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The Impact of Digital Tools on Parametric Architecture

*Maram W. Rezk[1, *], Ashraf A. Almokadem[2], Heba A. Ahmed[3], Nancy M. Badawy[4]*

[1] *Architectural Engineering and Urban Planning Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: m.rezk@eng.psu.edu.eg*

[2] *Architectural Engineering and Urban Planning Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: elmokadem1@eng.psu.edu.eg*

[3] *Architectural Engineering and Urban Planning Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: heba.adel@eng.psu.edu.eg*

[4] *Architectural Engineering and Urban Planning Department, Faculty of Engineering, Port Said University, Port Said, Egypt, email: n.badawy@eng.psu.edu.eg*

**Corresponding author, m.rezk@eng.psu.edu.eg,* *DOI: 10.21608/pserj.2023.176865.1203*

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ABSTRACT

The architectural interest in parametric design has grown dramatically in the last few decades. However, there is a confusion between parametric and digital architecture, as a result of the conflict in defining the parametric architecture roots. Moreover, this research aims to settle on the origins of parametric architecture, and define the most important factors that influenced the development of it, assuming that the emergence of digital tools has the greatest impact on it. In this regard, the history of parametric architecture was divided into two historical eras: the first is the pre-digital era, and the second is the digital era. In each era, the most prominent parametric projects were reviewed and analyzed to deduce the most important evolution features in terms of capabilities, goals, characteristics, scale, and phase of application for both of eras and conclude the impact of digital tools on parametric architecture. It was found that the roots of parametric architecture go back thousands of years, but it has developed greatly, and the digital tools had the most influence on this development. Despite this, the pre-digital era could not be considered as a single phase as it passed through two main phases, which differ greatly in characteristics.

Keywords: Parametric design, Design tools, Parametric Architecture, Parametric Urbanism.

1.INTRODUCTION

Over the past five decades the number of publications focused on parametric design have increased more than 40-fold, from less than ten research papers per year in the 1960s and 70s to more than 400 research papers per year from 2019. Over the same period, there has been a growth in the numbers of available parametric design software, such as Grasshopper, a parametric design plugin in Rhinoceros 3D modeling software, which now has over 30,000 users and generated more than USD 30 million in revenue in 2022. This significant increase in research output and parametric design tools emphasize the importance of this design approach.

The field of parametric design is expanding every day and intersecting with many other fields [1-15]. **(Fig.1)** shows a visual map for the term "Parametric Design". Scopus database was used to collect the data, the open-source VOSviewer used to visualize the data, no time limit is set for the search. However, the first paper found discussing this term was in the 1960s, thus, it can be considered that the time limit for the analysis is from the beginning of the sixties until 2022. It was found that there are relationships between the term "Parametric Design" and many fields such as architectural design, landscape, urban design, structural design, interior design and etc. as illustrated

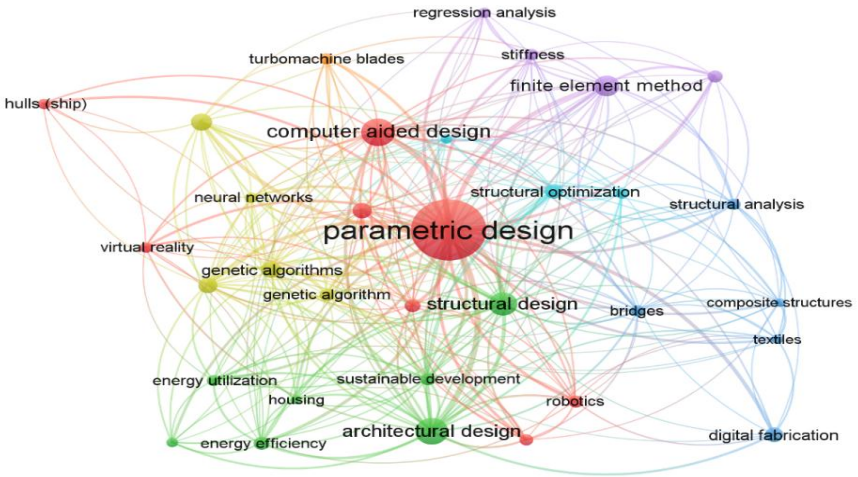


Fig. 1. Network of keywords related to parametric design shows how it relates to many different field.

Despite this interest, most of these studies focused only on the applications of parametric design, and there was a little focus on the roots, and the development history of the parametric design, which led to confusion at some points, such as defining parametric architecture and confusing it with digital architecture, the roots of parametric architecture, and the role of modern digital tools in the development of parametric architecture.

Therefore, the aim of this research is to settle on the roots of parametric architecture and deduce the most important reasons for its development by reviewing the history of parametric architecture from its first appearance until its arrival to what it is now. In this regard, parametric architecture history will be divided into two main historical eras, the first is the pre-digital era and the second is the digital era. Then, the most important projects that formed each era of Parametric Architecture will be reviewed and analyzed in terms of capabilities, characteristics, goals, scale and phase of application to deduce the most important development features of parametric architecture at each era and thus conclude the main reasons of parametric architecture development.

By achieving the objectives of the research, a clear vision of parametric architecture will be provided to architecture students and researchers, as well as programmers and software developers, to enable them moving forward and developing parametric architecture continuously.

In order to achieve the aforementioned aims and objectives, several steps will be followed. **(Fig. 2.)** shows the research structure from the introduction until reaching the conclusion.

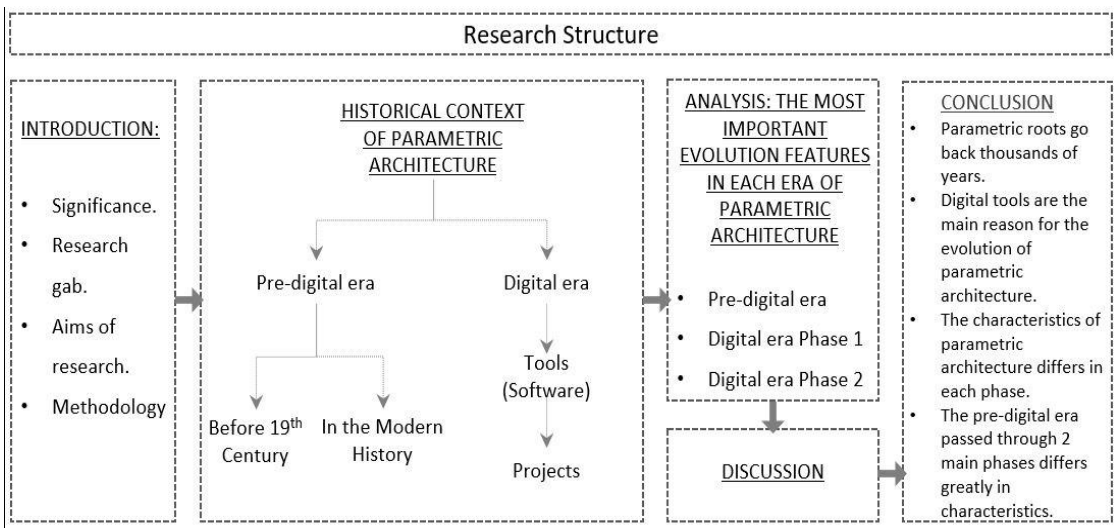


Fig.2. The research structure, Adapted by authors.

2. HISTORICAL CONTEXT OF PARAMETRIC ARCHITECTURE

Few studies focused on studying the origins and development of parametric architecture. However, a great conflict about the origins and roots of parametric architecture could be seen. Schumacher 2009, states that the roots of parametricism came from digital animation in the mid-1990s, but it appeared fully with the technological development of parametric design systems [16]. Stavrik and Marina 2011, referred to parametric architecture as one of the forms of digital architecture, completely ignoring the origins of parametric architecture before the advent of digital tools [17]. While John Frazer 2016, attributed the roots of parametric architecture beginning with the works of Antoni Gaudi, he also saw that the concept of parametric design did not differ fundamentally from its first concept presented by Luigi Moretti [18]. A similar view of parametric design was provided by Heidari 2018 [19]. Assasi 2019, stated that Parametric Design is nothing new to the architects and it refers to algorithmic thinking to solve design problems [20].

As a result of conflicting opinions about the origins and the development of parametric architecture, many definitions were found as shown in **(Table. 1).** As we can see, there is a big difference in the definition of parametric architecture over time and a difference in the formulation of its goals. Many limited their goals to achieving interconnected forms, and others included environmental and social goals as the main driver for it. This difference shows how the parametric architecture is developing every day and confirms the importance of studying this development and its characteristics.

In order to trace the origins and development of parametric architecture, it was divided into two historical eras: the pre-digital era and the digital era.

Table 1. The most prominent definitions for parametric architecture by the time, Adapted by authors.

Author	Year	Definition
Luigi Moretti	1971	The study of architectural systems with the goal of "identifying the connections between the dimensions' based on the various factors."[21].
Kalay	1989	A computational representation of geometric relations that are updatable and changeable, and its results shown at the same time on the computers screens [22].
Monedero	2000	A computational representation of a design intention with a series of associative operations, controlled by constraints and parameters [23].
Szalapai	2001	The application of geometric restrictions as well as dimensional relationships and data [24].
Kolarevic	2003	A method in which the parameters of a given design are disclosed rather than its shape, allowing for the generation of several alternatives while retaining overall consistency [25].
Schumacher	2008	First presentation of the concept of “Parametricism” as a global style for architecture and urban design.
Woodbury	2011	The process of exploring associative connections of geometric concepts [26].
Frazer	2016	A process in a rapidly evolving process that embraces new technologies and environmental and social purposes [18].
Oxman	2017	A new paradigm of design thinking. Pioneering concepts of design thinking developed, moving from typological thinking to topological design thinking in creative design, which should be considered one of the most remarkable changes in design thinking [27].

2.1 Pre-digital Era

2.1.1. Before 19th Century

Mathematics had been used in architectural design and associated arts for thousands of years. Moreover, the idea of parametric first appeared in mathematics [28], as the Oxford Dictionary, Parameter is defined as "A numerical or other quantifiable component that defines a system or determines the conditions of its operation," or "A limit that limits the scope of a specific process or activity", while Parametric is defined as "related to or stated in terms of a parameter or parameters." [29]. This link between parametric architecture and mathematics had a long history dating back to ancient civilizations, who had used mathematics, astronomy, geography and engineering in architectural and urban design. Beginning with the

ancient Egyptians who had used astronomy, mathematics and other sciences to shed light on the statues of kings on specific dates, as well as in designing Pharaonic temples to be permeated with sunlight, and also in building the pyramids of Giza directed to the original directions and in fixed proportions. Then Romans and Persians who had used these sciences in building domes, celestial bodies and structures [20]. Then came the Islamic architecture, in which the abstract decorative shapes had emerged **(Fig. 3.)**, and it called Al-Khwarizmi's art in relation to the scientist Al-Khwarizmi, whose name was also attributed to the design methods that depend on algorithms [30]. They had used complex arithmetic operations to create these magnificent decorations and display them with flat mosaics on curved surfaces, such as vaults, and they had directed mosques in various Islamic countries to Mecca and had linked the circular domes to their rectangular bases with transitional polygons [20].

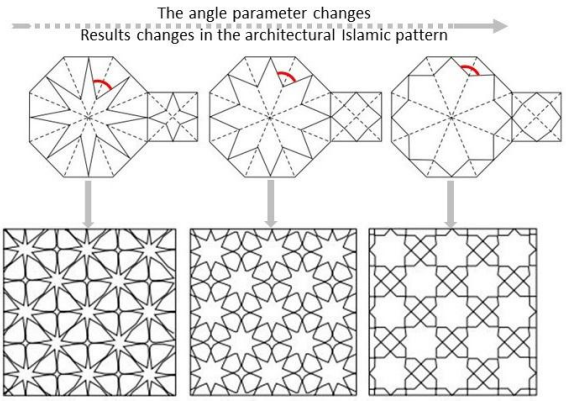
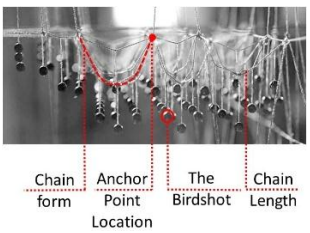


Fig. 3. 2D algorithmic Islamic pattern uses parametric concepts, Adapted by authors (Source: [31])

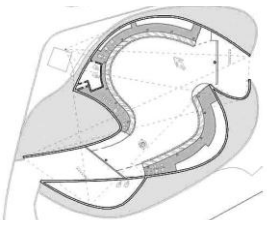
2.1.2. Modern History Attempts

In the modern history of the pre-digital era, many attempts had appeared that were later considered parametric. As the digital tools had not been appeared yet, analogue parametric models had been used in such attempts. Below we review the most important models and projects in which parametric principles had been used in this period.

Table 2. The most prominent architectural models and projects in the modern history of the Pre-digital era, Adapted by authors.

Project/Model Info.	Program	Parametric Model Implementation	Remarks
Gaudi's Hanging Model • Architect: Antoni Gaudi  **Gaudi's hanging, Adapted by authors (Source: [32])**	It is one of Gaudi's most well-known works that demonstrated his use of parametric concepts [33]. Gaudi utilized this concept to design [32]: • Colonia Güell Chapel. • Sagrada Familia basilica. The model would always rest into a form that would sustain in full compression when reversed.	The hanging chain model was based on various factors, which acting as independents which could be moved or changed independently such as: • String length. • Weights. • Anchor points. With this model, Gaudi could deduce many possible alternatives for modeling the shape of the church by changing one of the parameters exactly like the computer-generated parametric models [32].	Antoni Gaudi was known for his passion for using mathematics and other sciences in his architectural projects [34]. We can recognize the simplicity of the relationships between the different parameters of the model.
Philips Pavilion • Year: 1958 • Location: Brussels, Belqium • Architect: Le Corbusier, Iannis Xenakis	This pavilion was conceived as a container to house a stunning audio-visual scene and provide guests with a multi-sensory experience [36, 37]. The work comprised a musical piece in which the	At the beginning of the design process, Le Corbusier put a curved shape as a delimiter for the pavilion entry and exit on both sides, then Xenakis recommended using eight ruled surfaces generated parametrically by the movement of one horizontal path as a geometric producer to cover an area of 500 m2	In this project we note that the designers had not used physical parametric model and they had replaced it with manual sketches.

Philips Pavilion (Source: [35])



Philips Pavilion floor plan (Source: [35])

sound appears in various intensities and places, narrowing and expanding to synchronize with visuals reflected on the exhibition walls to present excerpts from human history [38].

The three primary connected sections that made up the tour was as following [35]:

- The entry and technical hall.
- The large area for the audience.
- The exit.

with concrete precast panels to create curved walls from straight surfaces.

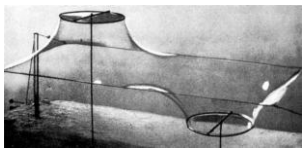
The parametric control of form was achieved by projecting curves in intersection planes with vertex spots and straight lines.

The radius of curves was used to generate profiles that link them, and loft in varied height diagonals to produce changeable surfaces crossed [37]. To achieve spatial consistency and new expression, this geometrical portrayal informed the design of walls with mutual support and a small curved structure [35].

We can also note the simplicity in the parameters' relationships.

Otto's Soap Film Model

- Architect: Frei Otto



Otto's Soap film model (Source: [39])

Otto used this model as an experiment to produce forms. This method allowed him to create a great number of different and efficient tensile forms

He used this idea later to design the ceiling of the Olympic Stadium in Munich [40].

Frei Otto expanded analogue computing approach to incorporate, among other features, minimum surfaces produced by soap bubbles and simple pathways discovered by dipping wool in liquid.

This model considered parametric because when a parameter was altered the result was unexpected and only observed through the model.

Otto (1996) used the term "**Form Finding**" to refer to creating forms from such parametric models emphasizing the experimental aspect of the parametric architecture [41].

2.2. Digital Era

The term parametric was not applied to all the previous works at that time, as the term parametric design was emerged in Luigi Moretti's publications from 1940 [42].
The digital era of parametric architecture began in the second half of the twentieth century, with the advent of digital tools, which had a significant role in parametric architecture development. Therefore, the review of the digital era was divided into two main parts. The first is for the most prominent digital tools that were used in parametric architecture from the beginning of its emergence until now. The second is for the most important architectural projects that shaped parametric architecture in this era.

2.2.1. TOOLS (Software)

At the beginning of the sixties Sutherland took use of computing capacity to develop **Sketchpad**, the first interactive CAD application for Public. A designer might use a light pen to create different geometries that could be connected using what he referred to as atomic restrictions [43]. Sketchpad was not referred to as parametric at this time, but it carried all the basics of parametric concepts [44].
20 years later, **AutoCAD** was launched, the time in which PCs became relatively affordable. It did not take long for AutoCAD to lead the emerging computed design business [45]. Instead of a pen, the mouse and keyboard were utilized to create various geometries. Then, more parametric features were added in many versions later starting from AutoCAD2010 [44].
The breakthrough new parametric components in AutoCAD2010 were available in a tool from many years back. Samuel Geisberg, a former mathematics professor, established PTC (Parametric Technology Corporation) in 1985. In 1988, they released **Pro/ENGINEER** Which gave the possibility of creating 3D shapes and controlling and modifying them at any later stage [46]. Geisberg emphasised two key issues, Firstly, digital parametric design must allow users experiment a wide range of concepts to find the optimum solution [46]. This accomplished in Pro/ENGINEER by manipulating both parameters and the model's basic relations. Secondly, digital parametric tools must make it possible for users to

make decisions at any further stage, which was an appealing feature of parametric modelling.
Dassault Systèmes included several of Pro/ENGINEERS's parametric capabilities to **CATIA** v4 in 1993 historically used in the design of vehicles and aeroplanes[45].

In 2004, **Digital Project** emerged, a software which wrapped **CATIA v5** parametric features in a tool designed specifically for architects, particularly those attempting to create complex and unique shapes like Frank Gehry. This software was also similar in many features and the basics of modelling with Pro/ENGINEER [44].

Former PTC developers established **Revit** Technology Corporation (RTC 2000a). Which was defined as a parametric tool by its founders at the first before being bought by Autodesk in 2002. Although Revit definitely utilised parametric foundations for its automated updates, in contrast with conceptual parametric design tools like Sketchpad, CATIA or Pro/ENGINEER. Revit's parametric connections are concealed in its programming. Rather than building parametric models, the emphasis is on using them. Following Autodesk's acquisition of Revit, The term parametric disappeared in relation to Revit and the term BIM was emerged to describe it appropriately and its means Building Information modelling [45].

Since AutoCAD emerged, textual programming interfaces have not evolved substantially. Instead, during the last decade, visual interface has been emerged. Visual programming entails expressing programmes as diagrams rather than words. Robert Aish had a head start on the first attempts to create a visual programming language for architects, but he failed to license his software called Generative Elements.

Then Davis Rutten was assigned by Robert McNeel & Associates tasked to develop a new version of architectural visual programming software and it was **Grasshopper** which named **Explicit History** at the first [47]. Grasshopper based mainly on graphing which trace the transmission of relationships from different parameters to functions defined by the designer, generally culminating with shape creation that alters according to model's parameters or connections to transmit, causing the geometry to be redrawn automatically.

The emergence of Grasshopper was followed by a revolution in the world of parametric design generally and parametric architecture specifically, and gained a great fame in the architectural profession. When compared to other parametric applications such as 3D Max, Grasshopper can handle a large number of parameters at once and deliver quick results compared with other tools [21]. Rhino software, which includes the Grasshopper visual algorithm editor as a plug-in, works in a different way from conventional text-based approaches. Modelling is accomplished in Grasshopper by organising "components," which correspond to pre-defined instructions [48]. Not only at the level of architectural form, Grasshopper can also contain other considerations such as environmental considerations and others. for example, Grasshopper can be connected to a variety of plugins to make it easier to integrate various disciplines using the same simulation technique. Diva, Ladybug, and Honeybee are used as plugins to produce a weather simulation for environmental modelling. These plugins can be linked to Grasshopper and used as an engine for Ecotect, EnergyPlus, OpenStudio, Radiance, and Daysim, as well as defining the weather parameters of a specific region using an EPW file. To identify the optimum solution, the genetic algorithmic plugin "Galapagos" is utilised as an optimization tool [21]. Many other plugins can be integrated with Grasshopper to achieve different goals desired by different design processes.

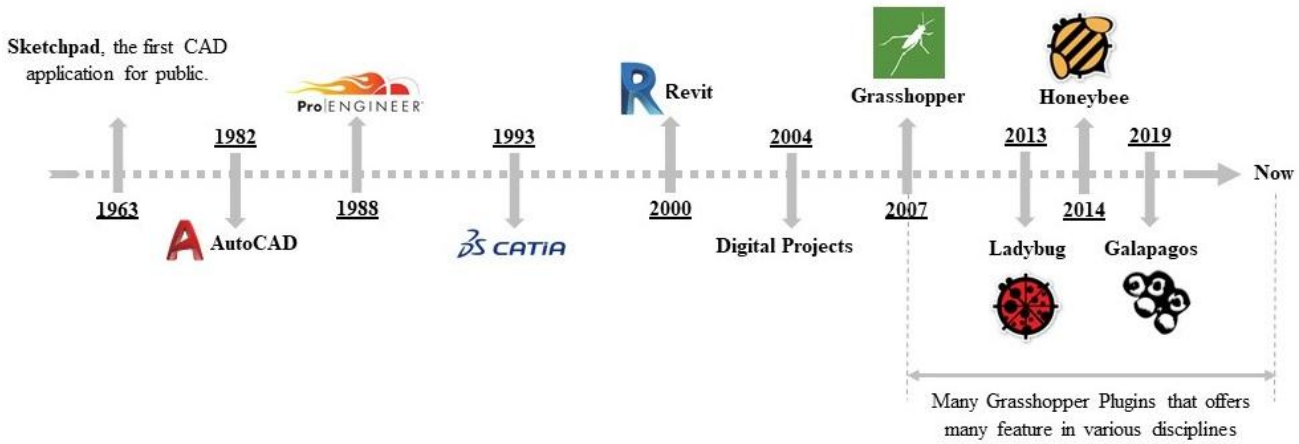
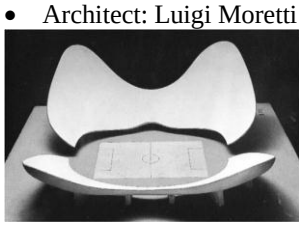


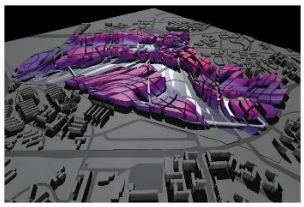
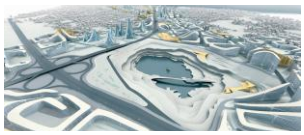
Fig. 4. Timeline for the most important software used in the parametric architecture, By authors.

2.2.2. Projects

As a result of the emergence of such digital tools, they were used in many architectural projects that shaped the parametric architecture in this period. Below we review the most important of these projects.

Table 3. The most prominent architectural projects in the digital era, Adapted by authors.

Project Info.	Program	Parametric Model Implementation	Remarks
Luigi Moretti's Stadium Model • Year: 1960 • Architect: Luigi Moretti  **Moretti's Stadium (Source: [42])**	By 1960, Moretti was able to design the first model using a computer, it was a stadium model and presented at the Twelfth Milan Triennial's Parametric Architecture.	Moretti constructed three-dimensional architectural form through the use of a complicated set of parametric connections resolved by digital computing with the aid of a 610 IBM computer, since digital tools have not been appeared for public at this time [44]. The stadium was the result of a nineteen-parameters parametric model.	After Moretti's attempt, many digital design software appeared that provided the opportunity for parametric design to appear through many architectural projects designed using the help of computer.
Barcelona Fish • Year: 1992 • Location: Barcelona, Spain • Architect: Frank Gehry  **Barcelona Fish (Source: [35])**	Barcelona fish was part of the Olympic Games' plan to restore the shore line. It is 56 meters long and 35 meters high and acts as a canopy for the restaurants that connecting the Hotel Arts to the seaside.	CATIA was used in order to develop parametrically the curve of the surface and thus enabling to define the steel profiles of the mesh required to build it [49]. Length and high of each section profile was used as main geometrical generators, while curve's control points were used as variables [49].	This project presents the exaggeration in the abstract formal goals. It was the beginning of using parametric concepts in the structural phase.
Bilibao Guggenheim Museum • Year: 1993-1997 • Location: Bilbao, Spain • Architect: Frank Gehry  **Bilbao Guggenheim Museum (Source: [50])**	Bilbao Guggenheim museum was also part of the Olympic Games' plan to restore the shore line. The shape of the museum is an abstraction of the shape of the boat to reflect the historical background of this coastal city and the important commercial port in Spain.	The design team created a parametric model using CATIA program, which contributed in both stages of design and implementation to produce this project with such precision and on a specific budget, as in most of Frank Gehry's projects [51]. This software allowed users to work on a three-dimensional digital model and connect it to the fabrication or digitization of material models [35].	This project reflects the thirst for such parametric tools, which led to the complexity in terms of form. It also employed the parametric principles in the architectural and structural phases.
Waterloo International Station • Year: 1993 • Location: London, England • Architect: Nichols Grimshaw	The major goal was to express the smooth flow that reflects the industrial era and the development in transportation [52, 53]. Due to its asymmetric design in the steep profile of the region and the idea that it had to rise progressively to meet the height of the trains, the cover posed a unique	Microstation Generative Components software was used to design the model and adjusting the inner measures of each module using a Pythagorean relation to retain the centers for the radial arrangement of the smaller parts. By propagating the formula, it was possible to modify the width of the structure (curve chords) while keeping the central axis in the shape of a curved profile.	In this project, we note that parametric tools were used to achieve formal goals as well, to reflect the flow, as they were also used in the design and construction phases.

 **Waterloo International Station (Source: [35])**	technical difficulty. The eastern side of the building is totally encased in glass [35].	As a result, a continuous surface with a changing section was created, with proportionate heights of the beams based on the support lights [24].	
<u>One-North</u> • Year: 2001-2019 • Location: Singapore • Architect: Zaha Hadid Architects  **One-North (Source: [16])**	It is a 200-hectare region in an industrial section in Singapore's technological corridor headed by four strategies as follows [54]: • Dynamic and mixed use. • Seamless connectivity. • Constant revitalization. • Original identity.	The parametric model included numerical data such as density, area, contextual and formal constrains which exported from tables, graphs, and 3D models [54]. By modifying elements depending on density parameters, it extends the concept of artificial landscape to a large urban quarter [55]. The aesthetic, functional and social goals were achieved in a coherent form and interdependent with the surrounding fabric and a high ability to adapt at any stage [54].	This project was the first in a succession of radical masterplans that led to the notion of parametric urbanism. It also opened the door to many applications and software in the field of parametric urbanism.
<u>Galaxy SOHO</u> • Year: 2009-2012 • Location: Beijing, China • Architect: Zaha Hadid Architects  **Galaxy SOHO (Source: [56])**	It is an office, retail and entertainment complex on 330,000 square meters. [57]. In addition to achieving functionality, there were two main goals as following: • Reflect the Chinese civilization by inspiration from its classical courtyard. • Achieve sustainability in the project.	In order to design this project, Zaha Hadid Architects developed a parametric model using many software including BIM and Digital Project [57]. Unlike the Wangjing Soho project, which is also part of Soho city, but was designed with more stringent requirements in terms of cost and complexity of manufacturing using a different technology, which is VB in Rhino [58].	In addition to the large scale of the project, we also note the multiplicity of goals and focus on achieving environmental goals in a large scale, which have not been achieved by parametric tools in the past.
<u>Kartal-Pendik</u> • Year: 2006 • Location: Istanbul, Turkey • Architect: Zaha Hadid Architects  **Kartal-Pendik (Source: [59])**	It is a sub-center on Istanbul's Asian side that was built to relieve strain on the historic core. The project location was bordered by a fine-grained suburban fabric. This fabric was the main design generator of the new urban fabric, and one of the main goals was to link the two regions in as one of the fundamental approaches in parametric urbanism.	Maya software was used to generate the model, towers and blocks were the two main generative elements allowing for a broad variety of variation. To indicate the route grid, towers were constructed above crossing places. As the sites are smaller and the blocks get taller, the surrounding block links an inverse elevation to the plot area, transforming the courtyards into the inner atria. The blocks are separated along the secondary track network lines, which, along with considerable height differentiation, allows the block type to be accommodated alongside the cross tower type [16].	We note that the design goal in parametric urbanism began to go deeper, as we can see, the design generator here was to link two urban fabrics parametrically, which was later considered one of the most important model approaches in parametric urbanism.
<u>Louvre Museum</u> • Year: 2017	Louvre Abu Dhabi is a classical art museum.	A parametric model was generated with various kinds of parameters as	This project, in our opinion, is a

• Location: Abu Dhabi, UAE • Architect: Atelier Jean Noveau  **Abu Dhabi Louvre Museum (Source: [60])**	Gallery space covering 22,500 square meters. The dome forms the design's focal point and it have many goals [60]: • Environmentally, it provides shade and coolness. • Aesthetically, it filters sunlight and creates rain of light under the dome. • Operationally, it has lighting function and cooling the interiors • Culturally, it inspired form the "Arabic Mashrabiya".	following [61]: • Structural parameters (self-weight). • Aesthetic parameters (cultural texture). • Environmental parameters (angle of the sun's rays) data. A geometry consisting of squares and hexagons, which is the shape that best symbolizes the filigree pattern of the region's mashrabiya origin, was determined, this model was rotated, repeated, and scaled parametrically with respect to the desired criteria using Digital Project, SMART Sizer and SVN, and prototype textures of each canopy was created [61].	vivid illustration of parametric architectural development in all directions. Since most of the parametric development features occur at the level of goals, and this project has many environmental, cultural, operational and aesthetic goals.
Morpheus Hotel • Year: 2019 • Location: Macau, China • Architect: Zaha Hadid Architects  **Morpheus Hotel (Source: [62])**	This 40-storey hotel designed as a rectangular envelope of 160m in height [62]. The hotel was constructed as two towers supported by the exoskeleton, while sky bridges create three distinctive visual voids. It considered as an engineering masterpiece as it is the world's first free-form tower sporting a complex exoskeleton [62].	Grasshopper was used to generate the model and coordinate it onto the free-form façade in the architectural level. The parametric design employed in the structural level in generation, documentation, and optimization of the 2,500 connections of the exoskeleton of the steel structure [63]. It also used on many other levels of this project as following [62]: • Generating the design. • Digital fabrication. • Generating documentation. • Gathering the exoskeleton connections and cladding.	This projects shows the parametric architecture e by using it in generating, documenting, and optimizing the building structure, and also in the digital fabrication of the structural and architectural elements of the project.

3.ANALYSIS: THE MOST IMPORTANT EVOLUTION FEATURES IN EACH ERA OF PARAMETRIC ARCHITECTURE

In this part, the projects that represent each era of the history of parametric architecture were analysed to conclude the most important characteristics of parametric architecture development, and the most important reasons that helped in this development.

3.1. Pre-Digital era

In this era, the term parametric has not been appeared yet, so these works were not called parametric at this time. One of the most important features that characterized this period was the weakness of capabilities and the lack of parametric tools, as digital and computer tools have not been appeared yet, and therefore the uses of parametric principles were characterized by simplicity and uncomplicatedness, so the parametric tools were limited to physical models, as in Colonia Güell, Sagrada Familia basilica and Munich Olympic Stadium, or sketches as in Philips Pavilion.

Because of the difficulty of applying the principles of parametric design, we found that they were applied in part of the building not the whole building, the ceiling was often the parametric part because it was the most flexible element in the design without prejudice to the rest of the building as we saw in all the previous examples.

As for the aims, Ferry Otto stated that these approaches were "**Form Finding**", therefore the parametric was

restricted to the design stage and did not infiltrate the remainder of the building construction stages.

The most prominent pioneer architects of the parametric architecture of this era were Antoni Gaudi and Frei Otto.

Accordingly, the most important development features of parametric architecture in this era can be summarized as shown in **(Fig. 5).**

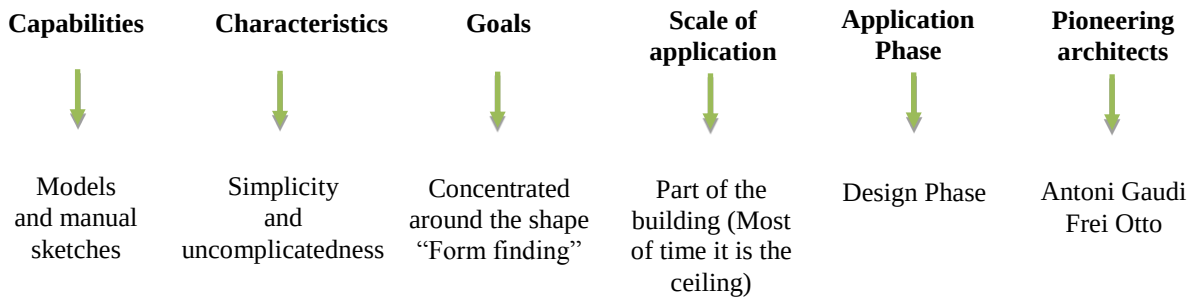


Fig. 5. The most important development features of parametric architecture in the pre-digital era, By authors.

3.2. Digital era

With the technological development and the emergence of digital tools, there has been a huge boom in parametric architecture, so the use of parametric principles has become more complex. By analyzing the projects in this era, we notice that they did not all proceed at the same pace. Therefore, this era was divided into two main phases which differs greatly in their characteristics:

- Phase 1
- Phase 2

3.2.1. Digital era (Phase 1)

This stage represented the period from the beginning of using digital tools in architectural design until the end of the nineties. In this phase of digital era, the characteristics of parametric architecture differed greatly from the previous to become more complex and full of details, as we saw in Bilbao Guggenheim Museum, to reflect the latest possibilities offered by the new tools such as CATIA and Digital Project. The use of parametric design has also expanded to include the entire building, after it was limited to a part of the building only, mostly the ceiling, and after it was limited to the design process and finding the shape, it's now employed in the construction stages to ensure the implementation of architectural forms with high accuracy. But the main goal of the parametric design remained the unique and distinctive architectural form. One of the most prominent architects who pioneered and developed parametric architecture in this era was Frank Gehry.

Accordingly, the most important development features of parametric architecture in this era can be summarized as shown in **(Fig. 6)**

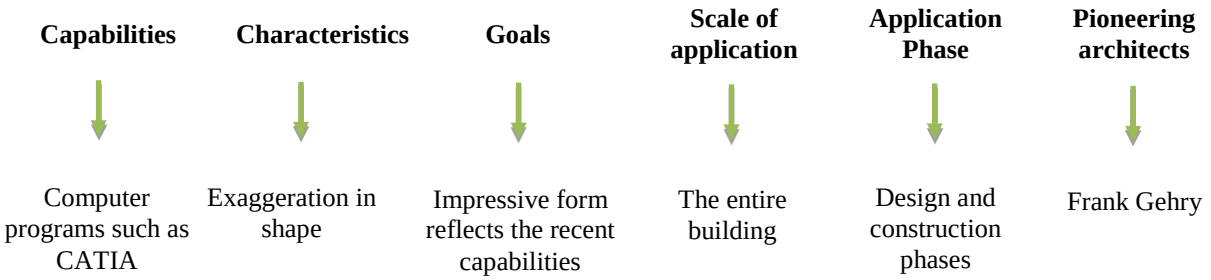


Fig. 6. The most important development features of parametric architecture in the digital era (phase 1), By authors.

3.2.2. Digital era (Phase 2)

Then, parametricism had begun to look in depth at real design problems such as environmental, social and functional problems. In our opinion, this is the essence of the difference between the first and second phases of the digital era. This deeper understanding of parametricism what allowed it to spread further, so parametric urbanism appeared, because urban design is not just a form, but it must be built on a social and environmental basis. The urban potential of parametricism has been investigated in a three year research agenda 2001-2004 at the AADRL and then appeared in several projects by Zaha Hadid Architects [16].

In the second phase of the digital era, the architectural form was no longer the only goal of the design process. Rather, the goals expanded to include environmental goals, as in Galaxy Soho, social as in Kartal-Pendik, and also economic goals. The application of parametric design expanded to enter the planning scale and include entire neighborhoods after what used to include the building or part of the building as in the pre-digital era. There is no doubt that it was due to the development of technological capabilities and the emergence of the most modern programs such as Rhino, Grasshopper and BIM tools such as Revit. These tools were used to include all stages of building construction, from concept design to the last stages of its implementation. Zaha Hadid is considered the most important and prominent architect whose name has been shining in parametric architecture in this period. She was also the first to use parametric design in urban design scale to create such fascinating projects and the most important of its kind in the field of parametric urbanism.

The most important development features of parametric architecture in this era can be summarized as shown in **(Fig. 7)**.

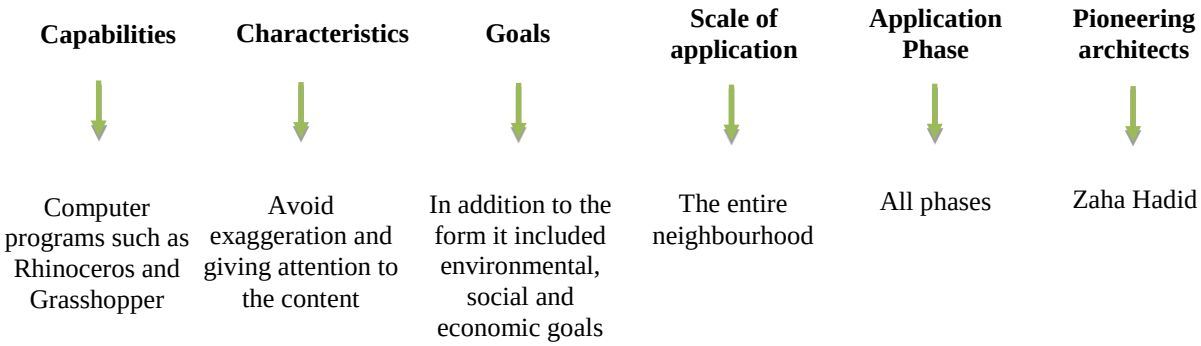


Fig. 7. The most important development features of parametric architecture in the digital era (phase 2), By authors.

4. DISCUSSION

In order to trace the history of parametric architecture and deduce the extent of the influence of digital tools on parametric architecture, it was divided into two historical eras, pre-digital and digital, and the most important projects in each era and the tool used in it were analysed as shown in **(Table. 4)** to deduce the most important development features of each era in terms of capabilities, characteristics, goals, scale and phase of applying parametric principles in the project and the most important pioneering architects, as shown in **(Table.5.)**.

By tracing the history of parametric architecture, we found that parametric architecture has been developed over time, and although the development was gradual most of the time, there were many turning points in the history of this development, whether they were projects or technological developments that enabled the existence of various programmes, or research that affected the general understanding of parametric architecture.

(Fig.8.) shows the development of parametric architecture and the most important milestones that changed the face of parametric architecture.

The study showed that:

- The beginning was by Antonio Gaudi's serious attempts to use the parametric concepts in architecture as it was not used before in the modern history.
- The emergence of the term "Parametric" in Moretti's writings, which opened the door for everyone to study this term and start researching it.

- The first model made using the computer built by Moretti let the architects believed in the possibility of using these tools in architectural design on the ground, which also prompted developers and programmers to produce programs that help architects in achieving this.
- The first public CAD application, Sketchpad, appeared, then programs and architectural projects that built using such programs rolled out.
- The first use of parametric design concepts in the urban space, to go beyond the architectural building, so the term "Parametric Urbanism" was established.
- Grasshopper, the most successful parametric program in the arena so far appeared, which is developing every day and showing different plugins that enable different features.
- Finally, the emergence and formulation of the term "Parametricism" as a modern architectural style that has concepts and goals that can lead architecture for decades. And since that time, parametric architecture has been constantly evolving, with new developments appearing every day.

Based on the aforementioned results, as well as the rapid technological development we are witnessing, it can be said that we are on the verge of another milestone that will spark a new boom.

Table 4. The most prominent architectural projects in each era of parametric architecture, Adapted by authors.

Project	Architect	Year	Location	Tool
Pre-digital era				
Sagrada familia basilica	Antoni Gaudi	Began 1882	Barcelona, Spain	Hanging model
ColniaGüell	Antoni Gaudi	1898-1914	Barcelona, Spain	Hanging model
Olympic Stadium	Frei Otto	1968-1972	Munich, Germany	Bubble-filled experimental model
Philips Pavilion	Le Corbusier, Iannis Xenakis	1958	Brussels, Belgium	Sketches
Digital era – Phase 1				
Moretti's stadium model	Luigi Moretti	1960	-	"IBM 610" computer
The Barcelona fish	Frank Gehry	1992	Barcelona, Spain	CATIA
Waterloo international station	Nichols Grimshaw	1993	London, England	I_EMS, MicroStationGenerative Components
The Guggenheim Museum	Frank Gehry	1993-1997	Bilbao, Spain	CATIA
Digital era – Phase 2				
One-North	Zaha Hadid Architects	2001-2019	Singapore	Maya
Kartal Pendik	Zaha Hadid Architects	2006	Istanbul, Turkey	Maya
Galaxy SOHO	Zaha Hadid Architects	2009-2012	Beijing, China	BIM, DP
Louvre Museum	Atelier Jean Nouveau	2017	Abu Dhabi, UAE	Digital Projects
Morpheus Hotel	Zaha Hadid Architects	2019	Macau, China	Rhino, Grasshopper

Table 5. The main differences in parametric architecture across the different eras, at the level of capabilities, characteristics, goals, scale and stage of application, By authors.

	Pre-digital era	Digital era (Phase 1)	Digital era (Phase 2)
Capabilities (Tools)	Models and manual sketches	Computer programs such as CATIA	Computer programs such as Rhinoceros, Grasshopper
Characteristics	Simplicity and uncomplicatedness	exaggeration in shape	Giving attention to the content than the form
Goals	Concentrated around the shape "Form Finding"	Impressive form reflects the recent capabilities	In addition to the form, it included environmental, social and economic goals
Scale of application	Part of the building (Most of the time it is the ceiling)	The entire building	Entire neighborhood
Stage of application	Design Phase	Design and construction	All Phases
Pioneering architects	Antoni Gaudi, Frei Otto	Frank Gehry	Zaha Hadid

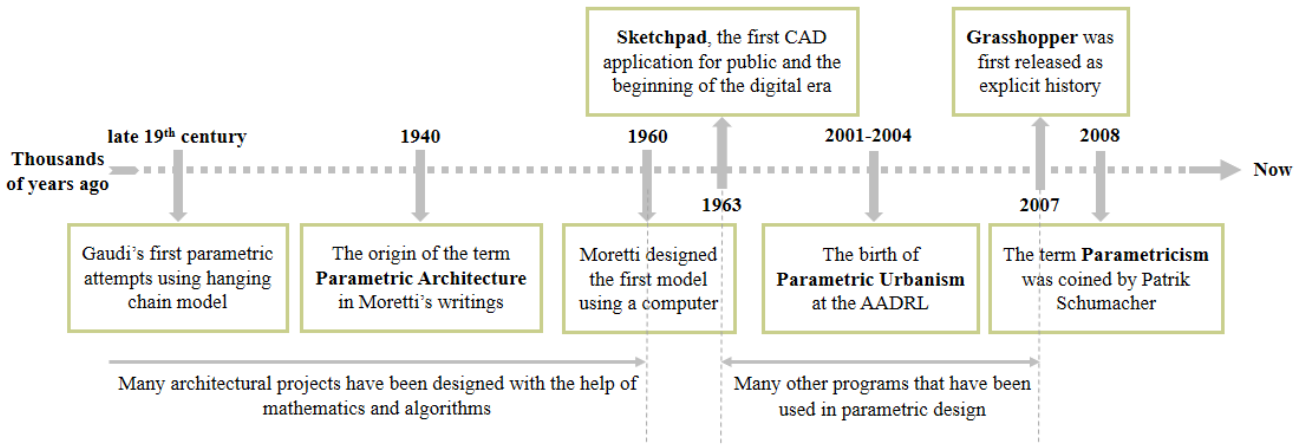


Fig. 8. Timeline for the milestones in the history of parametric architecture, By authors.

5. CONCLUSIONS

This research traces the origins of parametric architecture and its development through history, and analyses the impact of technological development and the availability of modern digital tools on parametric architecture. From the research, the following points can be concluded:

- Parametric design has deep roots dating back thousands of years since ancient civilizations, due to the close connection between the concept of parametric and mathematics, although the concept of parametric is somewhat different from what it is now.
- The Pre-Digital era of Parametric architecture in the modern history started in the 20th century, when the first serious parametric architecture attempts were pioneered by Antonio Gaudi and Frei Otto. Digital tools had not been appeared yet. Parametric architecture at that time was characterized by simplicity and distance from complexity, its goal was directed towards finding the shape, so it limited the use of parametric concepts in the design stage.
- With the technological development, Parametric architecture entered the digital era, as many programs and modern digital tools were produced that were used in the parametric architectural design, which caused a great development in it and led to an evolution in its features, so we found that the architectural form has become more complex and tended to

exaggerate, and the use of parametric concepts expanded to include the whole building as it passed the design stage and was used in the construction stage as well to ensure that the shapes are executed accurately.

- Over time, the understanding of the parametric concepts deepened, the term parametricism appeared, and more advanced programs were produced. The use of parametricism concepts moved away from exaggeration and focused on the content. The form did not become the only architectural goal, but the goals expanded to include environmental, social and economic goals. also expanded the scale of application of parametric design and went beyond architecture and reached urban design and planning scale.
- From all the above, we found that the technological development that led to the availability of digital tools was the main reason for the development of parametric architecture and this would not have happened without such tools that allowed us these possibilities.

Although at the beginning of the emergence of this term no one expected it to reach what it is now, all of this would not have happened without the technological development that allowed us these possibilities and opened us new horizons and strengthened our abilities to dream and imagine.

Therefore, based on this conclusion, it is necessary to focus future work on the detailed study of what parametricism has reached, and the study of possible development methods and trends for digital tools that we can benefit from in the field of architecture ad urbanism, as researchers in this sector feel that the coding period has come to an end, and that new platforms and software with considerably more sophisticated approaches will be available shortly. As well as, it is expected that the influence of parametricism in architecture and urbanism will expand to reach the physical composition of the building to control the DNA of the building in the coming years, the technology that has yet to be applied outside research labs.

With the advent of these new software and technology, architecture students can now have access to the same facilities and equipment as a reputable architecture company. A procedure which has begun already and whose results are visible and clear [19].

Credit Authorship Contribution Statement

Maram W. Rezk: Generating the idea, Collecting data, Methodology, Original draft preparation & Editing.
Ashraf A. Almokadem: Reviewing & Supervision.
Heba A. Ahmed: Editing, Reviewing & Supervision.
Nancy M. Badawy: Editing, Reviewing & Supervision.

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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