible to achieve structures of a surprising scale despite the extraordinary lightness of the whole. As pointed out by Robert Le Ricolais, the tectonic efficiency of built form lies in where to place the voids rather than in where to distribute the material (Juárez, 1996).

Additionally, parametric and generative designs embody a degree of openness, where the architect programs form rather than shaping it directly. The open form generated from scripts defines a parameterized typology of potential forms within a range of parameters. Visual Programming Languages (VPL) and scripting languages facilitate the translation of scripts into 3D models, opening new paths for algorithmic or parametric architectural design. For example, the Loophole pedestrian bridge proposal by R&Sie in collaboration with THEVERYMANY demonstrates how geometry is codified in a script stepping over the limitations of traditional architectural representation.

Patrik Schumacher has claimed that parametricism has constituted a new global style (Schumacher, 2009). Although it is to be doubted if it may be so, it may be admitted that parametric designs have become one of the most conspicuous trademarks of digital architecture, and certainly, their appearance is the result of what Carpo has coined as the second digital turn.

DISRUPTIVE MATERIALITY. NEW MATERIALITY AND NEW PHENOMENOLOGY

The extraordinary potential to handle complex geometries before they could actually be built in the early 90s led to criticism. Frampton's work *Studies in Tectonic Culture* published in 1995, notwithstanding its undisputable value, could be interpreted as an implicit criticism in relation



Figures 9a, 9b, 9c. Thom Faulders, Airspace Tokyo, 2007, (Source: Thom Faulders). The façade design is an example of irregularity and customized mass production of singular elements.

to this lack of constructability or sense of realism of the first digital era, as Picon (2004, 114) has suggested. However, as predicted by the latter, much has been achieved since within the context of digital architecture as to continue to ignore its importance.

An emerging new materialization digitally borne through the convergence of CAD and CAM is now stemming from a truly digitally conscious approach. Digital architecture has found in CAM the counterpoint to CAD, merging the virtual and the physical with the accuracy attained by computers, thus allowing architects to vivify the master builder's tradition of getting involved in the physical production of architecture itself, something which Renaissance architects neglected (Kolarevic, 2003). Digital fabrication has established a new relation in the way we engage materiality, counterbalancing the bold imaginaries digitally borne.

Airspace Tokyo by Thom Faulders (**Figures 9a,9b,9c**) exemplifies this new materiality that addresses complexity through sensible architectural design with new tools. The site was previously occupied by a dense layer of vegetation which had to be replaced by the façade as the program had been significantly increased. The result is a contemporary digital façade design that evokes the pre-existing tree canopy (Iwamoto, 2009, 54).

Even traditional building materials such as brick may find opportunities for a new understanding of ceramics. In 2006 Gramazio and Kohler, worked with their students in a design studio called 'The Programmed Wall' at the ETH in Zurich. The idea was to work on the new possibilities that an old construction material had to offer through a truly digitally conscious design. Thus, the walls were defined with algorithmic design tools and fabricated by robots. Each brick was laid according to particular orientation in space through which complex visual patterns and curvatures could be accomplished. This digitally conscious design illustrates what Carpo has addressed in his work *The Second Digital Turn.* It implies a shift in the digital paradigm from planar geometric information and projections to consistently three-dimensional geometries not reducible to flat elements, thanks to the use of digital fabrication tools. Accordingly, mass

Figures 10a, 10b. Winery Gantenbein. Gramazio & Kohler + Bearth & Deplazes, 2006. Revolving bricks Serai façade, Farhad Mirzaei, Arak (Iran), 2015. Sources: (Bearth & Deplazes 2013, Archdaily, 2015).

customization (of each brick's position in space) is achieved and enhanced by the control of big data (Carpo, 2015). This is one of the reasons for a distinct differentiation from expressionist or deconstructive architecture, and the cause for irregularity to become a hallmark of the digital.

Beyond the latticed façade of the Swiss winery designed by Gramazio and Kohler in collaboration with Bearth & Deplazes Architekten, further developments on similar ideas have been recently built taking advantage of this CAD-CAM convergence (**Figure 10a**). Such is the case of the latticed façade of the building *Revolving bricks Serai* by Iranian architect Farhad Mirzaei completed in 2015 (**Figure 10b**). This permeable skin is superimposed to the more conventional façade contributing to define a new approach to ceramics enhancing another reading of critical regionalism. Glazed façades are not feasible in countries where strong solar radiation has to be faced; this kind of parametric latticed façades are a revealing sign of the growing interest and concern of architects addressing sustainability issues (Guitart, 2022). At the same time, it is a sensible way in which to use brick walls freed from their traditional load-bearing purpose. The revolving brick façade sincerely conveys its condition of a permeable enclosure freed from tectonic requirements.

The possibility to customize every single element in the design through parametric design finds in *mass customized production* its effective materialization thanks to digital fabrication, thus allowing the machinic to step over mechanical industrial mass production: laser cutters and robots work alike independently of the irregularity of the geometries involved allowing non-standard modes of fabrication. This provides architects expressive means but also enables them to address levels of complexity which may also work, for instance, to enrich the effects of transparency in latticed façades with varied degrees of visual permeability (**Figure 11a**).

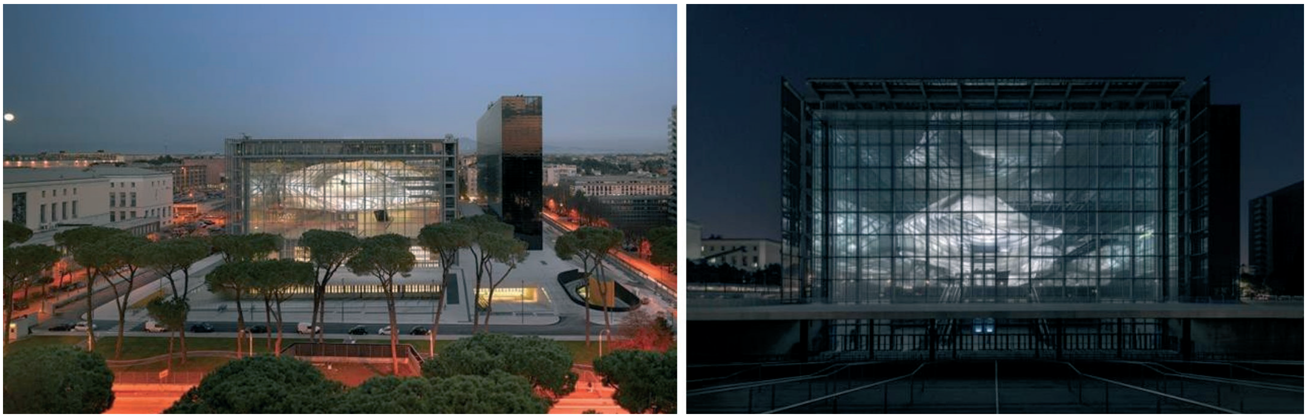
New frontiers in architecture are reached through extraordinary innovative practices based in the cross-disciplinary. The Mediated Matter Group at the MIT led by Neri Oxman is a good example of a new way to address materiality merging architecture and the natural sciences (Oxman, 2014). Moreover, digitally conscious architects typically approach architecture blurring the traditional disciplinary boundaries. In Chandler Ahrens (2016, 314) own words it implies "the superposition of theory and practice, displacements between representation and object, and overlapping rigorous scientific reasoning and aesthetic desire". The swiftness of computation has accelerated changes in architecture at a pace that is

Figures 11a. Architectkidd, Façade detail. Street Ratchada in Bangkok, 2017 Source: (Architectkidd, 2017). **11b** GreenPIX, Simone Giostra & Partners and ARUP. Beijing, 2008. **11c.** Facade night view and glazing (detail), Source: (Giostra & Partners, 2008).

difficult to follow, entailing, in some cases, deep alterations of well-established relations within the discipline.

A fruitful cross-disciplinary collaboration between Simone Giostra & Partners, ARUP, Schucco and SunWays lead by the architectural firm produced one of the finest examples of smart-façades, the GreenPIX façade (**Figure 11b**). The curtain wall was built with polycrystalline photovoltaic cells laminated within the glazing. These were distributed with varying densities over the building's phenomenological façade producing different patterns on the façade, thus shedding a certain appearance of irregularity. The photovoltaic cells that trap solar energy contribute to reduce heat gain by solar radiation because of their opacity while transforming it into energy for the *media wall*. These digital media walls are also another disruptive way in which to address materiality and enclosures. While their external materialization —basically a glazed façade— is relatively conventional, the image displayed on them opens a new way in which to engage temporality in architecture and defies the appearance of glazing itself.

According to Kwinter's (2001) metaphor of the surfer's dynamism, the designer is required to develop a great capacity for intuition and innovation that may allow him to establish a deep relationship with the ever-changing environment he dwells. It is a disruptive mental landscape, marked by connections, intersections and flows which need a reinvention of the concepts that define the disciplinary framework. It requires to operate at the confluences of cross-disciplinarity so that, surfing the disruptive wave, digitally conscious architecture may give an adequate response to this new reality. Its value may only be critically pondered in relation to the way in which architects are able to adapt to this deep conceptual and instrumental dynamic transformation while surfing the wake of history in the age of computation. Massimiliano Fuksas finished the completion of the Cloud (EU Convention Center in Rome) where, in



Figures 12a, 12b. Massimiliano Fuksas, 'the Cloud' — EU Convention Center, Rome, 2016. Source: (Roland Halbe, 2024; Archdaily, 2024, respectively).

collaboration with Rimond Consulting (specialized in digital design and manufacturing for the fabrication of non-conventional architectures), managed to establish a sound dialogue between the characteristic modernist gridded building and the informal cloud apparently floating in the colossal atrium, only made possible through the convergence of CAD-CAM technologies (**Figures 12a, 12b**).

Only now are we beginning to see the extraordinary advancements that AI is bringing to every field. Architecture is not alien to this new computer driven revolution. AI may easily and convincingly simulate extremely complex imaginaries reducing it to simple words or instructions — prompts— thanks to what is known as Generative Adversarial Networks (GAN), which has been a turning point in architectural graphic narrative and the creation of generated imaginaries through artificial intelligence (Goodfellow et al., 2014). It is only now commencing to show its full potential in the co-creation of human-AI design, where authorship, a traditionally exclusive human role, is now being transformed (Mancini and Menconero, 2023).

CONCLUSIONS

This study argues that digital architecture constitutes a disruptive force, challenging modernist principles across the interrelated domains of structure, form, and materiality. By examining innovative digitally designed projects, it demonstrates how computation enables previously unfeasible geometries, surpassing modernist limitations.

Addressing the first research question, the paper establishes the conditions for architecture to be considered disruptive in the age of computation: rapid transformation, displacement of pre-existing canons, innovative tectonics, novel conceptual frames and architectural languages. In investigating the second research question, the study delves into the various ways digital architecture challenges the standards set by modernism across the intersecting domains of structure, form, and materiality.

Tectonically, the paper highlights how digital tools enable innovative structural logics and complex geometries that diverge from modernist principles. In terms of materiality, the study emphasizes the shift towards engaging the material world through the convergence of computer-aided design (CAD) and computer-aided manufacturing (CAM). This paradigm shift in materiality moves beyond the mere emergence of new materials, focusing instead on the novel ways in which architects can engage with and manipulate matter through digital means.

Aesthetically, the paper highlights digital architecture's embrace of irregularity, complexity, and plurality, which subverts modernism's emphasis on regularity, simplicity, and a unified aesthetic vision. The introduced projects showcase intricate, non-repetitive geometries and fluid, organic forms, made possible by advanced computational tools and algorithms. Furthermore, the paper also highlights the role of parametric design and scripting in enabling architects to create open-ended, adaptable design systems that can generate a wide range of formal variations based on input parameters. This approach challenges the conception of the architect as the sole author of a fixed, predetermined design, instead promoting an iterative design process that embraces contingency and collaboration.

Future research can develop the framework of digital disruption and the triad of structure, form, and materiality using perspectives from philosophy, sociology, sustainability and technology studies. The impacts of parametricism, generative design, and automation in architectural theory require further examination from this lens. The AI logic of design is only starting to show its extraordinary potential to accelerate and enhance architectural computational design. By elucidating disruption's manifold dimensions, architectural discourse can navigate the potentials and shortcomings of the digital to meaningfully inhabit our computational world in transformation.

Architecture is required to look to its past and to valuable precedents in order to face the future as much as it needs to fly on the wings of its time. Accordingly, this computational architecture goes beyond the exploration of form for its own sake, introducing design approaches that are capable of the optimization of form in relation to structural, thermal, wind, seismic, acoustic, and even energy efficiency instances. This smart design approach is necessarily beyond human grasp and is shaped following a computational logic.

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Anahtar Sözcükler: Yıkıcı değişim; dijital mimarlık; dijital dönüşüm; sıradışılık; karmaşıklık.

BİLGİSAYARLI HESAPLAMA ÇAĞINDA MİMARLIKTA YIKICI DÖNÜŞÜMLER: DİJİTAL MİMARLIK ÜZERİNE ELEŞTİREL BİR İNCELEME

Her yaratıcı çaba gibi mimarlık da insan yaratıcılığının yönlendirdiği değişime tabidir. Yıkıcı dönüşüm (*disruption*), mimarinin tasarlanma ve inşa edilme biçimlerinde önemli yenilikçi değişiklikler olması ve önceden var olan ilkeleri yerinden etmesidir. Yakın tarihte dijital dönüşümler, disiplini farklı şekillerde ve derecelerde etkilemiştir. Otuz yılı aşkın dijital mimarlık deneyiminden sonra dijital mimarlığın önem ve anlamlarını eleştiren bu makale, dijital mimarlığın, modernizmin dönüştürücü etkisine benzer şekilde yıkıcı bir yenilik olup olmadığını araştırıyor. Çalışma, strüktür, form ve malzeme açısından örnek dijital projeleri analiz ederek dijitalliği bağlamsallaştırıyor ve modernist ilkelerden teknik-estetik sapmaların izini sürerek önemli dönüşümleri ortaya seriyor. Dijital yapısal mantıkları, dijital araçlarla üretilen biçimsel karmaşıklık ve düzensizlikleri ve bunların nasıl modernist ortodoksiyi yerinden ettiğini tartışıyor. Makalede sunulan örnekler gösteriyor ki, bilgisayar destekli tasarım ve üretim (CAD/CAM) yakınsaması, kitlesel ve özelleştirilmiş üretim yeni bir materyal kültürü doğuruyor. Bu değişiklikler, enerji verimliliğini artırmak, karbon ayak izini azaltmak, güneş koruması veya doğal havalandırmayı iyileştirmek gibi amaçlarla yapıyı, malzemeyi veya formu optimize etmek için hesaplama, parametrik ve algoritmik tasarım araçlarının kullanımıyla gerçekleştiriyor. Makalede bu gelişmeler sentezlenerek, dijital mimarlığın tektonik ilişkiler, biçimsel düzensizlik ve materyal deneyler ile modernizmi kendi şartlarında nasıl sorgulayıp genişlettiği ve estetik vizyonunu nasıl çoğullaştırdığını ortaya koyuyor. Yıkıcı dijital mimarlık uygulamalarının bu şekilde sistemik olarak ele alınması, devam eden bir evrimi ortaya seriyor. Sonuç olarak dijital tasarımı ilerletmek için öneriler veren bu çalışma, bunun sadece yeniliğin peşinden koşmakla değil, insani anlamı ve yaşanmış deneyimleri (lived experience) bütünleştirmekle olacağını savunuyor. Dijital yıkıcılığın etkisini tartışmak, teori, teknoloji, kültür ve çevre genelinde gelecekteki araştırmalar için yeni soruların ve eleştirilerin ortaya çıkmasına da öncülük etmektedir. Bu araştırma, yapı, form ve materyaliteyi kapsayan bir yıkıcı değişim kataloğu olmaktan öte hesaplama çağının getirdiği sarsıntılar ve olasılıklar aracılığıyla mimari söylemin disiplini nasıl yeniden yönlendirebileceğini açığa çıkarmaktadır. Dijital mimarlığın yıkıcı değişim yaratmasının ön şartı, mimari tasarım ve inşa için yeni yöntem ve yaklaşımları kullanmanın ötesine geçerek tasarımsal karmaşıklığı eşi benzeri görülmemiş dijital araç ve yöntemlerle yönetebilmektir. Gerçek anlamda bilinçli tasarımlar, dijital araç ve yöntemlerin yardımı olmaksızın gerçekleştirilemeyecek binaları tahayyül etmemize olanak sağlamalıdır. Eğer dijital mimarlık eleştirel bir değere ulaşacaksa disiplinin kurucu ilkelerinin göz ardı edilemeyeceği de akılda tutulmalıdır.

ARCHITECTURAL DISRUPTION IN THE AGE OF COMPUTATION: A CRITICAL REVIEW ON DIGITAL ARCHITECTURE

Architecture, as any creative endeavor, is subject to ever-changing progress driven by human inventiveness. Disruption is achieved within the discipline during moments of substantial innovative changes in the way buildings are conceived and built, displacing pre-existing canons. The so-called digital turns have disrupted the discipline in varied ways and to different degrees. After over three decades of digital architecture, it is time to critically ponder their importance and significance. This paper investigates whether digital architecture qualifies as disruptive innovation comparable to modernity's transformative impact. It contextualizes digitality by analyzing exemplary digitally designed projects across structure, form, and materiality. Tracing technical-aesthetic divergences from modernist principles, significant transformations are surfaced: digitally-enabled structural logics emerge, formal complexity and irregularity generated through digital tools displace modernist orthodoxy, and a new materiality arises from CAD/CAM convergence or mass-customized production. These changes are consistent with the use of computation, parametric and algorithmic design tools to optimize

structure, matter, or form to enhance energy efficiency, reduce the carbon footprint, solar protection, or natural ventilation, to mention a few. Synthesizing these developments, digitality seems to question and expand modernism on its own terms, through tectonic relevance, formal irregularity, and material experimentation while pluralizing its unified aesthetic vision. This mapping of disruptive digital architecture practices reveals an ongoing evolution still unfolding. Advancing digital design requires integrating humanistic meaning and elevating lived experience, not just pursuing novelty. Elucidating digital disruption's impact triggers critiques highlighting unsettled questions for future inquiry across theory, technology, culture, and the environment. This disruptive catalog across structure, form and materiality unfolds future directions by which architectural discourse can reorient the discipline through the upheavals and possibilities in the computational age. Digital disruptive architecture requires new ways of conceiving and fabricating buildings, benefiting from the computational potential of digital tools to manage complexity in unprecedented ways. Truly digitally conscious designs should allow us to design buildings that could not have been so without their assistance while benefiting from their potential to simulate the designed building's behavior and, accordingly, improve the design itself based on requirements. Yet, if digital architecture is to achieve critical value, we ought to bear in mind that the founding principles of the discipline cannot be neglected.

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