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Parametric Design as a Tool / As a Goal: Shifting Focus from Form to Function

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Chapter Highlights

- Parametric design is known by the public as a building morphology that is characterized by curvilinearity, continuity, and gradual transformation.
- Although its real potential lies in improving building performance holistically, parametric design was promoted and practiced as a way of creating complex non-orthogonal forms.
- The dominance of form in parametric design was strongly criticized by the architectural community, as it became a goal rather than a tool for better designs.
- In recent years, there has been a gradual shift of focus in parametric design from form to function, where its true potential lies, with the help of new technological developments.
- In the future, two important shortcomings of existing parametric design tools: the limited variety of parameters modeled and the inflexibility of a single parametric schema can be resolved by data-driven approaches such as big data processing and machine learning.

16.1 Introduction

Parametric design refers to defining relationships between parameters, algorithmically, in order to create variation and search in a set of solutions. The term "parameter" is defined as "a quantity whose value is selected for the particular circumstances and in relation to which other variable quantities may be expressed" (Oxford Dictionary of English, 2015). As this definition implies, parametric systems emphasize the manipulation of the parameter values in order to change the design geometry within the framework of pre-defined rules and relations. Computational design is a broader term referring to processing information through algorithms. Parametric design can be conceptualized as a subfield of computational design specialized in setting parameter relationships through algorithmic thinking.

It has been well-documented that the idea of relational thinking is not new in design. Architects like Antoni Gaudi and Frei Otto are known for their analog parametric experiments (Ahlquist & Menges, 2011). However, parametric design was popularized in the 2000s largely due to the public interest in the works of avant-garde architects such as Frank Gehry, Zaha Hadid, and Norman Foster. These architects have created iconic buildings with complex and non-standard forms using parametric design tools. The influence of this new form-finding process has been so strong that Patrick Schumacher declared "Parametricism" as the new global architectural style (Schumacher, 2009). This reflected the general opinion about parametric design in the profession and education: it has been embraced merely as a tool for form generation. Although parametric design has great potential to improve the performances of buildings, this potential has not yet been realized to its full extent.

Parametric approaches are especially important for housing design, since houses constitute a large share of the world's building stock, consume a lot of energy, and have tremendous effect on the wellbeing of occupants. However, to the best of the author's knowledge, parametric housing design has not been scrutinized by academic studies. The present chapter aims to fill in this research gap. Although parametric design is characterized by fluid non-orthogonal forms, there is a gradual

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shift of focus from form to function due to the strong arguments against parametricism as well as recent developments in parametric technology. The chapter aims to present the historical trajectory of this shift along with a critical analysis of the current situation and projections for the future. Bibliometric analysis is used as an empirical tool to test the validity of the observations. The chapter consists of four sections. The development of parametric thinking in architectural design, the early boom of parametrically designed buildings, and the critiques of form dominance in parametricism are covered in Section 1. In Section 2, current developments in parametric housing design are reviewed according to bibliometric analysis. Section 3 covers key methods and tools, and the final section discusses the future of the field.

16.2 The Rise of Parametricism and Objections to Its Limitations

Although relational thinking is essential to architectural design and was operationalized through analog means by architects like Antoni Gaudi and Frei Otto, the term "Parametric Architecture" was coined by Italian architect Luigi Moretti in the early 1940s (Frazer, 2016). Having used the computer technology of the period, Moretti presented drawings and models of a parametric stadium in his "Parametric Architecture Exhibition" at the 12th Milan Triennial in 1960 (Bucci & Mulazzani, 2002). In this work, he showed how the form of a stadium can be informed by parametric equations regarding nineteen parameters. Ivan Sutherland's Sketchpad (1964) can be considered the first computer program on parametric design. In his PhD study at MIT, Sutherland aimed to develop an interactive tool that was able to "communicate with designers." The program enabled designers to draw lines and arcs with a light pen, which then related these with each other by some pre-defined constraints. Although the idea underlying Sketchpad had been revolutionary, parametric software was not commercialized until the mid-1980s. Parametric Technology Corporation, a technology firm founded by former mathematician Samuel Geisberg, released Pro/ENGINEER, the first commercial parametric design tool in 1988.

While engineering design was adopting 3D parametric design models in the early 1990s, the architectural community was under the influence of deconstructivism, a postmodern architectural movement characterized by formal complexity resulting from the distortion and dislocation of established elements of architecture. Costanzo (2009) discusses that the dominance of the form in that decade paved the way for the exponential rise of the signature architect. Bernard Tschumi, Peter Eisenman, Frank Gehry, Zaha Hadid, Rem Koolhaas, and Daniel Libeskind are architects who are often considered deconstructivists. Geometric complexity inspired by deconstructivism and the use of the new computational tools promoted "Folding in Architecture" a term referring to formal and conceptual continuities in design. In 1993, Greg Lynn published an influential paper on folding in a special issue of *Architectural Design*.[1] During the same period, advances in engineering design were penetrating into pioneer architectural firms. Dassault Systèmes integrated many of Pro/ENGINEER's parametric features into the solid modeling program CATIA and this formed the basis of Frank Gehry's complex buildings like the Guggenheim Museum in Bilbao (1993–97) and later the development of their own parametric modeling program called Digital Project, later around 2004.

Zaha Hadid Architects (ZHA) played an important role in the parametric boom of the early 2000s. Although the firm was established in 1980, with the exception of Vitra Fire Station (completed in 1994), Hadid and her partner Patrick Schumacher had mostly been influential in academia during the 1990s. Maturing parametric technology and demanding market conditions gave rise to the commercial success of many ZHA buildings in the 2000s such as the BMW Central Building, Phaeno Science Centre, and Evelyn Grace Academy. In 2007, Schumacher coined the term "Parametricism" and a year later the "Parametricist Manifesto" was published at the Venice Architecture Biennale. Schumacher defined parametricism as the next important style after modernism. Continuous differentiation, ordered complexity, and fluidity were defined as the hallmarks of parametric aesthetics. A balance of repetition and variety is sought after in every type of design; however, the morphology of parametricism is totally based on this balance. Scaling and geometric fit are used gradually to create complex forms with continuously changing surface curvature. The gradual transformation of non-orthogonal geometries provides a sense of ordered complexity and fluidity. The resulting buildings have non-standard, almost natural looks. The Parametric Manifesto prioritized the formal aspects of the approach so much so that Schumacher defined some taboos and dogmas for design. Taboos included avoiding rigid geometric primitives, simple repetition of elements, and juxtaposition of unrelated elements or systems. Dogmas consisted of designing forms to be parametrically malleable, differentiating gradually, and relating systematically (Schumacher, 2009).

1 Since the 1990s, Wiley's iconic journal Architectural Design has published a series of special issues on computational design, which addressed the milestones in the field.

From 2000 to 2010, several ambitious parametric buildings were constructed including Yokohama International Passenger Terminal by Foreign Office Architects (completed in 2002), Beijing National Stadium by Herzog & de Meuron (completed in 2008), Water Cube by PTW Architects (completed in 2008), Yas Hotel by Asymptote (completed in 2009), and the Guangzhou Opera House by Zaha Hadid Architects (completed in 2010). However, these high-tech gigantic structures were often criticized for being placeless, soulless, and unsustainable. Rybczynski (2013) discussed that although parametric design had been embraced for futuristic form-making, its true potential lay in improving building performance. He also observed that in conventional applications the parameters and algorithms underlying parametric design were decided mostly arbitrarily to obtain visually compelling results. Having recognized a promising potential in building simulations of the period to improve environmental performance, Rybczynski (2013) pointed out two shortcomings of early simulation technology: the separateness of different types of simulations and the problem of the computability of architectural information, especially that is related to human behavior. Likewise, Coyne (2014) claimed that the complex and the "ill-defined" nature of the constraints of architectural design limited the functionality of early parametric design approaches. He argued that focusing only on a limited number of parameters in design might cause ignorance of "use, history, culture, politics, and the complexities of human inhabitation" (para. 10).

These and other similar oppositions from the architectural community led Schumacher to revise his "Parametricist Manifesto" in 2016. He acknowledged the arguments against parametricism and declared that parametricism was "marginalized." In an effort to prevent this marginalization, Schumacher referred to the larger research initiatives in computational design and proposed social functionality as a new agenda for parametricism (Schumacher, 2016, 2020). In fact, parallel to the development of parametricism, a more technical and engineering oriented approach to computational design had flourished in academic institutions including AA School of Architecture, MIT, ETH Zurich, and Stuttgart University. Supported by enhanced methods of numerical simulation and extensive computing power, the new computational methods in architecture enabled rational and aesthetically pleasing solutions to complex problems via borrowing techniques and algorithms from nature (Menges, 2012; Oxman, 2012). Integration of parametric design with a variety of computational design methods seems to be the next phase of development. The section below reviews the emerging studies in this track according to the findings of a bibliometric analysis.

16.3 Shifting Focus from Form to Function: A Bibliometric Analysis

In order to understand the trends in parametric housing design, a bibliometric analysis was conducted. Bibliometric analysis refers to a quantitative inquiry into the publications pertaining to a specific theme (Mayr & Scharnhorst, 2015). The bibliometric data were retrieved from the ISI Web of Science. The search string TS = "parametric design" AND (TS=housing OR TS=residential OR TS=dwelling) was used to find the relevant journal papers. Only the papers indexed by journal citation indices (Science Citation Index Expanded, Social Sciences Citation Index, and Arts & Humanities Citation Index) were included in the search process. The publications indexed by Conference Proceedings Citation Indices, Book Citation Index, and Emerging Sources Citation Index were excluded. The search period was set to include all years (from 1979 to 2022). 137 papers were accessed as a result of this search.

Vosviewer© bibliometric analysis software was utilized for analysis. It is a freely available tool for creating maps based on network data and for visualizing and exploring them. The bibliometric data (full record and cited references) were exported to Vosviewer© in tab-delimited format. The keywords of the papers were also refined in order to combine the same but differently written keywords (e.g., genetic algorithm/genetic algorithms) and to eliminate mistakes. Vosviewer© uses a thesaurus file for this purpose.

Keywords indicate the core content of publications and demonstrate the spectrum of area studies within any knowledge domain (Van Eck & Waltman, 2010). In Vosviewer©, the output of the keyword co-occurrence analysis is a distance-based network visualization in which the distance represents the strength of the relations between two keywords, i.e., the number of co-occurrences. A larger distance indicates a weak relationship between the items. The item label size is proportional to the number of publications in which the keyword was found and different colors represent different knowledge domains clustered by the software's clustering algorithm.

The keyword co-occurrence analysis revealed the most important keywords and keyword clusters that correspond to the main research themes in the field. The keywords which were used at least in three papers were included in the keyword co-occurrence network. The final network with 13 keywords, six clusters, 21 links, and a total link strength of 43 is shown in Figure 16.1. As seen in the figure, the link between parametric design and optimization is very strong. This indicates that the majority of the studies utilized parametric design for optimization. The figure also illustrates that genetic algorithms and shape grammars are the methods that are widely used for parametric optimization.

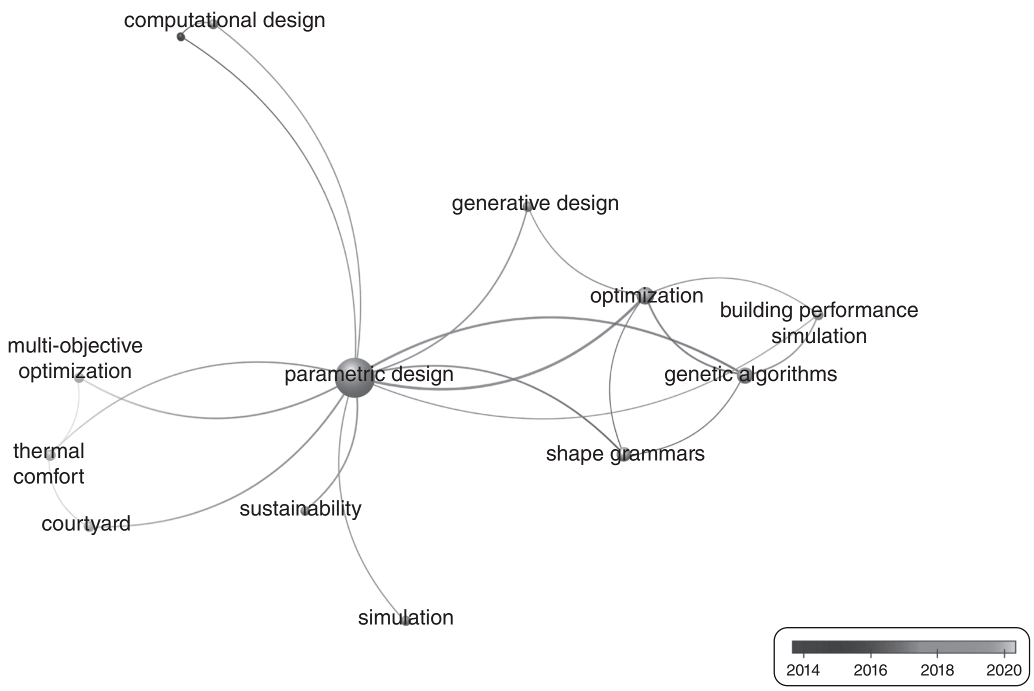

Figure 16.1 The keyword co-occurrence network timeline related to parametric housing design research from 1979 to 2022.

Color coding in Figure 16.1 represents the average year in which the keyword was used in literature. In the visualization, colors range from blue (earliest year), to green, to yellow (latest year). According to the figure, the latest keywords used in the papers are "multi-objective optimization" and "building performance simulation". The use of multi-objective optimization along with building performance simulation describes a recent trend in parametric housing design. The keyword co-occurrence network shows that multi-objective optimization has often been associated with thermal comfort recently. The other keywords in the network such as "optimization," "generative design," "computational design," and "shape grammars" are relatively old.

In order to obtain a comprehensive review of the recent trends in parametric housing design, the same bibliographic search was repeated for the time period between 2020 and 2022. This search resulted in 35 papers. After a careful examination of these, 25 papers are found to be relevant and included in further analysis. The selected papers were thoroughly examined to extract information in five categories: author(s) and date, application area, design scale, objectives, and tools. Application area refers to the aspects of housing design parametric approaches are applied. Design scale indicates the level at which parametric techniques were applied to the built environment, e.g., single building level or district level. Objectives are aims for parametric modeling and analysis. Tools are software applications used in the examined studies (Table 16.1).

A close examination of Table 16.1 reveals that the majority of the applications (80%) were at the building scale and only 20% of the applications were at the district scale. While building level applications range from bracket connection design to whole buildings, district scale studies focus on housing mass and layout design. When the objectives are analyzed, it is observed that 76% of the studies focused on increasing environmental sustainability. Reducing carbon emissions, providing thermal comfort, optimizing daylighting, and minimizing energy use were some of these concerns. Geometry and form creation constituted the aims of 8% of the analyzed papers. The remaining 8% dealt with information management i.e., extracting and utilizing data from the existing models. Only 4% of the papers were related to the parametric design of occupants' spatial experiences.

When methods and tools applied in parametric housing design were analyzed, multi-objective optimization (MOO) stood out as a recent trend in parametric housing design. 44% of the analyzed articles utilized some form of multi-objective optimization. A few studies employed shape grammars for layout design and the rest either aimed at single-objective optimization or tackled another problem in housing design like information management. Grasshopper and its plug-ins are the most widely used tools. 76% of the articles used Grasshopper along with some other plug-in. 16% of the studies developed a custom tool for parametric housing design and 8% used Design Builder software. The following section expands on the key methods and tools used in parametric housing design.

Table 16.1 Contents of articles on parametric housing design (2020–2022).

Article	Application Area	Scale	Objectives	MOO (Y/N)	Tools
(Tabadkani et al., 2022)	Courtyard design	Building	Increasing indoor thermal comfort, decreasing costs	N	Grasshopper, Ladybug, Honeybee
(H. Wu et al., 2022)	HVAC system design, photovoltaic system design	Building	Lowering HVAC load, increasing photovoltaic power generation, lowering investment cost	Y	Grasshopper. Wallacei
(Liang & Jing, 2022)	Building exterior wall design	Building	Increasing indoor thermal comfort, decreasing costs	Y	Grasshopper, MATLAB
(Tong & Wilhelm, 2022)	Hillside settlement design	District	Creating hillside settlement designs according to topography and principles of serial construction	N	Grasshopper
(Khidmat et al., 2022a)	Hyperboloid wooden house	Building	Minimizing normal force average, displacement and cost, and maximizing building volume. Optimizing useful daylight illumination in summer and winter	Y	Grasshopper, Ladybug, Honeybee, Karamba, Octopus, Colibri
(Khidmat et al., 2022b)	Expanded metal shading	Building	Minimizing annual sunlight exposure, maximizing spatial daylight autonomy and useful daylight illuminance	Y	Grasshopper, Ladybug, Honeybee, Octopus
(Eleftheriou et al., 2022)	Cement bamboo frame technology	Building	Using parametric design to gather the data required to carry out simplified life cycle assessment of social housing projects	N	Custom tool
(Ansah et al., 2022)	Life cycle assessment of whole building	Building	Minimizing energy use, carbon emissions and cost	Y	Grasshopper, Ladybug, Honeybee, Wallacei
(Yang et al., 2022)	Renovation of building envelopes	Building	Minimizing carbon emissions of residential buildings in severe cold regions	N	Design Builder
(Thajudeen et al., 2022)	Bracket connection design in industrialized post and beam building system	Building	Supporting the reuse of design assets	N	Custom tool
(Kim et al., 2021)	Residential building mass design	District	Ensuring valid sunlight hours	N	Grasshopper, Ladybug
(Zhang & Ji, 2021)	Optimization of daylighting, ventilation and cooling load in apartments	Building	Optimizing daylighting, ventilation and cooling load	Y	Grasshopper, Octopus
(Bande et al., 2021)	Shading structure design	Building	Reducing cooling load and cost	N	Grasshopper, STAAD, BIMSolar
(Sakiyama et al., 2021)	Naturally ventilated house design	Building	İmproving thermal comfort by maximizing natural ventilation effectiveness and diminishing energy demand	Y	Grasshopper, Honeybee, Matlab, Colibri, Opossum
(Shahi et al., 2021)	Modular extension design for existing buildings	Building	Optimizing energy use, daylighting, life cycle impact, life cycle costing and structural complexity	N	Grasshopper, custom tool

(Continued)

Table 16.1 (Continued)

Article	Application Area	Scale	Objectives	MOO (Y/N)	Tools
(Y. Wu et al., 2021)	Microclimate-sensitive urban design	District	Maximizing project development profits and providing a comfortable wind environment	Y	Custom tool
(Wang et al., 2020)	Historical Chinese courtyard dwelling design	Building	Producing variants of historical Chinese courtyard dwellings	N	Grasshopper
(Agugiaro et al., 2020)	Urban planning	District	Using actual sizes of dwellings to predict the city of tomorrow	N	Grasshopper, Custom tool
(Soflaei et al., 2020)	Courtyard house design in subtropical desert climate	Building	Maximizing thermal comfort	N	Grasshopper, Ladybug, Honeybee
(Mahdavi Adeli et al., 2020)	Window to wall ratio in warm climate housing design	Building	Ranking orientations for CO_2 emissions	N	Design Builder
(Sarkar & Bardhan, 2020)	Ventilator and furniture positioning optimization	Building	Maximizing indoor air flow, minimizing indoor air temperature and contaminant concentration	Y	Custom tool
(Zhang et al., 2020)	Residential spatial form and building envelope design	Building	Reducing energy consumption	Y	Grasshopper, Ladybug, Honeybee, Octopus,
(Kiss & Szalay, 2020)	Residential form, envelope, fixture and heating energy source optimization	Building	Optimizing life cycle environmental impact	Y	Grasshopper, Ladybug, Honeybee, Octopus
(Kim & Cho, 2020)	High-rise housing complex layout design	District	Improving sunlight access and ensuring compliance with building code restrictions	N	Grasshopper, GECO, Ecotect
(Nguyen et al., 2020)	Agent-based modeling of social-spatial processes in housing design	Building	Providing social-spatial comfort to occupants	N	Grasshopper, Custom tool

WOS Indices: Science Citation Index Expanded, Social Sciences Citation Index, Arts and Humanities Index.

16.4 Key Methods and Tools

The bibliometric analysis presented in this chapter indicated that multi-objective optimization is an important trend in parametric housing design. Multi-objective optimization is concerned with resolving optimization problems with more than one objective. These objectives are often conflicting, so the optimal solution set is called to be Pareto optimal, i.e., it is not possible to improve one objective without aggravating the other. Housing design involves many conflicting objectives; for example, improving daylighting by enlarging window areas increases heat loss through these windows. Evolutionary (genetic) algorithms are especially useful for solving such problems because they use principles of natural selection, reproduction, mutation, and recombination. When used for multi-objective optimization, evolutionary algorithms result in a set of optimal solutions which contains elements that are equally optimal in the sense that no solution is better than any other solution in the set. In order to reach to a single optimal solution, a decider metric is chosen according to the context of the problem (Deb, 2014).

Besides single- or multi-objective optimization, shape grammars is another method in parametric housing design. The procedure aims to provide algorithmic definitions of "languages" of architectural design. A grammar is used to generate a specific type of design. A typical grammar consists of shapes and rules which govern the transformation of one shape to another. A rule includes an input shape, a transformation rule, and an output shape. A parametric shape has a definition so that certain points are specified in terms of equations or constraints (Stiny, 1980). Parametric shape grammars were applied in housing design in order to create optimum housing layouts (Tong & Wilhelm, 2022; Wang et al., 2020).

Regarding the software tools in parametric housing design, it was observed that in the majority of the analyzed studies, Grasshopper was used as the main modeling environment. Grasshopper is a visual programming tool working with Rhinoceros 3D modeling software. The program has components that convert input parameters to output parameters. The output parameters of one component become input parameters for another component and the whole algorithm is displayed visually as a data flow diagram representing information flow from left to right. The geometrical results of the algorithm can be seen dynamically in the accompanying Rhinoceros window (Figure 16.2). The visual nature of Grasshopper and its user-friendly interface made it a popular tool in parametric design. Grasshopper and Rhino have several apps for specialized applications. The bibliometric analysis revealed that the most widely used apps for parametric housing design were Ladybug, Honeybee, Octopus, Wallacei, and Opossum. Ladybug is utilized to visualize and analyze weather data in Grasshopper. This tool enables the production of diagrams such as the sun path, wind rose, and psychometric chart. Furthermore, several analyses regarding geometry such as radiation, shadow, and view studies can be conducted. Honeybee integrates Grasshopper with widely used simulation engines like EnergyPlus for estimating energy use, HVAC design, and ensuring thermal comfort and Radiance for daylighting and glare simulation (Roudsari et al., 2013).

Octopus, Wallacei, and Opossum are multi-objective optimization apps. While Octopus and Wallacei employ evolutionary algorithms, Opossum utilizes a model-based machine learning algorithm besides an evolutionary one to produce surrogate simulations (Food4Rhino, 2023). Simulations are very useful for improving building performance; however, they are often time-consuming and expensive. This seems to be the main reason for the lack of simulation-based design in the building industry. Surrogate simulation produces a model of the results of a simulation rather than performing thousands of simulation iterations. This accelerates the process and decreases costs (Wortmann, 2017).

In recent years, machine-learning techniques have widely been used in surrogate modeling (Zorn et al., 2022). Machine learning, a subfield of artificial intelligence, deals with studying and designing systems that can learn from data. Alpaydin (2010) defined machine learning as programming computers to optimize a performance criterion using example data or past experience. Machine learning is also utilized to detect patterns in existing data and make predictions based on such patterns (Murphy, 2012). These definitions highlight the usefulness of machine learning in surrogate modeling. Surrogate

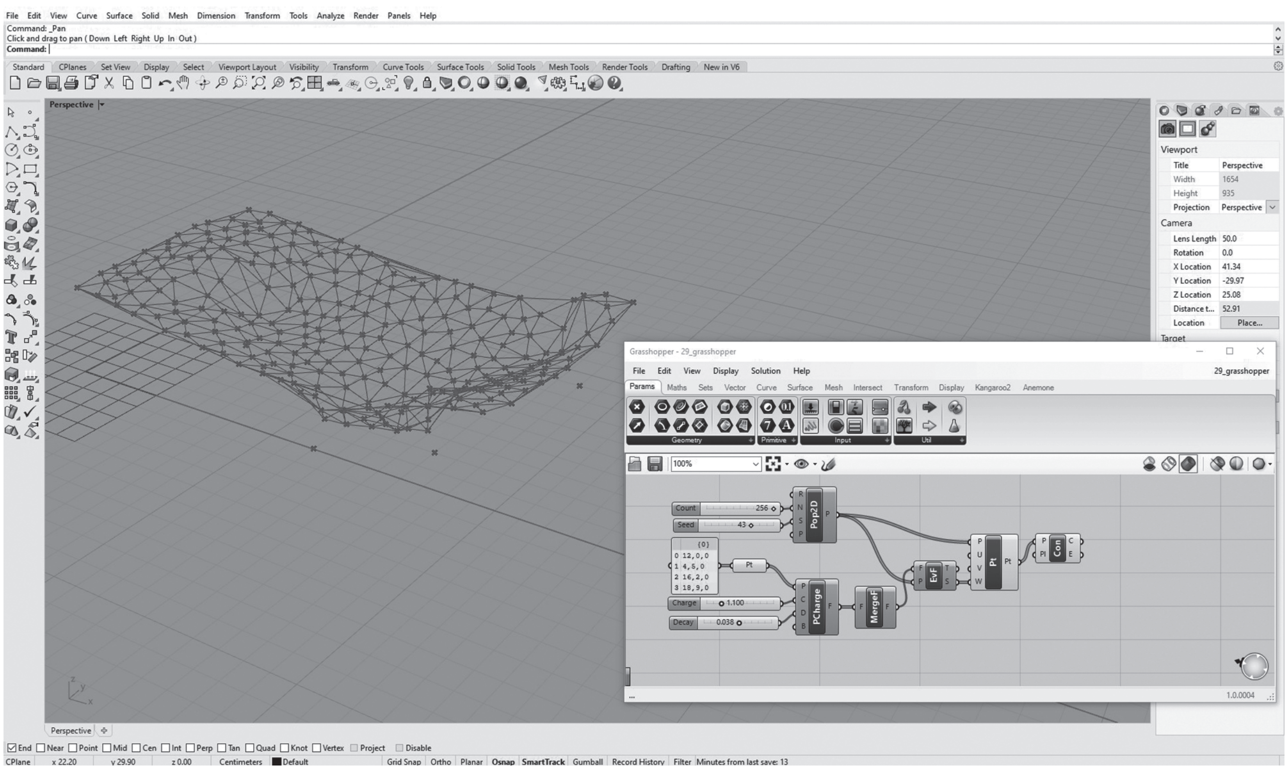

Figure 16.2 Grasshopper interface.

modeling employs supervised learning, i.e., feeding the machine with labeled data. In this case, labeled data consists of design parameters, simulation results, and outputs. Through evaluating the data, the machine learning system creates a statistical model to accurately approximate the simulation output. The training data is extracted via sampling simulation outputs from critical locations. Pairing design parameters with resulting building design performance enables the system to make accurate predictions about the future performance of designed buildings without numerous simulation cycles. Machine learning-based surrogate simulation has been the last important development in parametric housing design.

16.5 A Future Outlook

It is challenging to anticipate the future in terms of technology, but making an effort to do so can help in evaluating the significance of different potential advancements. This way, designers and managers can make more informed decisions. The last decade has witnessed an exponential growth of data and computing power. Data is generated via various means including sensors, building management systems, post-occupancy evaluation, building services, maintenance systems, security and surveillance systems, etc. This proliferation of expansive data is called "big data." Big data is used in education, healthcare, manufacturing, banking, service, and entertainment industries to improve user experience. Although the construction industry is lagging behind in harnessing big data, it is increasingly automating and improving its processes due to enhanced data gathering and utilization techniques (Munawar et al., 2022).

It seems that automation and process improvement is just the beginning. Parametric design is a data-intensive approach and parameters consist of geometrical features as well as performance measures. The performance of the built environment can be conceptualized from a wide perspective beyond the environment. Although current studies are mainly focusing on improving environmental performance and sustainability of buildings, there are many different types of design knowledge that have rarely been parametrized. User-building interaction is one of these less explored aspects of performance. Such interactions are especially important in housing design, since people spend a lot of time in their houses and their experiences account for physical and emotional wellbeing. The computability problem of experience-related information in building design has been previously addressed (Coyne, 2014); however, only recently has the expansion in data technologies enabled the application of parametric design methods in this area. For example, Nguyen et al. (2020) implemented an agent-based parametric system for considering social-spatial processes in housing design. The system employed a human behavior definition adapted from Schmidt's (2000) PECS (Physical, Emotional, Cognitive, Social) model. The proposed parametric design tool generated simulations of user occupation in housing design and design decisions could be evaluated according to occupants' individual and collective dwelling comfort and satisfaction.

Although the widely known examples of parametric buildings that were constructed in the early 2000s were criticized for taking only a few parameters into consideration to create complex forms, the academia had already recognized the wide range of parameters involved in building design (Keeling, 2017; Kiraz & Kocaturk, 2019). As an early example, Madkour et al. (2009) developed a parametric system for housing design that employed both social and environmental references. Social criteria included accessibility, privacy, sociability, multi-functionality, and occupancy. Environmental criteria consisted of the orientation of the unit, floor configuration, and controls of glazing surfaces. The parametric system enabled designers to develop multiple living scenarios requiring different criteria. The dependencies between social/environmental parameters and geometrical/layout parameters were expressed as parametric rules. The system also included a module for urban design which evaluated housing tower mass according to layout parameters such as density, shading impact, and view blocking. Although they were very promising, Madkour et al.'s (2009) and similar studies have not been commercialized and widely used in the industry. The main reason for the lack of holistic parametric design applications is the incapability of such tools in compromising multiple objectives. Madkour et al.'s (2009) system could provide insights into many dependencies between parameters; but, when there were conflicting objectives, it could not offer a solution. The game changing development in recent years is multi-objective optimization which enabled informed negotiation decisions. The bibliometric analysis presented in this chapter indicated that multi-objective optimization has been a recent research trend. In near future, more parametric design tools will emerge, which will model and resolve many different aspects of housing design in a more integrative and holistic manner. Beyond form and environmental performance, many intangible dimensions of humans' experience of houses could be taken into account by such systems.

Besides focusing on only a limited type and number of parameters, another shortcoming of the existing parametric design systems is the inflexibility of their one model-one graph approach (Harding & Shepherd, 2017; Turrin et al., 2011). The conventional parametric design tools force designers to follow a top-down decision-making process and create a single parametric schema. Once this schema is constructed via the data flow diagram, it is very difficult to make changes and explore alternative designs. Previous research showed that designers are less likely to produce topographically different design alternatives while designing in parametric environments, although these tools support creating variations of a single schema (Tünger & Pektaş, 2020). An interesting track of research has emerged recently to tackle this problem: AI-assisted parametric modeling systems for supporting design exploration. Toulkeridou (2019) addressed the limitations of single parametric schema of the existing tools and proposed the use of a machine learning system trained on a data set of parametric graphs to suggest alternative data flow paths to the designer. The system can synthesize data driven completions to an evolving graph so that the design exploration space is expanded. Toulkeridou's and similar studies (Liao et al., 2020; Zhou & Park, 2023) pave the way for AI-augmented architectural design which can be the new paradigm in digital design. The role of the digital in this development is likely to be beyond mere assistance (as earlier computer-aided design paradigms envisaged); but an idea of merging minds and intelligences, a kind of symbiosis with man and machine is increasingly being discussed (Llabrés & del Campo, 2020).

16.6 Conclusion

This chapter provided a historical and analytical trajectory for the shift of focus in parametric housing design from form to function. As a way of thinking, parametric design has always existed. Considering the notion that the design process can be defined as a series of decisions on parameters, one can even claim that all types of design are essentially parametric. Proto-parametric procedures of pioneer architects like Gaudi and Otto carried parametric thinking a step further through their inventions of non-digital tools for parametric computation. However, parametric design has still been known by the public as a new building morphology that is characterized by curvilinearity, continuity, and gradual transformation. The formal aspects of parametric design had been so dominant that the approach was embraced by practicing architects and architectural schools as a goal rather than as a tool for better designs. This situation attracted criticism from many fronts and, as a result, the highly provocative "Parametricist Manifesto" was subdued.

In recent years, there has been more interest in performative applications of parametric design. Parametric optimization has been used to develop sustainable housing designs with regard to energy use, thermal comfort, daylighting, carbon footprint, and life cycle cost. The bibliometric analysis in this study documented this shift systematically. It also showed that parametric optimization models are increasingly becoming multi-objective. As a result, many conflicting criteria in housing design can be resolved simultaneously. Last but not least, data-based techniques like machine learning are also transforming parametric housing design. Machine learning-supported surrogate simulation has already been recognized in the industry. Furthermore, this chapter highlighted two important shortcomings of existing parametric design tools: the limited types/numbers of parameters modeled and the inflexibility of a single parametric schema can be alleviated by big data processing and machine learning. As a final word, it can be said that the evolution of parametric housing design is very likely to continue in the future towards more holistic, performative, and sustainable solutions.

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