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Perspective

Advances in Climatic Form Finding in Architecture and Urban Design

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Abstract: Researchers, architects and planners are increasingly urged to develop and apply sustainable methods and solutions to reduce the impact of the built environment on climate, adapt cities to climate change and reduce or eliminate resource depletion and building-related carbon emissions. In recent years, taking advantage of state-of-the-art computational and environmental design tools, researchers and designers are developing new digital workflows, methods and solutions to investigate climate-optimal and performative buildings and urban forms. This perspective paper analyses state-of-the-art computational methods; form generation processes; and tools, criteria and workflows that present how these are integrated into climatic form finding, allowing the improvement of building and urban environmental performances. Additionally, current challenges and future directions are presented.

Keywords: building and urban form generation; sustainable built environment; climate adaptation; energy use reduction; energy generation; indoor and outdoor comfort; computational design

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1. Introduction

Designers and planners are increasingly urged to develop design solutions for climate adaptation that result in reduced impacts on climate and resource depletion since the built environment consumes 36% of the energy globally produced and is responsible for 37% of energy-related global CO_2 emissions [1]. This trend is expected to grow with the increasing share of the urban population, which is expected to reach 68% by 2050 [2]. Thus, sustainability, carbon-neutral development, and the reuse of urban areas fall within the agenda of countries and international organizations via plans with respect to the Sustainable Development Goals [3], the European Green Deal [4] and the Roadmap to a Resource-Efficient Europe [5].

Buildings and urban forms have a major impact on building energy use, passive heating and potential energy generation [6–8]. Building orientation, articulation and envelope have significant influences on heat avoidance in order to reduce cooling energy use and on the healthiness and liveability of indoor spaces [9,10], and they can improve the quality of daylight [11], which is the source of interior building illumination that is most appreciated by occupants [12]. Urban density, building heights and patterns determine the liveability of urban areas and outdoor thermal comfort experienced by people [13,14].

Computer-aided design (CAD) tools have been developed more than half a century ago to help designers in conventional tasks such as drafting, visualizations and quantity calculations. Early simulations were used for the structural and heat transfer analysis of the building components of already defined buildings. Consequently, in the early 2000s, environmental design programs such as Ecotect allowed realizing annual sun path and shadow studies; and solar radiation, daylight and thermal simulations during the early stages of the architectural project [15]. However, the possibilities to generate conceptual design options on the basis of climatic conditions were limited until parametric design software was also introduced during the 2000s, and environmental design tools were integrated into computational design workflows. Introduced to the design community by the GenerativeComponents software [16], parametric design become widely used in building information modeling (BIM) via Dynamo [17] and in architectural and urban design and performance-driven design via Grasshopper (GH) [18] for Rhinoceros [19] due to the wide and unparalleled ecosystem of climatic and environmental tools available.

The present work aims to provide a view with a particular focus and trajectory about the utilization of climatic and performance analysis tools in architecture and urban design. Differently than other works that deal with different aspects such as building envelope and glazing properties, materials, occupant use and systems operation, the novelty of the present paper is to focus on building and urban form generation processes and their integration with simulations and analyses in parametric workflows as decision-making tools that can reduce climate impact and resource depletion and provide adaptation to the climate of the built environment. Since it is the most used in climatic form finding, this paper refers to the methods, procedures and workflows realized via GH.

2. State-of-the-Art Methods in Climatic Form Finding

The introduction of parametric design allows the designer to develop dynamic models rather than univocal solutions, integrating several aspects of the design workflow and creating connections between the functional, spatial and material features of the object relative to the design and external factors such as climatic and environmental conditions. The potential of parametric design methods and form procedures permits exploring the design spaces of the ranges of solutions to find the optimal building and urban forms in the consideration of occupant health and energy use and generation, which are strictly dependent on climatic factors. This study is organized into five main sections that present the state-of-the-art methods of climatic form finding in which (Section 2.1) Computational Methods, (Section 2.2) Form Generation Procedures, and (Section 2.3) Simulation and Evaluation Workflows, which are mutually related, are presented and discussed (Figure 1). Following, the main (Section 3) Challenges and Gaps and (Section 4) Opportunities and Future Directions are presented.

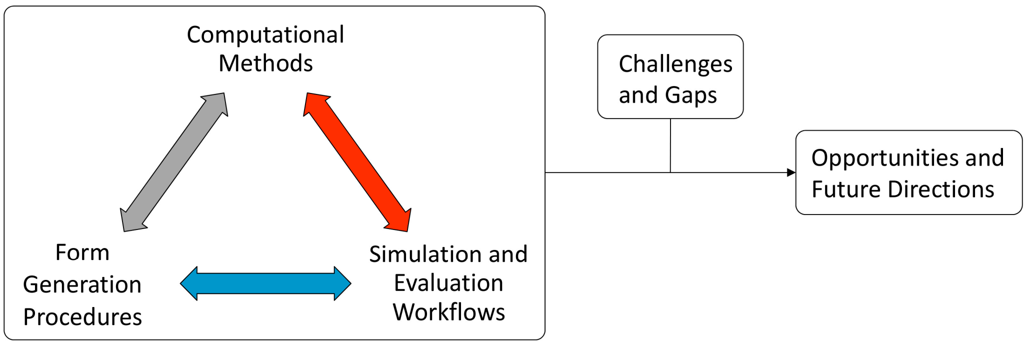

Figure 1. Relation of the five main sections of the study.

2.1. Computational Methods

Climatic form finding workflows are developed via computational methods that take advantage of the potential of the integration of parametric design, climatic analyses and performance simulations. The workflows are realized via the use of different components (i.e., programming nodes), which comprise the following: geometrical objects such as rooms, building volumes, envelope features and urban elements are generated; parameters and variables are defined; climatic and environmental simulations are performed; and calculations are performed and the results are assessed. The components are connected to constitute different workflows and computational methods that integrate geometrical parameters, climatic factors and simulations in order to generate forms and perform analyses. Computational methods facilitate and reduce the time for selecting optimal design solutions or trade-offs in consideration of several climatic performances, as opposed to the time-consuming and inefficient trial-and-error methods of conventional CAD, BIM and simulation software. For the present study, four main methods are presented; automation; design–analyse–evaluate–adapt; optimization; and design exploration.

2.1.1. Automation

A significant potential of parametric software is to automate form generation, calculations and simulations for evaluation processes. The scope is primarily to automatically generate a large number of design variations that are different for building and urban morphology, i.e., form, size, density, orientation and envelope characteristics; occupant and energy use; and climatic conditions related to the location and period of analysis in order to select optimal solutions or tradeoffs (Figure 2). Automation is primarily a method of form generation and performance simulations after which evaluations and assessments are performed. It is possible to generate design solutions via the automatic variation of one or several design variables. For each variation, automation tools record the data relative to the design parameters; climatic analyses; simulation inputs and outputs; and relative calculations and assessments [20]. The data are then recorded in the parametric model in data files or exported to tabular format files such as csv and xlsx.

Automation is used efficiently in climatic form finding to analyse the daylight and energy performance of the design variations of indoor spaces by taking into account room sizes, façade orientations, window-to-wall ratio (WWR), presence and size of shading, and distances from and heights of opposite buildings [21]. Parametric models also allow automating a selection of predetermined building types, such as block, linear, grid, single and multi-courtyard, and L-shaped buildings; then, the models carry out geometrical variations, e.g., of height and depth, introducing additional dimensions of the design space for more climatic and performance-driven solutions for investigations [22]. Automation also allows the investigation of contemporary building and urban-scale performances such as energy use and outdoor thermal comfort via the automatic generation of all possible combinations of building envelope parameters, such as WWR and orientation, and urban layout parameters, such as buildings type, size, height, rotation, and distance [23].

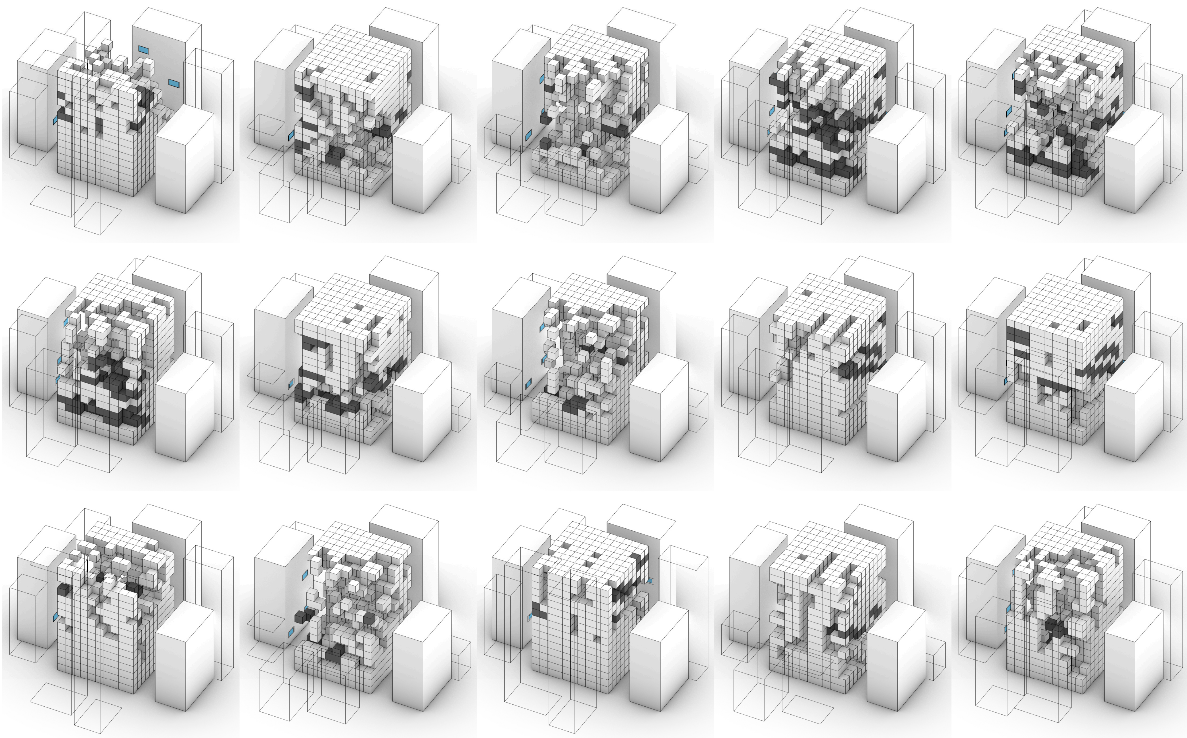

Figure 2. Conceptual building form variations that obtained automated building space analyses with respect to energy reduction and the sunlight exposure of surrounding premises (source: [24]).

2.1.2. Design–Analyse–Evaluate–Adapt

The design–analyse–evaluate–adapt computational method capitalizes on the interoperability of parametric modeling workflows and simulation software [25]. The workflow firstly generates a design solution via a set of parameters related to building and urban form and properties (design). Then, the workflow analyses performances using climatic analysis and simulations (analyse). Consequently, the design solution generated at each iteration is tested against the thresholds of metrics or the formal and functional goals set by the designer (evaluate). Finally, if the design iteration does not fulfil the requirements, it is modified via the automatic selection of the next design parameter combination (adapt), and the process repeats until a compliant solution is found (Figure 3). The design–analyse–evaluate–adapt workflow is a method that integrates form generation, performance simulations and assessments. Here, we refer to it as the iterative method.

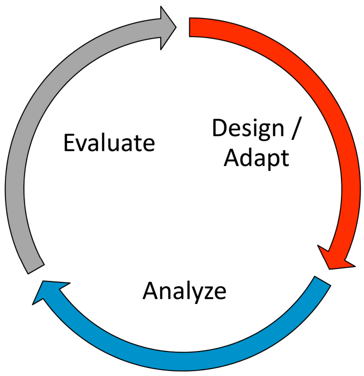

Figure 3. Diagram of the iterative computational method design–analyse–evaluate–adapt.

The method is applied to a large variety of climatic form finding processes to generate the configurations of buildings and urban environments in order to improve energy performance and human indoor or outdoor comfort. It was used to iterate the location of trees in predetermined points of outdoor areas using thermal comfort maps until the minimum quantity and configuration providing comfort were reached [26], and it was also used to iterate the generation of building forms in urban environments via an additive process of staking floors after adapting the layout of each to the desired levels of received solar radiation until a determined final configuration was reached [27].

The advantage of the iterative adaptation method that compares automation is the limited number of tested solutions and simulations performed before finding a compliant design solution instead of analyzing an entire pool of combinations. The disadvantage is that the compliant solution is not necessarily the one with the highest performance for a specific metric or indicator, which instead could be found via the automation of the generation of all possible combinations.

2.1.3. Optimization

Optimization processes are used to search for optimal solutions when multiple parameters called variables define the properties of the design problem at hand. Several optimization methods and algorithms exist in the computational design environment. Evolutionary algorithms (EA) combine several variables (genes) and analyse the resulting fitness landscape populated by genomes (gene combinations), which constitute a generation, in order to select the fittest ones, i.e., those with properties that are closer to those required in the design solution. The process is repeated generation after generation, and it always improves the fitness of the genomes approaching the optimal solution or that are indefinitely trending towards it depending on the problem [28]. Blackbox optimization, as the model-based method, is used to investigate design problems that involve climatic, environmental and energy simulations [29]. Optimization is a method that efficiently integrates form generation, performance simulations and assessments.

Single objective optimization is used when the task is to find an optimal design solution for one performance. It is also used to create fitness functions comprising multiple objectives when the task is to find a single solution optimised for different design problems. Pareto optimization, on the contrary, is a multi-objective optimization (MOO) method that finds trade-off solutions optimised for distinct objectives. In research works investigating climatic form findings, buildings and urban environments were optimised in relation to all climatic factors influencing human health and energy: providing wind comfort to pedestrian areas and solar access to building envelopes using parallel single-objective optimization processes [30]; guaranteeing daylight for visual comfort and reducing direct solar radiation to decrease cooling energy use via fitness functions [31]; and exploring the trade-offs of different objectives via MOO, such as urban density and solar access [32] or daylight availability and energy use [33].

2.1.4. Design Exploration

Design exploration is an approach to climatic form finding that helps assess the environmental performance of design solutions, from the building to the neighbourhood scale, via the multidimensional analysis of relations between several design parameters and the results of climatic performance simulations of different domains, such as the building's interior, envelope and outdoor areas [34]. The climatic form finding of buildings and urban areas is a complex process that often involves conflicting criteria and competing objectives. Design exploration allows finding optimal solutions that balance multiple building and urban performances in order to reduce energy use and carbon emissions; solutions that improve energy generation, occupant and outdoor thermal comfort; and design solutions that fulfil several metrics and standard criteria [21].

Differently than optimization processes that either provide one optimal design solution or a limited number of trade-offs for one or multiple objectives, respectively, the designer investigates design parameters and their combinations via design exploration, which allows the improvement of one or more performances and to analyse their relationship (Figure 4). Thus, design exploration is an evaluation method that takes advantage of automated form generation and simulation processes, and these are used in research and the construction sector via programs, analysis charts and web applications [35,36].

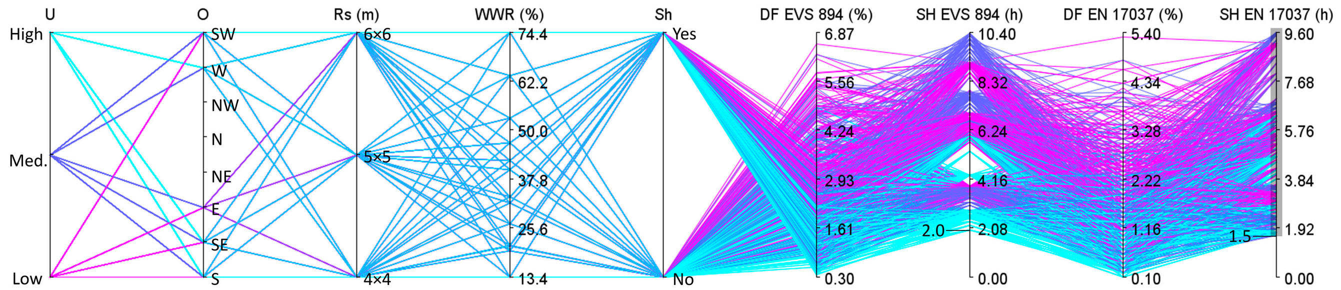

Figure 4. Design exploration of building orientations and envelope characteristics in different urban environments to analyse the fulfillment of different daylight standards (source: [21]).

Design exploration applies to exploring all possible building and urban performances. It is used to investigate urban solutions by selecting building typology, form variation, orientation, function and envelope characteristics; and urban densities to maximize generated energy (load match) and daylight [37]. Other studies tested variations in building massing forms, envelope and glazing thermal properties and structure in different climates to reduce energy use and embodied and operational carbon emissions [38]. Additionally, research work used the method to develop simplified metrics that explore the correlation between simulation results and design parameters [39].

2.2. Form Generation Procedures

In climatic form finding processes, the computational methods presented in the previous section are used together with different form generation procedures. The form procedures take advantage of the potential offered by three-dimensional and parametric modelling [18,19] that is largely used by architects and planners in creating, assembling and modifying the geometrical representation of buildings and urban environments, in and around which environmental and climatic simulations are performed using the same parametric workflows used for buildings and urban areas generation. The form generation procedures are related to a single building or group of buildings at different scales from a block to the district, and they are used to investigate the climatic performances of building shapes, orientation and envelope, layout articulation and massing; and patterns constituted by several buildings or in some cases of existing buildings. Three main form procedures are presented: boundary volumes; discretized forms; and urban patterns.

2.2.1. Boundary Volume

The procedure called boundary volume is used to determine either the maximum volume and shape that a building, the articulated parts of a building massing or a cluster of buildings cannot exceed in order to fulfil the climatic requirements of neighbouring buildings and open areas such as parks and street sidewalks. The boundary volume is a significant form procedure for regenerating urban environments via the preservation and improvement of the conditions of existing and new buildings.

This form generation procedure was introduced with the solar envelope, and it was used for determining the maximum volume and form of new buildings to allow adequate or required direct solar access for existing neighbouring building facades [40]. The procedure uses the solar altitude and azimuth angles to define sun vectors (sun rays) at the required hours during which sunlight must be guaranteed. The volume is generated from the ground up until the upper surface constitutes the highest boundary that allows all sun vectors that hit the premise's windows to be taken into account during the required period. Automation and iterative methods are used to generate solar envelopes.

A large body of research expanded on the solar envelope method in consideration of the solar access of neighbouring and new building facades [22,41,42], the form of which was limited by the solar envelope (Figure 5). Other investigations considered building form generation for the solar rights of surrounding facades and for solar energy collection during the cold season for the passive heating of the new building [6]. Further developments allow the generation of solar envelopes by taking into account not only sunlight hours with respect to neighbouring buildings but also the intensity of solar radiation that benefits human health or the sun's altitude, which allows maximizing the building size or tradeoffs of the criteria [43]. Other methods allow the designer to generate the boundary volumes in consideration of the urban environment using 3D geospatial databases [44].

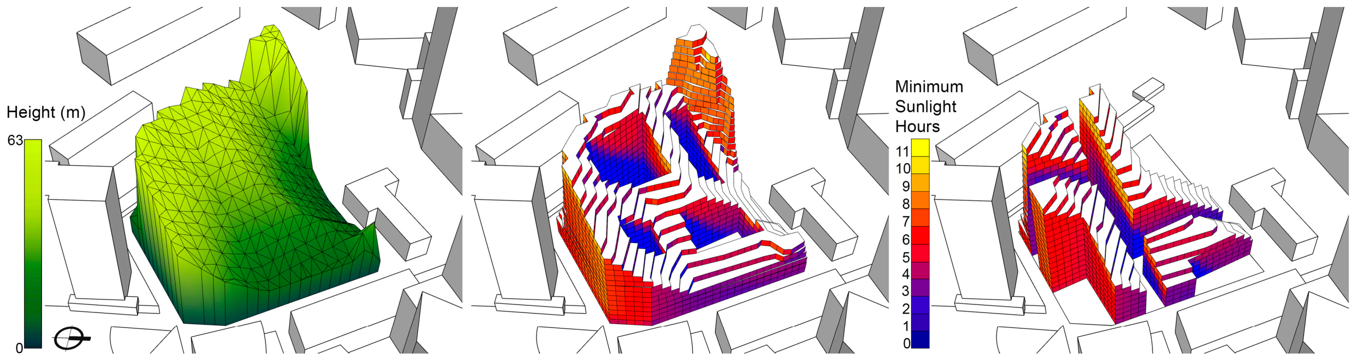

Figure 5. (**a**) Boundary volume of the solar envelope; (**b**,**c**) analysis of sunlight exposure of two building forms generated using the maximum height allowed by different layouts (source: [22]).

Climatic form finding processes have been developed using the boundary volume procedure to first determine the massing limits of buildings that can provide a neutral or positive effect on existing urban environments; then, these processes explore and select optimal building forms and articulations to maximize the buildable floor area and control direct solar radiation on new building facades in order to minimize the risk of overheating, thus reducing cooling energy use during the warm season [45,46].

2.2.2. Discretized Form

Climatic form finding is increasing in momentum in recent years via research developments that have a strong foothold in the early studies on climate and form generation using discretized building elements [47]. Recent research capitalizing on the potential of computational form generation focuses on determining conceptual building massing and shapes via the subtraction or addition operations of three-dimensional cells from or to the arrays of cells, respectively. In subtractive processes, the maximum allowed building mass is subdivided into three-dimensional cells, and the influence of each cell on the environmental and energy performance of surrounding buildings and on the liveability of open areas is assessed by evaluating the potential obstruction or admittance of direct solar radiation within different periods of the year and seasons.

Using automated and iterative computational methods, each cell's influence on planning requirements, metrics and standards, or specific building performances of the surrounding built environment is calculated. Thus, voxels, i.e., cells storing one or more performance indicator values, that do not meet the requirements are eliminated. The remainder constitutes the potential building form that has a neutral or positive effect on the surrounding premises and outdoor areas in relation to climatic factors (Figure 6). The procedure is highly flexible. It allows obtaining several building massing variations via combinations of fit voxels and analyzing the performance of trade-off solutions [48]. Additionally, the subtractive generation procedure of discretized forms allows for initial performance analyses of alternative generated conceptual building massings [49] (Figure 6).

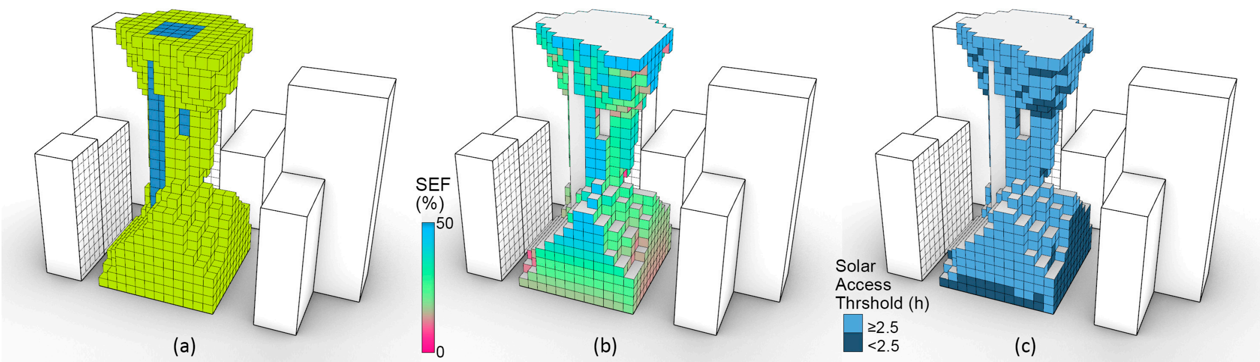

Figure 6. (**a**) The discretized form generated by subtracting voxels that do not allow the required solar access on neighboring facades; (**b**) analysis of the sky exposure factor; (**c**) analysis of solar access requirements on the conceptual building form (source: [49]).

Subtractive form finding procedures were also developed by eliminating clusters of cells, and these are determined via designer input based on the orientation and location in the building's layout, thus taking into account the internal spatial organization [50], and on the basis of performance analyses on daylight availability in the modules of each building floor [51]. Following an inverse process, the additive procedure was used to add voxels to the spatial grids of potential locations if they are inside a maximum building volume [52] and volumes as living modules to predefined schematic building massings [53]. Further, current research is investigating the potential of discretized form generation procedures to generate conceptual building massings that improve climatic and energy performances and human health for the entire built environment, existing and new buildings and indoor and outdoor spaces, thus providing efficient methods for regenerative designs.

2.2.3. Urban Patterns

Climatic form finding processes are used to investigate design solutions at different scales. Besides the generation of single or articulated building forms, a large body of research investigates the different microclimatic conditions, comfort and energy performance of several buildings that are influenced by varying urban patterns at the block and neighborhood scale. Due to the large amount of design parameters and climatic performances involved, urban patterns are generated using automated methods, and variations are investigated by comparing results and carrying out design exploration to select design solutions with optimal climatic, energy and comfort performances for entire districts.

The main variations investigated are pattern layouts and building distances and orientation. The majority of research studies also take into account urban density and building height and different typologies, e.g., block, slab and courtyard on regular grids [23,54–57]. Several studies considered articulated buildings inside regular urban blocks [34,58,59] and neighborhoods with irregular building patterns [56,60], whereas the majority of research studies locate building patterns in hypothetical urban environments; some studies used existing urban areas to obtain specific results [13,58,60].

The performances investigated at the urban scale concern the building envelope, the indoor environment, the outdoor microclimate or their combination. Urban patterns are analysed for their potential with respect to collecting solar radiation on building facades [6,53] and their influence on heating and cooling energy use [54]. Several studies contemporarily investigated the influence of urban patterns on different building performances. A majority of studies analysed patterns that improve daylight availability and reduce energy use, which are the two performances that are potentially in conflict or synergistic depending on whether the buildings are dominated by cooling or heating, respectively, and improved energy generation via building integrated photovoltaic (BIPV) systems [37,39,58].

Using a holistic approach, current research integrates indoor and outdoor building performance evaluations. Several studies investigated energy use reduction and daylight availability, together with outdoor thermal comforts allowed by different urban patterns in different climates and seasons [13,23,34,61,62]. The analysis of wind velocity and direction as modified by buildings and structures is a critical factor for the form finding of urban patterns. Wind can be accelerated by effects such as downwash and channeling due to tall buildings and urban canyons, respectively, or decelerated by irregular urban patterns of different size buildings and large structures [63]. Increased wind velocities can have a positive or negative effect on people's outdoor thermal comfort during warm and cold seasons, respectively, whereas decreased wind velocities have the opposite effect. Increased wind speed can create physical discomfort, and in some cases, extremely accelerated urban winds can cause casualties [64]. Thus, different studies integrated building envelope solar access and urban wind patterns analyses (Figure 7) to investigate optimal urban patterns for building occupants and outdoor livability [30,60].

A particular type of research method on urban patterns is one that analyses existing urban environments [65,66]. Although it does not involve form generation, urban patterns and density, building types are investigated in relation to solar access, which has a direct influence on indoor environmental quality and energy use, to obtain indications for future developments, deep renovations and developments of new urban form indicators.

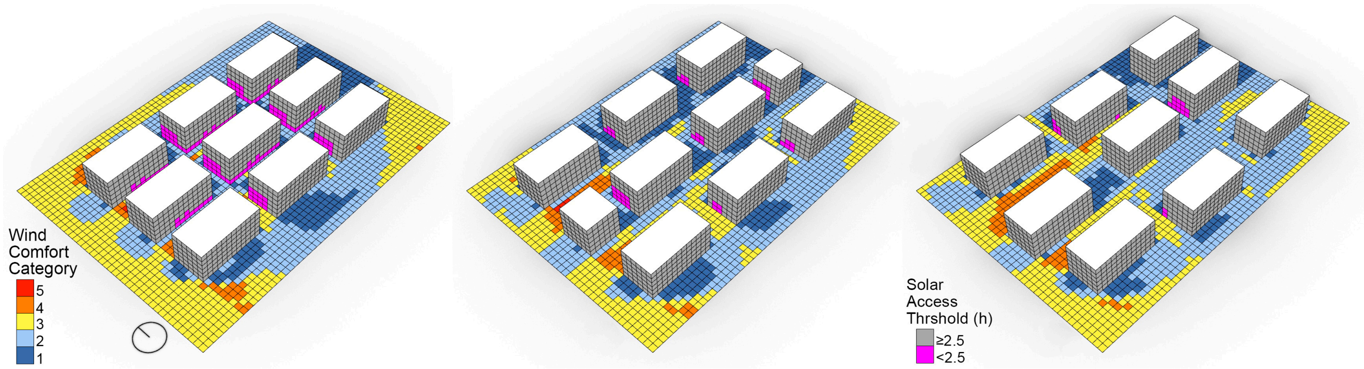

Figure 7. Integrated analysis of wind comfort in outdoor areas and solar access requirements on building façades allowed by different urban patterns (source: [60]).

2.3. Simulation and Evaluation Workflows

Climatic form finding processes in research and design are conducted by taking advantage of the potential of parametric designs to integrate computational methods and form generation procedures with software tools for environmental, energy and microclimatic simulations; for analyses using evaluation criteria; and for optimization and design exploration using simulation workflows of different complexities relative to the task at hand. The following sub-sections introduce state-of-the-art software for environmental, energy and microclimatic simulations, and the software is used together with tools for automation, optimization and design exploration, metrics and standards and simulation workflows in consideration of different analysed performances, domains and scales.

2.3.1. Software Tools

Simulations and environmental analyses are performed in parametric design workflows mostly in two ways: (1) using validated simulation software external to the parametric model and connected via specific components; and (2) using calculations performed by programmed components (via equations) for simpler tasks. The most used validated software in climatic form finding is as follows: Radiance for daylight simulations [67], the Radiance-based Daysim for dynamic climate-based annual daylight simulations [68] and EnergyPlus for thermal modeling and energy simulations [69]. Computational fluid dynamics (CFD) simulations are performed in urban wind pattern studies using the validated software OpenFOAM [70]. The simulation software is integrated into parametric workflows using climatic and energy design GH plugins such as Ladybug Tools [71,72], ClimateStudio [73] and Eddy [74], the latter of which is used specifically for CFD simulations and wind comfort analyses. Environmental design plugins can also perform calculations without needing simulation software for simpler tasks, such as determining sun paths and calculating sunlight hours and sky view factors (SVF) and direct and diffuse solar radiation received by urban surfaces.

The vast majority of simulations and calculations require the use of statistical weather data in the form of the typical meteorological year (TMY), which presents the most representative values for data on solar radiation (direct, diffuse and global), air temperature (dry bulb), wind speed and direction and relative humidity for every 8760 h of the year [75]. Due to the large quantity of native GH parametric design tools, the computational methods and form generation procedures generate building massing and urban patterns; then, environmental design plugins perform simulations and calculations, the outputs of which are finally used as the input for GH tools such as Galapagos for single-objective optimization [18], as inputs for Opossum plugins for single- and multi-objective optimization problems [76] and as inputs for Colibri for automation and iteration methods [20] to generate the necessary data for parametric studies and design exploration using tools, such as parallel coordinate charts, and web-based applications, such as Design Explorer and Thread [35,36].

2.3.2. Evaluation Criteria

In climatic form finding processes, the potential of building forms and urban patterns to reduce energy use and carbon emissions provides energy generation and indoor comfort, and the liveability of public spaces is assessed using key performance indicators, metrics and standards. The evaluations are either integrated into the parametric workflow via iteration methods and optimization using the performance requirements as objectives, or they are conducted using comparisons and design exploration after pools of solutions are generated via automation.

The potential of building interiors to receive adequate natural light is assessed via several metrics. The pioneering Daylight Factor [77], which predicts daylight levels as a percentage of exterior illuminance from a uniform overcast sky, is still widely used in daylight standards [78]. More advanced daylight autonomy metrics use climate-based daylight simulations to evaluate the ratio of occupied hours during which the space is properly lit [79]. The most advanced of these, Spatial Daylight Autonomy (sDA), also defines a ratio of occupied space [80]. Solar access (SA) is evaluated in terms of the hours of direct sunlight on windows assuming a hypothetical clear sky all year round and using country-based thresholds [81]. Solar radiation on building facades can be prescribed by local standards and is maximized or minimized according to the energy task at hand. The energy use objective is its minimization, and the indicators are set by local building energy regulations. The energy generation objectives are its maximization and the temporal balance with the energy used via indicators such as the load match index [82].

Outdoor thermal comfort is assessed via metrics such as Physiological Equivalent Temperature (PET) [83] and the Universal Thermal Climate Index (UTCI) [84], which predict the perceived temperature of humans on the basis of air temperature, relative humidity, mean radiant temperature, wind velocity and physiological and clothing models, defining a thermal comfort zone with minimum and maximum perceived temperatures and different levels of cold and heat stress. Wind comfort is assessed by taking into account wind speed and the frequency of occurrences. The Lawson wind comfort criteria assess the quality of space using wind comfort levels for specific activities [85].

2.3.3. Simulation Workflows

The computational methods, form generation procedures, software tools and evaluation criteria are integrated into simulation workflows that are realized in the parametric design environment. Due to the complex relations of the built environment with respect to climate and its changing conditions and the daily and seasonal variability of meteorological and occupant use, state-of-the-art climatic form finding processes are based on holistic approaches that integrate different domains, connect scales and use building and urban co-simulations processes. This subsection presents the most innovative integrated workflows applied in climatic form finding. In multi-domain workflows, indoor spaces, building envelopes and outdoor environments are investigated simultaneously to explore solutions that fulfil the building and urban evaluation criteria in order to balance energy and carbon reduction and improve healthiness and safety or to find overall optimal solutions.

To investigate optimal building patterns or trade-offs in consideration of urban density, buildings distance, massing and orientation, studies used multi-domain and co-simulation approaches to improve outdoor thermal comfort by analyzing wind patterns and direct solar radiation at the ground level and guarantee adequate indoor daylight provision [61]. Other research works were finalized to minimize energy use in consideration of the heating- or cooling-dominated building type and the local climate and period of the year [13,23,57]. Co-simulation was used at the building scale to investigate optimal urban pattern layouts for energy use and generation using BIPV systems [37,58].

More comprehensive approaches investigated building types, envelopes and patterns for outdoor thermal comfort; building energy used and generated load match; and daylight availability [34,62]. Several works integrated the analysis of sunlight and solar energy on the building envelope with the wind comfort performance of spaces between and around buildings [30,60,86]. Other research focused on optimizing building cluster layouts or the building massing's co-simulating solar radiation and sky view factor or direct solar access, reducing the former's cooling energy load and maximizing the latter to improve the quality or healthiness of interiors [31,59].

Recent research works investigated building massing and form generation in urban environments in consideration of the sunlight received by context buildings and the different performances of the generated building form related to daylight, solar access and views [45,46,49]. State-of-the-art research investigated co-simulation methods to define building forms that are capable of balancing used and generated energy [55], provide solar exposure or shading when needed and sky exposure [52], and reduce the energy use of surrounding premises [48]. Other studies focused on multi-evaluation approaches that integrate environmental simulations and building massing calculations to find the optimal trade-offs of sunlight or solar radiation received by the building envelope or the daylight and buildable floor area and volume in consideration of different urban environments [22,50,53].

3. Challenges and Gaps

The main challenges of climatic form finding are related to tool usability and simulation integration. The use of environmental and climatic design tools and simulation software is a complex process that requires either the expertise of researchers and consultants or a steep learning curve for designers whose work is conducted using conventional CAD and BIM software. Furthermore, expert knowledge is needed to validate the accuracy and reliability of results and to assess the performance against metrics and key performance indicators.

In this regard, researchers are analysing the use of simplified metrics such as solar irradiation exposure and shading, and analyses are performed using limited computational resources to substitute more complex and time-consuming energy use and generation, obtaining promising results and relating to building form factors and urban density indicators that can obtain simple yet reliable assessments [39,87]. Other studies proved the strong correlation between direct solar radiation and outdoor thermal comfort in urban environments, although these are limited to hot climate locations [88]. The use of simplified metrics and form factors can significantly help designers in performing climatic form finding, improving the performance of the design at hand.

The second main challenge concerns the integration of simulations and the utilization of different results in the processes of climatic form finding when the design solutions must fulfil several criteria. In this regard, several researchers are involved in developing, testing and validating integrated climatic computational workflows [26,34,37,49,61,62,89] with a twofold objective. On the one hand, one objective is to improve the efficiency and usability of workflows integrating form parameters, different simulation inputs and outputs and the computational methods of automation, iteration, optimization and design exploration. On the other hand, the objective is to investigate the environmental performances of building forms and urban pattern solutions. Co-simulation workflows are also developed by integrating automation, optimization and design exploration computational methods to further enhance the potential of form generation procedures [21,50,52,55].

A significant challenge for co-simulation approaches is integrating wind simulations via CFD with other simulations in multi-domain workflows investigating indoor performance and outdoor microclimate, wind and thermal comfort. Whereas energy and daylight, indoor comfort and solar radiation simulations use the same building and urban three-dimensional geometry realized by simple polysurface objects, CFD analyses use different simulations domains, i.e., very dense mesh objects, composed of millions of nodes, which require separate generation (meshing) of the virtual wind tunnel. Additionally, CFD simulations are very computationally intensive, requiring severalfold simulation times when comparing energy and daylight. Nonetheless, advancements have been made to integrate these different simulations in parallel workflows, which proved to be efficient methods [13,26,34,60,61].

Moreover, as building performance simulations are based on mathematical models, which are an approximation of complex physics and real-world phenomena, the challenge of obtaining accurate results is present at all stages of building design and is particularly affecting the schematic design phase and climatic form finding processes, the simplified models and tool interfaces, and the underlying assumptions used. In this regard, researchers are involved in validating simulation methods that are used in climatic form finding, and they use several approaches as follows: comparative analysis of numerical and experimental studies of the airflow around cluster buildings [90]; error analysis of rapid energy simulations using representative zones against full building energy simulations at the district scale [91]; and fast simulation algorithms for surface temperatures and mean radiant temperatures against measured data for outdoor thermal comfort analyses [92].

4. Opportunities and Future Directions

The last section of the paper explores present opportunities and future directions in computational and simulation workflows and methods for climatic form finding to further improve the performance of design solutions, expand the fields of application and provide possible answers to challenges and gaps.

A relevant future direction for climatic form finding is its application to the design of positive energy districts (PEDs) [93], which are strategic sectors for the fulfilment of goals related to reducing climate change using a carbon-neutral built environment [4]. The current main focuses of designing PEDs are managing and optimizing the balance between energy generated from on-site renewable sources and energy purchased from the grid and the energy efficiency of buildings. Passive design strategies that reduce building energy use are rarely used and limited to the building scale. Prior to improving districts' energy efficiency, climatic form finding integrated into the design of PEDs can significantly minimize the energy use of buildings by applying solar heat gains and passive heat conservation and avoidance measures that are typical at the building scale to neighbourhood and district scales [94]. Studies have already developed methods for designing optimal urban forms with the potential of balancing building energy use and generation [37] and building massings that are capable of reducing the energy use of surrounding existing premises [24,48], all showing promising results. Additionally, the livability and accessibility of outdoor areas, which so far is a secondary aspect in PED planning, can be considered of the same importance as energy via the multi-domain and co-simulation approaches of climatic form finding, as demonstrated in recently developed research studies [13,23,34,62].

The majority of climatic form finding research is based on the statistical weather data of a specific location, which allows the designer to predict the effects of a building form or cluster and neighborhood layout on the surrounding areas and inside the buildings in consideration of current specific conditions. The actually used weather data present two shortcomings. The first is that measurements are generally carried out in areas outside of cities, e.g., at airports, where microclimatic conditions are different compared to urban areas. The second shortcoming is that due to climate change, increases in air and surface temperatures are recorded every year globally. As a consequence, the solutions obtained via climatic form finding cannot be not completely reliable for areas inside cities, and in the best-case scenario, they represent valid solutions for a short span of years. A significant opportunity for climatic form finding is the continuous development of algorithms, methods and tools that are carried out to adapt to statistical weather data recorded outside of cities relative to different types of urban environments, accounting for phenomena such as the urban heat island effect [95,96]; this is also carried out to generate future weather data that are obtained via climate change predictions for years as far as 2050 and 2080 [97,98]. These climate-related tools represent opportunities for researchers and designers that can increase the impact of their form finding methods and developed solutions and assist in the improvement of the sustainability of cities and communities in present and future conditions.

A future direction that is worth noting in climatic form finding approaches integrates computational method optimization and design exploration, and it is used chiefly for the analysis of urban patterns. When analysing the urban scenarios of different building typologies and geometric factors; patterns and urban densities; and several performance results, indicators and metrics, it is often impractical to perform parametric studies of tens of thousands of solution combinations due to limited computational resources, and realizing efficient fitness functions for optimization processes is difficult and cannot provide reliable results. Thus, to allow for a more agile workflow, recent research work developed methods that first select relevant performance design parameters using sensitivity analyses; then, they are used in multi-objective optimization. Finally, only a limited number of non-dominated Pareto front solutions are used for the full-scale parametric study involving all design variables and simulations [55]. Further implementing the method will provide designers with simplified climatic form finding processes in consideration of multidimensional design spaces.

Finally, significant opportunities for climatic form finding are represented by the continuous development of design tools, programs and technologies. Regarding the design of positive energy districts, climatic form finding can take advantage of urban building energy modeling (UBEM) [99], which is implemented in tools such as Dragonfly of Ladybug Tools [100], and urban modeling interface (UMI) [101]. UBEM tools allow the automatic realization of energy models of entire districts via the use of building archetypes and urban datasets and simulations, including life cycle assessments using the prediction of embodied energy and carbon and the simulation of electrical networks.

The inclusion of nature-based solutions in climatic form finding is now facilitated by recently developed GH tools such as Morpho [102] and Dragonfly-Envimet [103], which integrate the capability of state-of-the-art software for the simulation of urban microclimate, including natural elements such as trees and green surfaces using ENVI-met [104] and GreenScenario [105], a GH tool for evaluating the effects of green infrastructure and water management when improving climate adaptation and reducing the carbon emission of urban design solutions. A promising direction in tool development is the application of machine learning (ML) technologies for fast and real-time microclimatic and environmental predictions without using computationally intensive and time-consuming conventional simulations [106–108]. Instantaneous predictions can be used efficiently in automation and optimization workflows and when a large number of design solutions are under investigation in climatic form finding processes.

5. Conclusions

The paper presents current research and future directions with respect to sustainable designs from the perspective of relations between architectural and urban form and climate and the computational methods used to investigate it. Climatic form finding addresses the need of architects and planners to use methods that can generate building and urban forms that can realize a built environment that adapts to climate, reduces resource depletion and impact on climate change and improves human health.

In the main section of the paper, different computational methods used to generate forms and optimise or explore design solutions in consideration of climatic, environmental, energy and human comfort factors are presented and discussed. Here, the key contribution of the paper is the identification of the main methods that generate and analyse forms that are allowed by the integration of parametric design and environmental analysis tools; on the one hand, the methods' different potential and types of applications are presented, and on the other hand, their integration is discussed by referring to the relevant literature.

Consequently, the main form generation procedures are introduced. The aim is to provide the reader with a concise categorization of state-of-the-art geometrical and typological operations in order to generate forms in climatic form finding. The procedures allow the realization of specific shapes and layouts and investigate configurations with improved climatic performances in the consideration of design tasks and climatic and environmental conditions at the building and urban scale.

Finally, the simulation and evaluation workflows allowing climatic form finding are presented and discussed. The paper's innovative aspect is the presentation of main software tools and evaluation criteria determining the form's configurations and their integration with computational methods and form generation processes in simulation workflows to maximize climatic performances as solar access, energy use and generation, daylight and indoor and outdoor thermal comfort from the building to the neighbourhood and district scale. Additionally, the novelty of the paper is to move beyond state-of-the-art aspects of climatic form finding, presenting, in two concluding sections, the actual challenges and gaps and initial solutions and opportunities and future directions that will expand the climatic form finding potential to help improve the quality of the built environment.

Two limitations of the study must be noted. The first is that differently from a literature review that analyses research developments starting from the methodology for source selection, the present work presents a perspective based on the knowledge and direct expertise of the author; thus, the relevant literature is presented as support for the different statements and formulations proposed in the study. The second is that as the paper is strictly related to buildings and urban forms, building envelope aspects, which are related to forms in climatic form finding, are not considered as a relevant part of the work but are only briefly mentioned when analysed together with form aspects by the supporting literature.

The author is confident that due to its breadth, the study will help young researchers and designers realize initial climatic form finding workflows in order to develop methods and solutions to improve building performances in the consideration of form and climate and will provide more experienced professionals in academic and industry sectors with knowledge and insights that contribute to the global effort aimed at improving the sustainability, carbon neutrality and resilience of the built environment.

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