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ORIGINAL ARTICLE

A parametric approach to plot-based urban design: A climate-responsive algorithmic control for the generation of urban block

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Abstract
In modern urbanism, (re)production of urban land predominantly relies on large parcels through intensive capital investments. Such a mainstream significantly shapes the overall urban form, subsequently influencing the quality of life through the perceived characteristics of the form and program of the planned districts. Consequently, critical urban design theory increasingly prioritizes the plot as the fundamental unit of future urban development. While 'plot-based urbanism' presents a responsive approach to this issue, there remains a notable gap in systematic methodologies that can be universally applied across different contexts. In this paper, the authors propose an algorithmic framework that would be employed as a design control tool based on the associative logic of plot-based urban formation. The model framework comprises three steps: (1) plot layout generation, (2) building configuration, and (3) incremental formation of the block fabric. The applied model demonstrates the compositional variation and coherence within the urban block while concurrently optimizing the climatic performance of the emerging fabric.

Keywords Plot-based development · Algorithmic design · Parametric modeling · Design control · Climate optimization

Introduction

Following the critical view on the last century's modern planning experience, contemporary urbanism has constructed its normative narrative on some specific morphological premises such as *coherence* (Alexander et al. 1987; Salingaros, 2000), *integrity* (Hillier, 1996; Hillier and Hanson, 1989), *density* (Martin and March, 1972), *enclosure* (Trancik, 1991; Peterson and Littenberg, 2020), *(con)textural diversity* (Rowe and Koetter, 1978; Duany, 2002) and *fine-grain* (Bentley et al. 1985: 42–46; Llewelyn–Davies 2000: 43, 65). Among these qualities, fine-grain can be considered the key indicator, emphasizing the plot as the fundamental unit of urban development and design. Since the plot is the smallest unit of the formation of the city fabric, one could assume that the granular quality of urban form may only be ensured by maintaining the development and transformation of the city at the plot level. In other words, when development occurs in pieces on a series of building parcels, the resulting fabric has the potential to exhibit finer granularity compared to an urban pattern developed on large portions of land. Such a morphological condition is championed by the emerging school of 'plot-based urbanism' (Porta et al. 2011, 2018; Porta and Romice 2010; Tarbatt 2012). In this sense, the current (re)production of large tracts of urban land (Labbé and Boudreau 2011; Monson 2008) through significant capital investments within many developing cities contradicts such an urbanistic approach.

Bentley et al. (1985) introduce the concept of a 'grain of variety' (p. 27), which refers to the presence of small, diverse elements within the urban fabric. This quality is inherently linked to urban land composed of smaller properties. By defining variety in terms of uses and activities (ibid), one could argue that functional diversity within the urban fabric is directly shaped by the morphological attribute of 'fine grain'. Such spatial quality is achieved by integrating

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plots in shaping the street, which serves as the principal domain for mixed-use environments. More specifically, research in urban geography highlights that small plot sizes are a fundamental prerequisite for the emergence of small-scale retail (Guy 2006; Cheshire et al. 2015).

The inherent nature of plot-based development patterns can be observed in the timeless qualities of traditional urban fabrics, which have been generated incrementally over long periods through diverse plot layouts. This morphological fact highlights the importance of creating generative frameworks rather than relying on holistic master plans that shape the built environment through large compounds or ensembles (Hakim 2008; Mehaffy 2008). Consequently, an alternative model approach advocates a bottom-up perspective on planning that is responsive to the incremental dynamics of urban formation (Campbell 2018). In practice, this corresponds to an algorithmic control system capable of generating a coherent urban fabric through the piecemeal development of urban land (Çalışkan and Barut 2022). Such a control system could be assumed to respond to the ever-lasting need for a flexible planning approach in the face of increased complexity through the various actors (i.e., local government, land owners, developers, designers, and users) in the (re)production of the space and form (Friedman 1997). Therefore, extending the scope of development control systems to the smaller-scale elements of the urban fabric, such as plots and blocks, rather than solely relying on large structural components like public infrastructure and land, offers a viable alternative for today's incremental (generative) urbanism.

Despite the growing body of literature on plot-based urbanism, there has been little progress in establishing a robust and systematic foundation for a generative planning and design approach that actively integrates the plot as a key agent of urban formation. In the current context, regulating urban development through master plans based on standard land subdivisions could be altered by a mechanism that enables the control and coordination of numerous small individual initiatives within the built environment.

In this regard, the current paper introduces an algorithmic model to integrate computational design into the development control frameworks within the emerging paradigm of plot-based urbanism. To that end, the authors first identify the basic parameters of the plot, which, in turn, are utilized to define the generative codes of land subdivision and building arrangement. Following the exploration of alternative configurations, the environmental performance (i.e., outdoor thermal and climate comfort) indicators are integrated into the model. Finally, some incrementally generated block configurations are simulated as optimized solutions in the service of design review and control processes. Though the model suggests a generic framework applicable within different urban contexts through specific sets of codes and parameters, the paper presents the model's application in the context of a typical urban fabric in Türkiye. In this way, the model's capability of generating fine-grain fabrics could be tested against an actual setting.

Theoretical background

This part scrutinizes the pivotal role of the plot in urbanism. It delves into the emerging concept of plot-based urban design, discussing its foundational principles and exploring its integration with parametric design. Current limitations are also addressed to enhance the plot's effectiveness in contemporary design practice.

Plot: The fundamental unit of urban form and formation

Providing the necessary framework for urban development, the plot can be viewed as the fundamental module or cell of the fabric (Caniggia and Maffei, 2001; Moudon 1986: 144). Plots aggregate to form the urban block, which is integrated into the street network of an urban fabric. One could also assume that the urban block, once consolidated with a robust plot system (i.e., with many narrow plots with frequent entrances), demonstrates its capacity for the constitution of the street (Campbell 2018: 148; Romice et al. 2020: 100; Pålsson 2023: 179). At the finest level of granularity, the block is subdivided into parcels known as plots, which may be allocated to different sub-developers and property owners (Love and Crawford 2011: 96). This collective allocation of plots renders urban form a socio-economic artefact. Described as a unit of property (Kropf 2009: 115), the plot can also be considered the unit of control in terms of the micro relationship between the public and private domains (Meyer and Smits 2008: 27).

As Campbell (2010) discussed, the plot is the most achievable delivery unit and the ultimate unit of urban development (Porta et al. 2011: 14; Ünlü and Baş, 2017: 106). The plot, as a legal unit, defines property rights in different urban contexts. Plots are the main urban development and transformation element in many local contexts where developers' production capacity is limited (Ünlü, 2011). Moudon (1986) considers this point a factor of resilience since the existence of many small plots within a fabric ensures variety in the resulting environment and slows down transformation through the involvement of multiple property owners (188).

Kropf (2014) describes the plot as the combinatoric system of the building, external area, and structures (e.g., a boundary wall) (48–49). Within the embedded hierarchy of morphological elements, the compositional features of a plot (e.g., size, shape) and its configuration with other plots in a layout might have a specific conditional effect on the arrangement, layout, massing, and typology of the building located on that parcel. Panerai et al. (2004: 166) identify this point as a dialectical relationship within the built fabric. Especially with the effect of the street's character (of centrality and connectivity), the plot's capability to modify, extend, and substitute the building is conditioned.

Conzen (1960) exposed the transformational nature of a plot within the context of traditional towns in Great Britain. The idea of the plot as the framework for the transformation of urban form was later revisited in the North American and Australian contexts, respectively, by Moudon (1986) and Siksna (1998) addressing the significance of the plot in the formation of the fabric since it conditions all the morphological factors from the building's units to the entire fabric (Kropf 2014: 48). Despite this fact, there is a small number of studies that focus on such a conditional relationship between the plot and building typology in contemporary literature on urban morphology and design (Caniggia and Maffei, 2001: 124–137; Guo and Ding 2021; Ünlü and Baş, 2017).

Nonetheless, there has been a significant increase in research interest in this issue from a quantitative perspective. Bobkova et al. (2017) analyzed various plot configurations to reveal urban diversity using area-based (i.e., openness, compactness) and location-based indicators (i.e., accessibility). In a comparative study across five European cities, Bobkova et al. (2019b) identified plots as a determinant of urban density, along with additional indicators like floor space index (FSI) and ground space index (GSI). Additionally, Bobkova et al. (2019a) conducted a big-data analysis to categorize plot system typologies in these cities based on these indicators. Usui (2021) proposed research to explore the effects of plot sizes and frontages on building and road network densities in Tokyo. Danenberg et al. (2018) found a correlation between economic productivity and plot characteristics in Stockholm, particularly related to street types. Bobkova et al. (2019a, b, c) analyzed the relationships between economic activities in retail and food services and plot systems in different cities. More recently, Efeoglu et al. (2023) explored the influence of plot morphology on the distribution, agglomeration, and diversity of retail businesses. Similarly, Tümtürk et al. (2024) examined the relationship between plot types and change in urban form, highlighting the superior resilience of finer-grained and compact plot typologies.

Cozzolino and Moroni (2021) emphasized the plot's significance as a crucial tool for flexible and diverse design implementations within self-organizing urban planning processes. Introducing the concept of 'plotting urbanism', Karaman et al. (2020) highlighted the generative role of plots in shaping cities within the context of urban informality.

Despite the increasing recognition in the literature concerning the role of plots in urban development, current spatial planning practices show minimal interest in utilizing this concept as a fundamental design and control element (Porta and Romice 2010). Campbell (2010) describes this as the 'lost art of subdivision' in urbanism, underscoring the disparity between theoretical comprehension and practical application, particularly regarding plot morphology. Considering the adaptive nature of plots during historical piecemeal urban fabric transformations (Conzen 1960: 65–73; Moudon 1986), one could argue that urban planning practices have not fully capitalized on the potential to create resilient built environments in a bottom-up manner. In this context, Moudon's (1986) early emphasis on comprehending *"the power of the lot to influence urban form evolution, as neighborhoods gradually evolve through building activities at the lot level"* (p. 144) highlights the necessity of developing an urbanistic approach that prioritizes plots in the planned production of the built environment.

Emerging perspectives on plot-based urban design: A critical review

Inspired by the early ideological (urbanistic) critique of the modernist approach to master planning that used to rely on totalistic and artificially created hierarchic structures via a static and top-down methodology (Alexander 1966; Rowe and Koetter, 1978), the contemporary urban design has long been in the search for alternative planning approaches aiming for an adaptive and resilient spatial fabric of the city (Verebes 2014; Campbell 2018; Romice et al. 2020). With a growing understanding of the plot's role in the generation of adaptable and cohesive urban fabrics as opposed to the so-called 'megablock urbanism' (Johnson et al. 2020), 'plot-based urbanism' has emerged as an alternative planning and design approach (Porta and Romice 2010; Romice et al. 2020). This approach reclaims the plot as the basic development unit for close-grain urban fabrics. Accordingly, parametric urban design (PUD) advocates for alternative land development, design, and control methods, where small plots are allocated to individuals who then construct their buildings according to predefined codes and guidelines, aiming to contribute to the collective urban fabric (Tarbatt 2012: 157). PUD opposes the modernist approach focused on super-blocks or ensembles (Porta and Romice 2010: 14–16), thereby challenging the prevailing dominance of developments through larger land parcels (Monson 2008). Implementing such an approach undoubtedly requires a regulatory system that recognizes the plot as the fundamental unit of development and control.

As PUD grants individuals the authority to build on small plots, akin to traditional urbanism, it has the potential to create an architecturally diverse and finely grained urban fabric in a modern context (Barbour et al. 2016; Kriken et al. 2010: 102; Porta et al. 2011). Spatial fabrics characterized by fine-grained plot patterns facilitate mixed-use development by accommodating diverse building forms and land uses. Such adaptability completes a dynamic economic environment, as a variety of plots allows for different types of businesses to emerge, attracts local customers, and adapts to changing market demands (Tarbatt 2017: 26). Therefore, by promoting incremental development, PUD aligns effectively with fluctuating market conditions, offering flexibility and adaptability to evolving demands. Unlike traditional master planning, which commits to rigid, long-term designs, PUD allows developers and residents to modify typologies in response to shifting market trends while preserving coherence and continuity, as highlighted by Friedman (1997).

PUD advocates for subdividing large land tracts into smaller plots, allowing various landowners and developers to participate instead of being monopolized by a single agency (Adams et al. 2013). In this regard, it fosters multi-stakeholder participation by encouraging communities to engage directly in developing their environment, allowing for local input and capacity building in decision-making. It minimizes risk by distributing development incrementally, unlike large-scale development programs through higher investment costs (Porta and Romice 2010: 34–35).

Pioneering implementations of plot-based urban developments have already shown the feasibility of the model within different contexts. Successful applications have effectively brought together various stakeholders under a unified developmental framework based on diverse plot configurations (Tümtürk 2018: 173–222). In this context, following the success of its Dutch counterpart, the plot-based redevelopment of Borneo-Sporenburg in Amsterdam in the 1990s, the Berlin Townhouse project in Berlin-Mitte, Germany, serves as a notable case study of plot-based urbanism. This project exemplifies the creation of a fine-grained, mixed-use urban fabric. Utilizing narrow-fronted plots, the development accommodated multi-occupancy buildings within a distinctly urban context (Campbell 2018: 9, 49).

In addition to new planned developments, PUD offers a framework for urban transformation. Barbour et al. (2016) provided an example of a master-planning practice for plot-based urban regeneration in Glasgow. Liu et al. (2020) discussed PUD as the primary planning strategy employed in Nanjing, China's historic old south area. With the increasing recognition of small plots as the constituent unit of placemaking, the emerging approach is beginning to influence the housing planning and design systems of various countries, including France, Switzerland, and the Netherlands (Porta et al. 2018: 4).

Nevertheless, a common observation is that while the master plans to advocate plot-based development (or regeneration) offer diverse architectural typologies, they often predefined the complete building layouts for individual plots (Fig. 1). This approach contradicts the incremental and organic nature of traditional urbanism as idealized in the theory of plot-based urbanism (Romice et al. 2020: 40–47).

In this context, plot-based master plans typically employ the plot layout in one of two ways: either as a detailed framework dictating the overall physical composition of the settlement (Fig. 1, left), or as a generic matrix that allows individual acts of building to occur without a design control system (Fig. 1, right) Alternatively, Campbell (2018) suggest

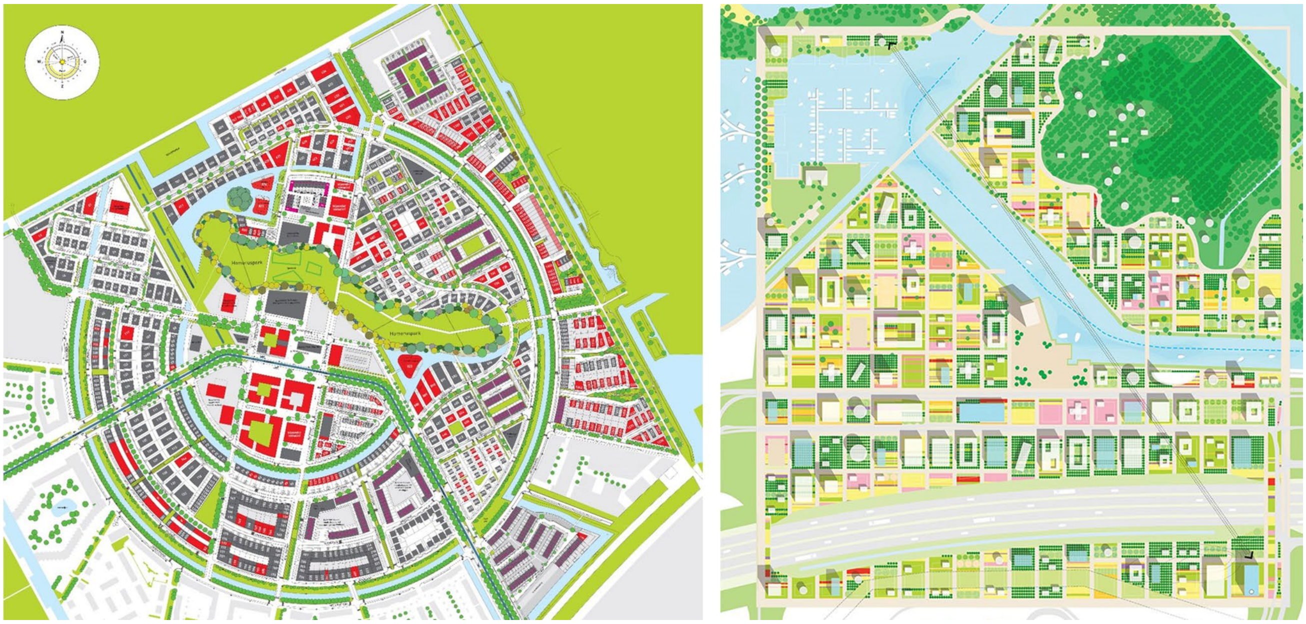


Fig. 1 The master plans of the Homeruskwartier, Almere (2014) (*left*), and Floriade, Almere (*right*) designed by MVRDV (by the courtesy of MVRVD, 2024; Municipality of Almere, 2024)

a more dynamic approach via a parcellation model based on the modular subdivision and combination of the so-called ‘universal lot’ as the basic unit of development conditioning further urban intensification in a flexible manner (pp. 162–165).

In all cases, the plot-based approach lacks a control framework to ensure a reciprocal relationship and dynamic interaction between the plot and its immediate surroundings. This critique is also echoed by Porta et al. (2018), underscores the need for rules linking plot characteristics to building resilience. However, merely defining the relationship between plot and building typology is insufficient for achieving true PUD implementation in a generative way. To unlock PUD’s full potential for creating a coherent block fabric, a design code system that regulates each building based on a relational plot configuration is essential.

Moreover, since plot-based urbanism aims for an adaptable change in the form and program of the fabric over time (Wolfe 2014), one could claim the necessity of a model approach that is operated flexibly within a temporal setting. That indicates the need for a design control model that could be incrementally run within different time intervals. More specifically, any urban land consisting of individual parcels can be developed in stages. Each development phase is shaped by the conditions set by the preceding one. Over time, as these phases unfold, the collective characteristics of the parcels evolve in response to the cumulative local (trans)formations.

Such an alternative design control necessitates an associative logic and its corresponding toolkit in planning and design. To enable such an approach in design control, the algorithmic setting of parametric modeling could potentially enhance the application of PUD in practice. At that point, one could argue that such a shift toward incrementalism in planning requires a financial system that would support the small-scale production of land through relatively smaller capital investment through a more decentralized land ownership pattern.

Parametric design as an instrument for plot-based urbanism

Operating based on algorithms, parametric design is a methodical approach to design utilizing a series of measurable variables (parameters) and geometric components allowing for the controlled generation of multiple form variations through various inputs (Sakamoto and Ferre 2008; Woodbury 2010; Tedeschi 2014). The flexibility in form generation enables designers to explore different design solutions, enlarging the domain of future possibilities. Simulating the alternative scenarios through design variations with diverse development rights and conditions, parametric models can establish an effective operational basis for design reviews that involve multiple stakeholders, including developers, planners, and local communities, across various scales (Steinø et al. 2013). Moreover, parametric modeling enables the creation of adaptive spatial models offering real-time optimization against a series of performance indicators (i.e., walkability, passive heating, solar radiation, and shading) (Peronato et al. 2015; Chen et al. 2020; Duering et al. 2020).

Along with the technical capabilities involved, parametric design became an emerging methodology employed across diverse fields, including engineering, architecture and, more recently, urban design (Steinø and Einar Veirum 2005; Mehaffy 2011; Çalışkan 2017). In the early applications of parametric urban design, it is possible to observe the control form generation through the cellular definition of network structure, infilling it through building composition in cells (blocks) in a top-down hierarchy (Çalışkan and Barut 2022). In those studies, form generation is conducted at the resolution of the building set within the cells (blocks) of the network structure. For example, the pioneering parametric study of Duarte and Beirao (2011) focused on the block-based formation of urban fabric without incorporating plots in the algorithmic setting. Similarly, Lee and Jacoby (2007), and later Holik and Brederlau (2009), proposed parametric models that generated urban fabric with buildings placed on a pure Cartesian grid, neglecting the role of plots in the associative morphology of algorithmic form generation.

In recent years, there has been a surge in incorporating plots into parametric urban design models. For instance, the DeCodingSpaces Toolbox, a Grasshopper® plugin, systematically generates urban patterns, including street networks, block layouts, plot subdivisions, and building footprints with varied setbacks based on selected plot layouts, considering minimum plot widths (URL-1). Koenig et al. (2017) developed a ‘slicing procedure’ using the minimum bounding box of the parcel. On this basis, Koenig et al. (2020) combined explorative modeling and performance optimization in the same model framework for holistic urban pattern formation (Fig. 2, above). Mei et al. (2021) proposed a ‘density-driven city generator’ that creates street networks and visualizes buildings based on specified floor area ratio and coverage. More recently, Blaistain and Fisher-Gewirtzman (2024) proposed a parametric method for generating and evaluating urban design alternatives based on the successive operations of grid formation, subdivision of the blocks, and building layout and massing through height differentiation (Fig. 2, below). In both cases, the generative potential of different plot configurations on the compositional variation of building typologies is not explored in an associative manner.

In their proposition of a ‘density-driven city generator’, Mei et al. (2021: 564) noted a common drawback of computational models incorporating plots in urban form generation and their limited capacity to utilize parcels for controlled variation within the building fabric. Typically,

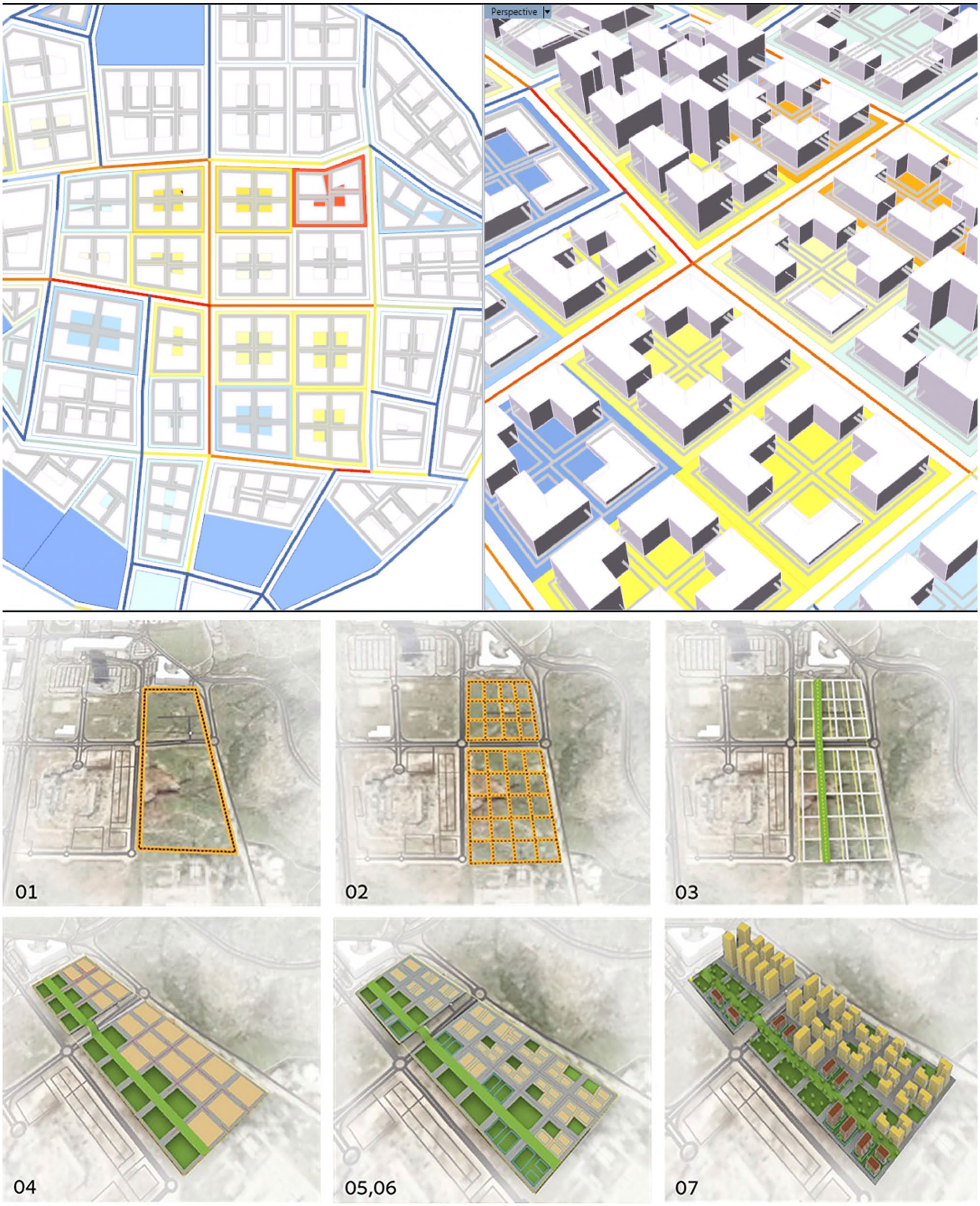


Fig. 2 'The dynamic urban development model' by DecodingSpaces Toolbox: The model controls the development of each urban block, including the generation of plot patterns and building typologies (*above*), and the interactive generative model computationally assessing the multiple design options at the level of the urban ensemble (*below*) (Sources: of Fink and Koenig 2019; Blaistain and Fisher-Gewirtzman 2024)

after generating a large-scale street network, buildings are generated within the entire surface of the urban block either through uniform typologies or without any parametric interaction with the individual plots (Fig. 2).

Alternatively, Çalışkan and Barut (2022) demonstrated a parametric development control model that generated a composite block fabric, subsequently expressed and coded through individual parcels. Similarly, Sun and Dogan (2022) proposed a form-exploration model with a simulation-based performance feedback system. This model constructs a generative ensemble comprising block subdivisions, ensuring plot size diversity while maintaining the same building typology.

The review of plot-based urban design (PUD) in both practical planning and computational design research reveals a critical gap in the methodological frameworks required to effectively operationalize plots within generative processes. This suggests that plots are not being fully leveraged to shape the collective urban fabric, whether through analogue or computational modeling techniques. To bridge this gap, a parametric model is proposed—a framework designed to generate building patterns by establishing controlled local relationships between plots through incremental processes.

Methodology

As an algorithmic design methodology, parametric modeling provides an operational framework for exploring form generation. Such a rule-based system empowers modeling to yield various configurational solutions responsive to different performance criteria (i.e., thermal comfort and energy) in particular contexts. In this context, Çalışkan (2017) argues for the use of parametric modeling as a means to effectively control urban development through algorithmic processes, rather than as a 'design machine' focused on the totalistic production of land within a single design scheme. Given the associative nature of the relationship between plot, building, and block, parametric modeling shows promise as a control tool for implementing PUD in practice.

From this perspective, the current study introduces a parametric model that sequentially integrates form generation, optimization, simulation, and articulation processes in the following framework (Fig. 3).

The model may be applied within two initial conditions: (1) using the current plot pattern or (2) generating a new plot pattern. In both cases, the resulting plot layouts and the given floor area ratios are essential inputs for the next stages. Correspondingly, the floor areas of the existing building are incorporated into the model during form optimization to guarantee that the new massing has the same development rights as the current situation. For generating a new plot pattern, the model aims to create plots with almost equal areas by minimizing variations in size. This is achieved by adjusting the standard deviation of generated plot areas to zero, ensuring uniformity in plot size while allowing for flexibility in their shape and dimensions. Even though the areas remain consistent, the plots may have different width-to-length ratios, giving the design flexibility while maintaining balance in land distribution across the urban layout. This is achieved using the standard deviation formula:

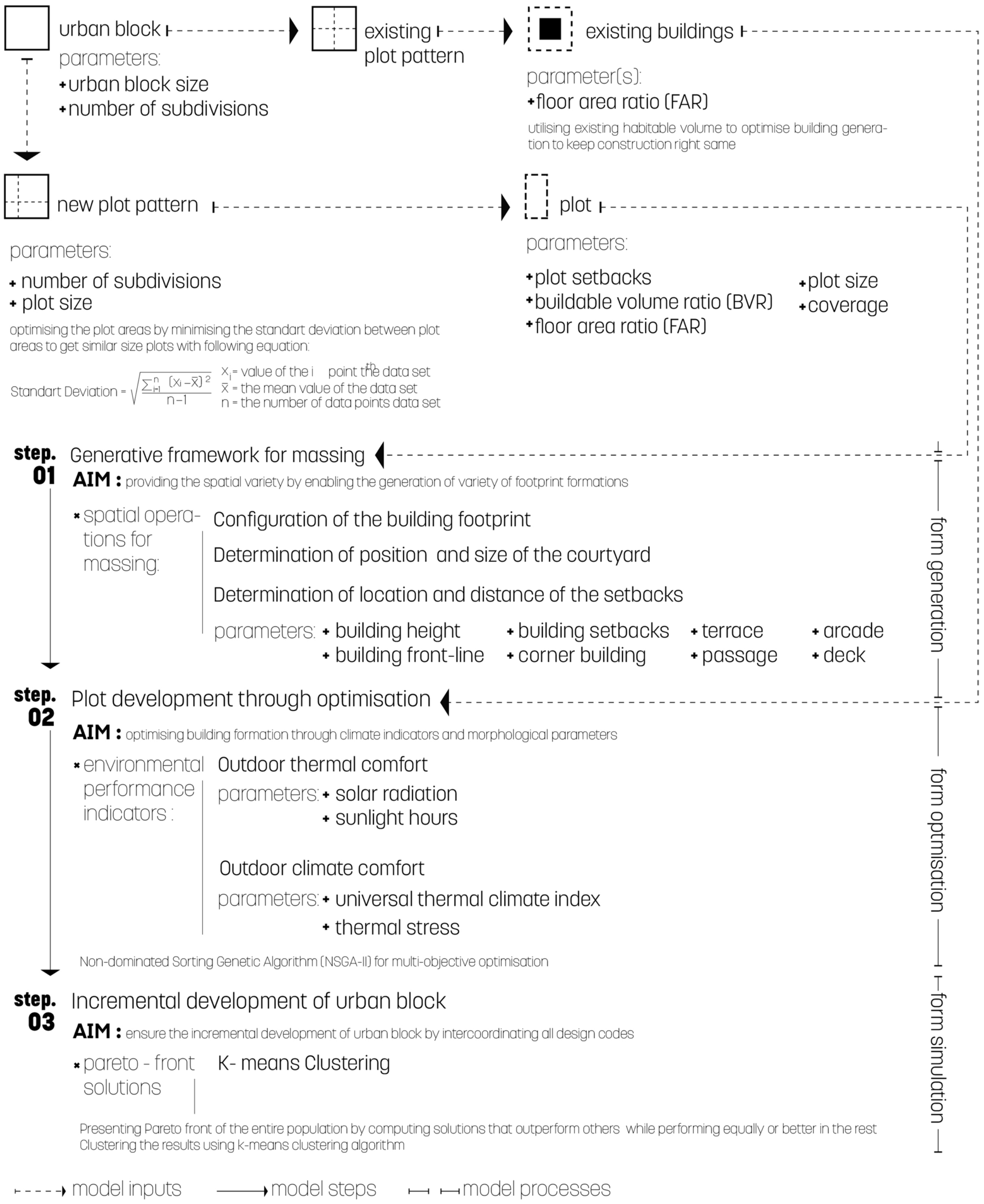
$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{1}$$

where $\bar{x}$ represents the arithmetic mean of the new plot areas, and n is the total number of new plots. Incorporating the formula into the model could generate a variety of plot layouts with different shapes while maintaining nearly equal plot sizes.

In this framework, *generation* involves algorithmic variations of form composition within set parameters, without additional filtering conditions. *Optimization* specifies performance criteria and parameters to generate the fittest alternatives, considering specific environmental concerns and habitable volume. Then, the *simulation* applies optimized form-generation processes within given spatial and environmental contexts. Lastly, *articulation* adds critical details to cohere urban block fabric with specified architectural form elements. Evolutionary algorithms and multi-objective optimization tools, supplementary in this parametric context, ensure desired diversity in response to predefined performance criteria. Grasshopper®, a graphical algorithm editor integrated with Rhino's 3-D modeling tools, was employed to construct the algorithmic setting.

During the generation phase, the model incorporates ten morphological parameters, including *block size, number of subdivisions, plot size, coverage, floor area ratio (FAR), plot setbacks, buildable volume ratio (BVR), building height, building front line,* and *building setback*. The parameters are utilized to generate either plot subdivisions in relation to the urban block or building forms within the geometric constraints of the plot.

To assess environmental performance, the model employed multi-objective optimization during the plots' incremental development. Ladybug® and Honeybee®, facilitating climate data visualization and analysis within Grasshopper (Roudsari et al. 2013), are utilized for environmental analyses. Optimization of outdoor thermal and climate comfort is achieved through environmental parameters: solar radiation, sunlight hours, and the Universal Thermal Climate Index (UTCI). Morphological parameters and environmental indicators operated synchronously to generate the urban block formation in a controlled manner. To that end, Wallacei Analytics® and Wallacei X® (Makki et al. 2019),



utilising existing habitable volume to optimise building generation to keep construction right same

optimising the plot areas by minimising the standart deviation between plot areas to get similar size plots with following equation:

$$\text{Standart Deviation} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

x_i = value of the i th point the data set
$\bar{x}$ = the mean value of the data set
n = the number of data points data set

AIM : providing the spatial variety by enabling the generation of variety of footprint formations

AIM : optimising building formation through climate indicators and morphological parameters

Non-dominated Sorting Genetic Algorithm (NSGA-II) for multi-objective optimisation

AIM : ensure the incremental development of urban block by intercoordinating all design codes

Presenting Pareto front of the entire population by computing solutions that outperform others while performing equally or better in the rest
Clustering the results using k-means clustering algorithm

Fig. 3 The workflow of the 'parametric plot-based urban design' (PPUD) algorithmic plugins, were employed to conduct evolutionary optimization processes.

Then the model demonstrates urban block fabric simulations via compositional variations, utilizing K-means clustering as an unsupervised machine learning algorithm. Simultaneously optimizing multiple objectives, the integrated model identifies prime spatial solutions within constraints. Leveraging the Pareto front highlights efficient choices, indicating trade-offs within the specified set rather than representing the entire parameter range (Abbass et al. 2001). By calculating optimal values in each design code, the model delivers ideal urban block formations under the given objectives.

In the final stage, the model employs six architectural form elements to ensure the articulation of the emerging urban block fabric. In this sense, *the arcade, deck, corner building, courtyard, terrace,* and *passage* are utilized to ensure morphological coherence by the controlled local relationships between the buildings in a parametric manner.

Morphological parameters and elements for the generation of the urban block based on plots

The generative algorithm is defined through the integration of ten morphological parameters, which govern the nested relationships among urban blocks, plots, and buildings. These parameters serve diverse functions, such as delineating plot boundaries and subdividing block surfaces into individual plots. Additionally, they account for the spatial context by considering the relationships with neighboring buildings within the urban block (Table 1).

As Campbell (2010) highlighted, effective dimensioning and design of urban blocks stem from a comprehensive understanding of building typologies and their intricate connections with plots (78). In pursuit of a robust methodology for PUD, it is crucial to consider the building as intrinsically linked with the plot. From this perspective, plot and building are conceptualized within volumetric frameworks called *envelopes*. The ‘plot envelope’, in this framework, typically governs development in a volumetric manner, while the ‘building envelope’ serves to direct the articulation of the building within a three-dimensional framework. Envelopes define the spatial boundaries of habitable volumes in three dimensions (Tarbatt 2012: 156). Therefore, within this framework, the massing of a building is determined by variational sets of height, coverage, and internal setbacks concerning neighboring buildings (Fig. 4).

Elements of form articulation

After generating the overall massing of the block fabric incrementally, the emergent form is further articulated by introducing six form elements on a parametric basis. Accordingly, *courtyard*, *terrace*, *deck*, *arcade*, *passage,* and *corner building* are incorporated into the model (Table 2).

Environmental performance indicators

In the algorithmic model, there are three environmental performance indicators to achieve comfortable climatic conditions within the urban fabric. Specifically, the model analyzed solar radiation, sunlight hours, and the UTCI during each iterative generation process.

Outdoor thermal comfort

Outdoor thermal comfort plays a critical role in optimizing passive heating and cooling solutions to minimize energy consumption (Galal et al. 2020; Johansson and Emmanuel 2006; Nazarian et al. 2019). In the research, solar radiation and sunlight hours are weighted to measure outdoor thermal comfort parametrically.

Solar radiation

Solar radiation is crucial for assessing solar energy potential and optimizing energy usage (Huang et al. 2022). The model, employing the parametric environmental plugin Ladybug® (Roudsari et al. 2013), quantifies the average annual total solar energy on building geometry. The Ladybug® quantifies solar radiation as the sum of three components: long-wave radiation from surrounding surfaces, the amount of sky-long-wave radiation absorbed by the human body, and additional absorbed solar short-wave radiation. The formula used to calculate the amount of solar radiation received on a surface is:

$$Solar\ Radiation = \frac{ERF_{Solar}}{f_{eff}.h_r} \tag{2}$$

where $\mathrm{ERF}_{\mathrm{solar}}$ (the effective radiative forcing of solar energy) represents the energy provided by solar radiation per unit area (often in watts per square meter), $\mathrm{f}_{\mathrm{eff}}$ is the effective fraction (or efficiency factor) of the body exposed to radiation that takes into account how much of the incoming solar radiation impacts the surface after various losses, and h_{r} represents the radiative heat transfer coefficient which adjusts for the way heat is transferred or distributed across the surface (Ibrahim et al. 2020: 2–3).

The computation includes the sum of results from each test point in $\mathrm{kWh/m}^2$ multiplied by the total area of the building surface to which the test point belongs.

Table 1 Morphological parameters of the model

Form element	Parameter	Description
Urban block	*Block size*	The surface area of an urban block influences its internal subdivision and the geometry of individual plots due to variations in the depth and width of the block surface. The metric characterizes the walkability of the total fabric through the number of turning points within the street network (Siksna 1997)
	Number of subdivisions	The total number of subdivisions is considered a determining factor that shapes the granularity of the built environment. As the number of plots subdivided within an urban block increases, so does the potential to generate a higher amount of various individual buildings. This, in turn, influences the coherence of the fabric based on the relational framework of the plot-based development control
Plot	*Plot size*	The plot size sets the basic condition of the building typology that could be accommodated on the parcel. The metric can be indirectly controlled by the depth and width of the plot. The varying dimensions, corresponding to different plot sizes, offer flexibility and adaptability in forming buildings through additional subdivisions or infill strategies (Campbell 2018: 170–73). Smaller parcel sizes, in this framework, are seen as the foundation of a fine-grained urban fabric
	Ground coverage (GC)	Ground coverage is the total footprint area of all non-vegetated surfaces (i.e., parking lots) and structures on an urban block (Çalışkan et al. 2025). It is calculated as the ratio between the building footprint and the total plot area. GC = Abfi ⁄ Ai, where Abfi is the coverage of the building on plot i, and Ai is the area of plot i. It conditions the overall dominancy of the building over the ground within a fabric
	Floor area ratio (FAR)	FAR indicates the building density in a plot. It is calculated by the ratio between the total floor space of the building and the surface area of the plot. FAR = Afai⁄Ai, where Afai is the total floor area of the buildings on plot i, and Ai is the area of plot i. It is a complementary index with coverage, and it is helpful to test the capacity of a plot layout, allocating a certain level of development within itself
	Plot setbacks – footprint	Setbacks determine the distances between the building and the boundaries of the plot. It varies the relationship between the building and the edge of the plot. Different distance values of the front, rear, and side setbacks would generate the varied building footprint options, even though the same ground coverage is in a plot
	Buildable volume ratio (BVR)	The plot could be defined as an abstract three-dimensional frame in which development right is determined in volume. The index of *buildable volume ratio* could be suggested as a supplementary parameter for the plot-based control of urban development. It is calculated by dividing the specified building volume (Abv_i) by the total volume of the plot envelope (Ape_i): $BVR = Abvi/Apei$ The index could also be utilized to ensure the porosity of the block fabric, indicating the volume of open spaces within the whole body of urban form (Adolphe 2001, 188)
Building envelope	*Building height*	Building height can be determined by both the total number of stories and the height of each story, including both the ground floor and upper levels. This parameter permits a range of height levels, allowing buildings to contain multiple units within a single structure. The use of the metric in plot-based design control promotes the development of composite forms within the block fabric
	Building front-line	The front line represents the boundary that delineates the active frontal facade(s) of a building, providing direct access from the street. The varied values of the metric condition the interaction between the building and the public space, influencing the placement of public and commercial amenities along the street. Variations in the length and configuration of the frontage offer diverse opportunities to connect the building's internal spaces with public areas, enhancing permeability as desired within the specific context
	Building setback	The street ratio holds significant importance in modern urban planning, particularly within high-rise and high-density urban environments (Lehnerer, 2009: 158–159). The metric of building setbacks serves multiple purposes beyond ensuring adequate daylight access; it also enhances the articulation of the built environment, optimizing the compositional relationship between building masses (i.e., through the extent of shared walls - in our current model, building setback refers to controlled recessions and projections on the vertical plane of a building, applied to its front, rear, and side surfaces).

Sunlight hour

Sunlight hour is a critical energy efficiency parameter, which signifies the hours of direct sunlight received by the input geometry (Kim et al. 2022). In the model, it is utilized to evaluate the outdoor thermal comfort of the emergent urban block, quantifying the average number of hours of direct sunlight within the given geographical context.

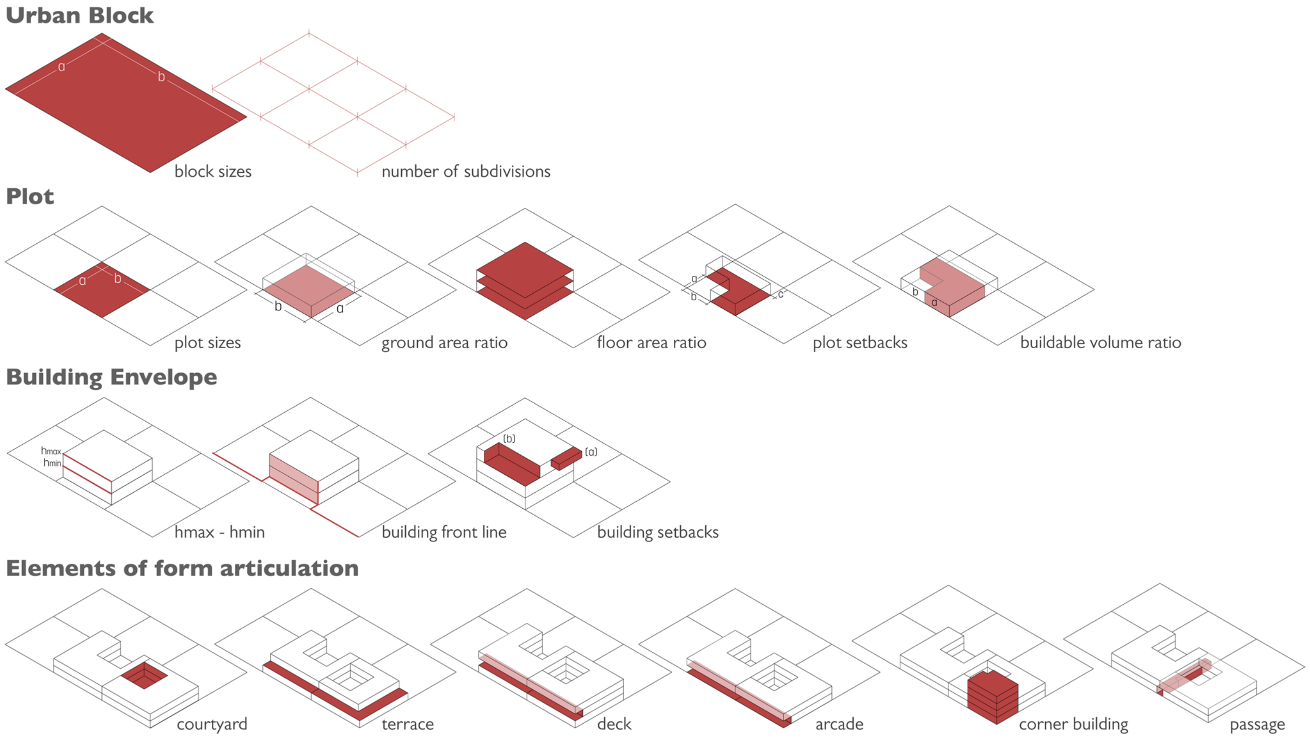


Fig. 4 Morphological elements and the parameters of the model

Outdoor climate comfort

The Universal Thermal Climate Index (UTCI) measures outdoor climate comfort by considering factors such as radiant temperature (typically solar radiation), relative humidity, and wind speed. It considers a combination of those factors to reflect how the environment "feels" to the human body. It is often used in urban planning, public health, and climate research to guide design and policy decisions that affect outdoor environments.

To calculate UTCI, the Mean Radiant Temperature (MRT) is determined first, which arises from outdoor shortwave solar radiation and longwave radiant exchange with the sky. Later, the climatic comfort of the area is categorized based on UTCI, featuring ten thermal sensation categories (Zare et al. 2018).[1] The model also offers an alternative classification based on thermal stress, with energy model values ranging from -1 to + 1, signifying:

- −1: cold stress—cold conditions (UTCI < 9 °C)
- 0: no thermal stress—comfortable conditions (9 °C < UTCI < 26 °C)
- +1: heat stress—hot conditions (UTCI > 26 °C) (Roudsari et al. 2013).

Results: application of the generative model in an actual context

The research has devised a four-stage algorithmic model to control the incremental generation of urban fabric through plot-based development. In the initial step, any given urban block is subdivided into plot layouts that are distributed in a nearly uniform manner yet exhibit a high degree of diversity. The second step establishes a 'generative layout' framework to guide building formation on individual plots. The third step optimizes the emerging composite building forms on adjacent plots by ensuring the designated environmental parameters. Then the fourth step provides a parametric ground for the incremental fabrication of the urban block. The fourth step offers a three-dimensional articulation of the generated urban blocks to achieve a cohesive fabric. Ultimately, the application concludes with the simulation of an ensemble composed of several blocks in a relational manner.

In this framework, first, the generative algorithm is set parametrically to come up with diverse layout options on the

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[1] Above + 46 extreme heat stress, + 38 to + 46 very strong heat stress, + 32 to + 38 strong heat stress, + 26 to + 32 moderate heat stress, + 9 to + 26 no thermal stress, + 9 to 0 slight cold stress, 0 to – 13 moderate cold stress, – 13 to – 27 strong cold stress, – 27 to – 40 very strong cold stress, below – 40 extreme cold stress.

Table 2 Architectural form elements of the model

Architectural form elements	Description
Deck	A deck is a raised, horizontal platform, devoid of enclosing walls or a roof (Ching 2011: 227). As an extension of living spaces, decks accommodate various activities like seating, dining, lounging, and recreation, blurring the boundaries between indoor and outdoor environments
Courtyard	Courtyards are considered *positive voids* that are usually enclosed on three or four sides yet open to the sky (Edwards et al. 2005: 316). Unlike backyards, courtyards can be situated within the footprint of a building (or buildings). While often positioned centrally, various spatial arrangements can be achieved by experimenting with their placement. Courtyards offer practical solutions for ground floors, enhancing climate comfort by optimizing air movement, natural light, and shading (Abdelmalek 2005: 55)
Terrace	A terrace refers to a flat, elevated platform designed to offer a vantage point or panoramic view. Typically integrated into buildings, balconies, or rooftops, terraces provide access to outdoor space, the surrounding landscape, or architectural landmarks. They serve as recreational areas or spaces, fostering a sense of connection to the outdoors while remaining within the urban environment
Passage	A passage refers to a narrow walkway that links various buildings or urban spaces, serving a vital function in pedestrian circulation and facilitating easy access and movement (City of Birmingham 2012). Thoughtfully designed passages have the potential to improve the overall pedestrian experience, fostering a sense of connectivity and coherence within the urban fabric
Arcade	An arcade is a covered walkway that is bordered by shops, cafes, or other amenities. It offers a protected environment for pedestrian movement and enhances visual appeal in the urban landscape (Fu et al. 2023). Additionally, they can serve as gathering spaces, fostering a sense of community within the urban fabric
Corner building	Corner buildings occupy prominent positions at the intersection of multiple streets, serving as important gateways to the neighborhood or district, thereby increasing visibility and access (Llewelyn-Davies 2000: 94; Pålsson 2023: 190–191). They offer diverse opportunities for various uses, including commercial spaces, residential units, or mixed-use developments (Herriott 2016)

given block surface. This is to ensure a controlled variation within the overall configuration of the plots (Fig. 5).

Generation of different plot layouts composed of parcels in various shapes through an equal surface area (Fig. 5, above) is a critical competence of the parametric model, especially in planning contexts where equal property rights are considered binding conditions.

In the second stage, a set of design codes is developed to establish a generative framework for massing. To enhance the control capacity of the algorithmic model at the plot scale, this stage employs three spatial parameters and operations:

- formation of the total footprint of the building,
- positioning of the courtyard in varied sizes,
- setting setbacks at varied distances (Fig. 6).

To that end, a generative grid is created within each plot to allow spatial diversity through different footprint formations. This framework enables control over formation using three different codes: (1) minimum depth of the building, (2) daylight exposure to the building, and (3) number of units forming the building.These codes allow internal control over each plot's generative framework and the establishment of parametric conditions with the adjacent plots.

The algorithm allows for diverse positioning and sizing of the courtyard within the plot, including its location (front, back, center) and dimensions (width and depth). Specifically, the dimensioning of the courtyard is linked to the daylight received by the first floor of the building and the minimum depth of the building.

This setup enables a responsive code that fosters the creation of various spatial formations on the ground floor while optimizing climatic comfort. Another parameter affecting massing is the setback distance. The model establishes a framework to control the setback location (front, rear, side) and length. The parametric control focuses on setting maximum and minimum setback distances. By managing setback distances, the model could expand the range of alternatives for ground floor design and facilitate spatial organization that fosters interaction between plots within the third stage.

The third stage focuses on gradual building formation on the generated plot layout, optimizing the emerging composition based on environmental performance indicators. Specifically, three climatic indicators are employed: UTCI (°C), solar radiation (kWh/m^2), and sunlight hours (h/m^2). The model provides 1-m^2 analysis grids for climatic analyses to aggregate results on these grids (Fig. 7).

For simultaneous climate analysis and building formation optimization, the Non-Dominated Sorting Genetic Algorithm (NSGA-II) (Deb et al. 2002) was selected as a multi-objective optimization algorithm, enabling concurrent optimization of various objectives. Accommodating input from design and climatic codes simultaneously, and fostering responsive plot evolution, NSGA-II optimizes spatial and climatic parameters within a multi-objective framework.

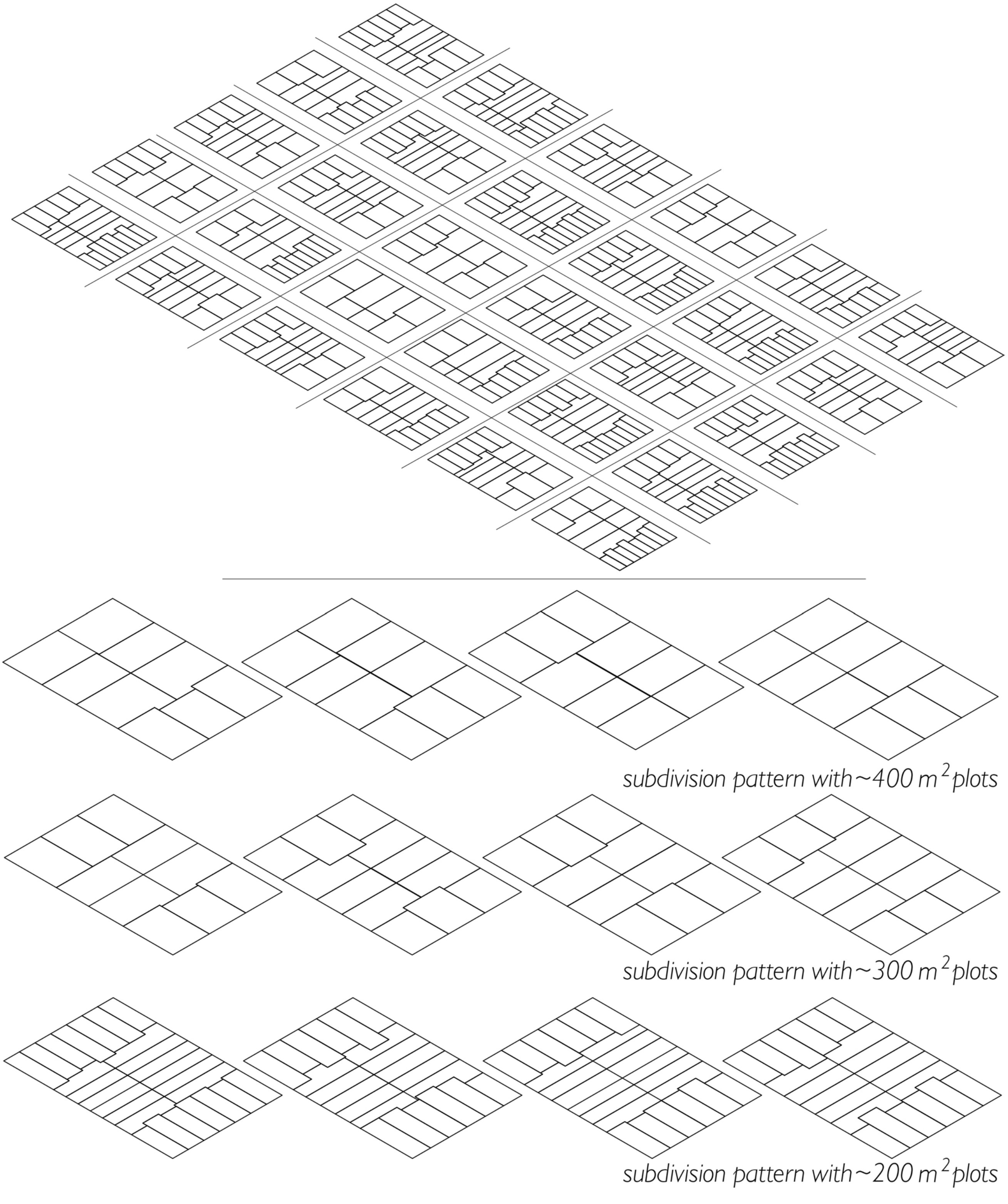
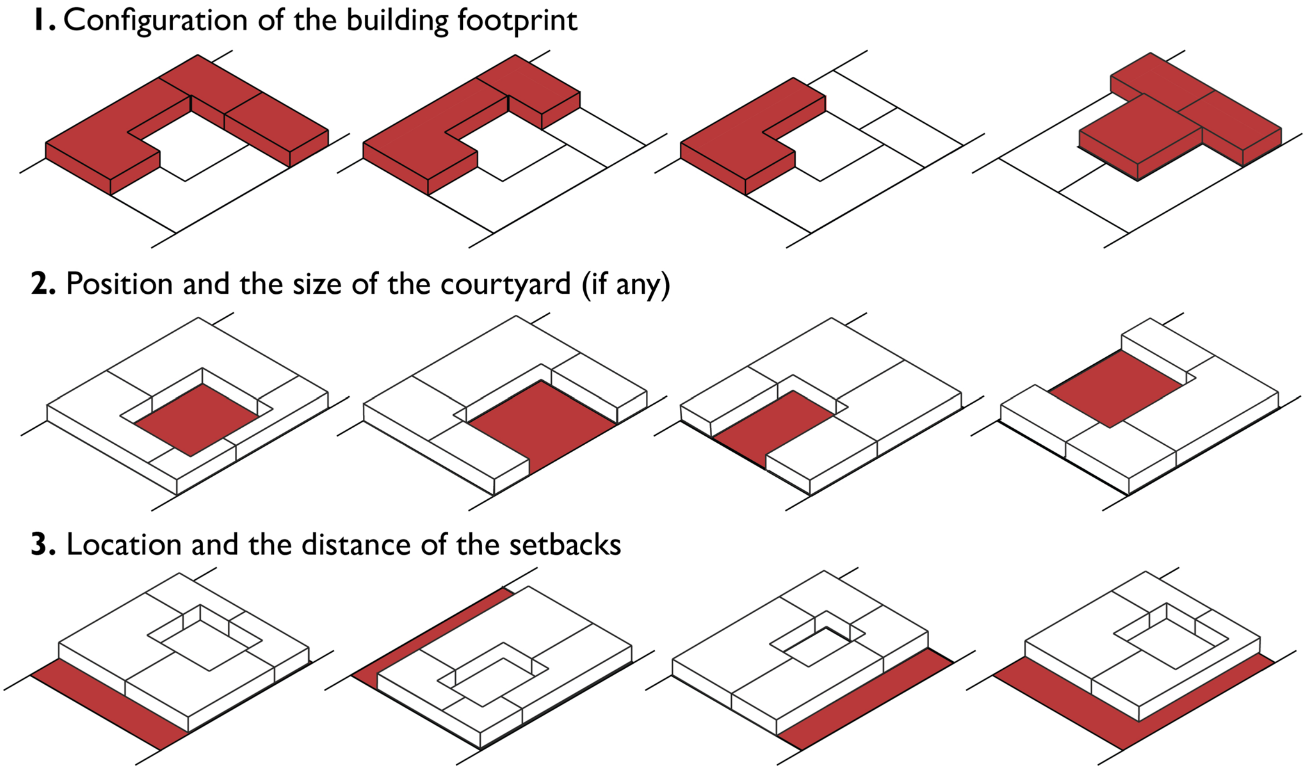


Fig. 5 Multiple variations of plot layout based on dimension and size of the parcel: Each iteration demonstrates a different subdivision pattern where plots are flexibly differentiated in either depth or width (*above*), and selected subdivision patterns that are composed of different plots with equal areas (*below*)



1. Configuration of the building footprint

2. Position and the size of the courtyard (if any)

3. Location and the distance of the setbacks

Fig. 6 Some possible variations during the generation of the building footprint and massing

The third stage is pivotal, as it governs the spatial interaction of plots and shapes the incremental development of the urban block. The core principle is to ensure that each newly developed plot establishes a coherent morphological relationship with the existing plots by adhering to the prescribed design codes. This enables the urban block to evolve over different timelines while maintaining consistency through the application of the initial development codes. This allows spatial and climatic codes to incrementally shape the urban block at the plot scale. In this sense, Fig. 8 illustrates a snapshot of the responsive development process of the plots within the given urban block. Here, each plot is built in such a way that it references any adjacent plots or with which it can interact according to the articulation code it has. In this context, while Plot 4, Plot 3, and Plot 1 were developed at different times, they interacted with the neighboring plot to form, for instance, an arcade or terrace for a continuous mass articulation (Fig. 8).

Then, Fig. 9 illustrates the Pareto front of the entire population, determined by computing solutions that outperform others in given criteria while performing equally or better in the rest. Two primary clustering algorithms, K-means and agglomerative hierarchical clustering, are employed to cluster results. K-means analyses the Pareto front, representing optimal solutions balancing spatial and climatic parameters. It groups solutions into distinct clusters based on shared characteristics like FAR and climate comfort. The model, aiming for diverse typologies within the urban block, identified five clusters categorizing FAR measures (Fig. 9, above).

Accordingly, the urban blocks within each cluster were classified using the given color code. Therefore, the colors in the matrix, which represent the building blocks in a collective framework, indicate the cluster to which they belong. The simulation of building blocks with varying FAR, all adhering to the same building codes, demonstrates the model's capability to generate urban form through control parameters (Fig. 9, below).

Discussion

Plot-based urbanism lacks a structured framework to deliver on the qualities highlighted in its emerging literature. This is largely due to the disparity in land development techniques and procedures across different planning systems and the absence of a robust methodological approach for plot-based development control. Hence, it could be argued that implementing computational design control adaptable to various legislative frameworks on a parametric basis could enhance the effectiveness of plot-based urban design (PUD) within practical planning scenarios. Thus, the study suggests a parametric model for design control, utilizing an

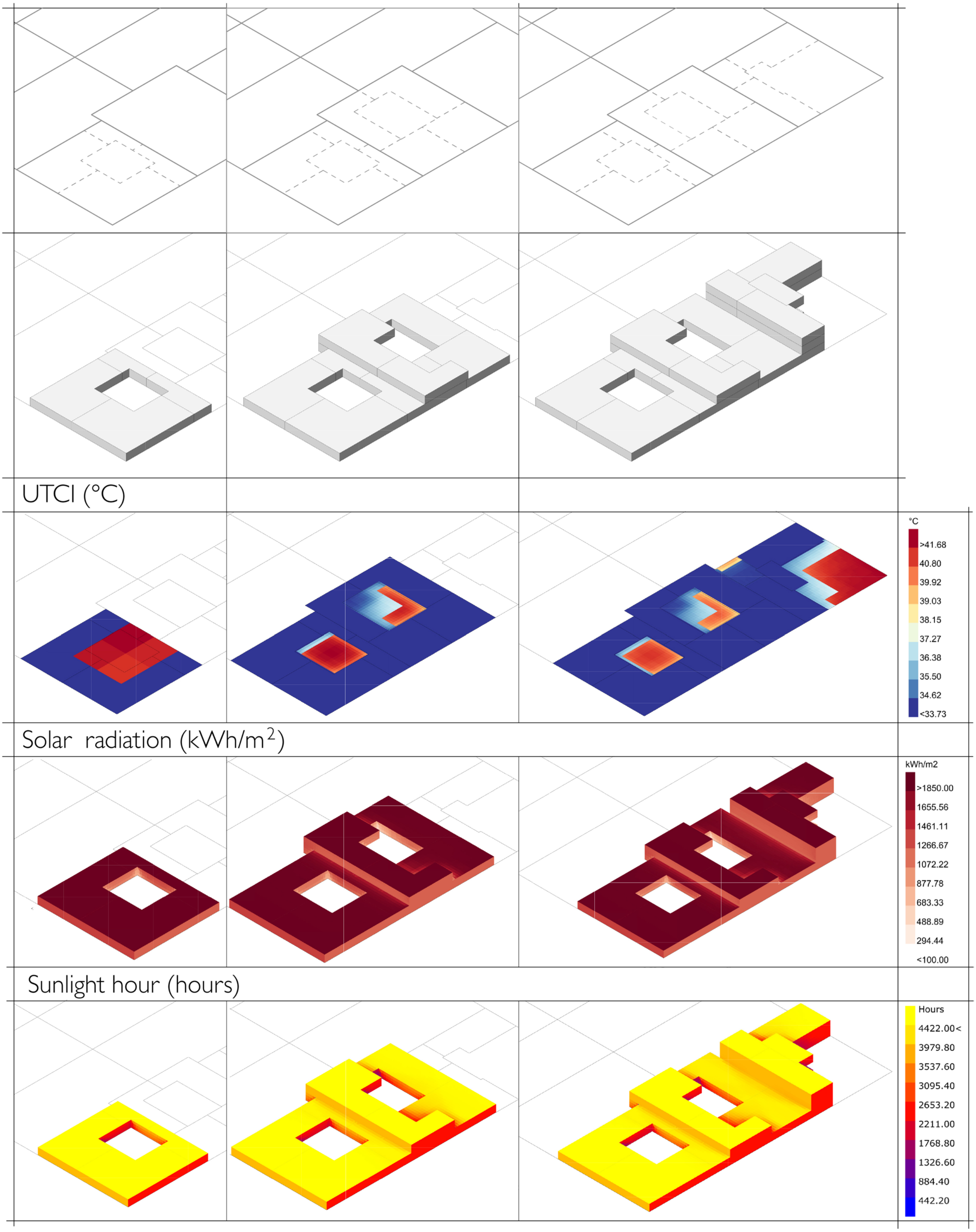
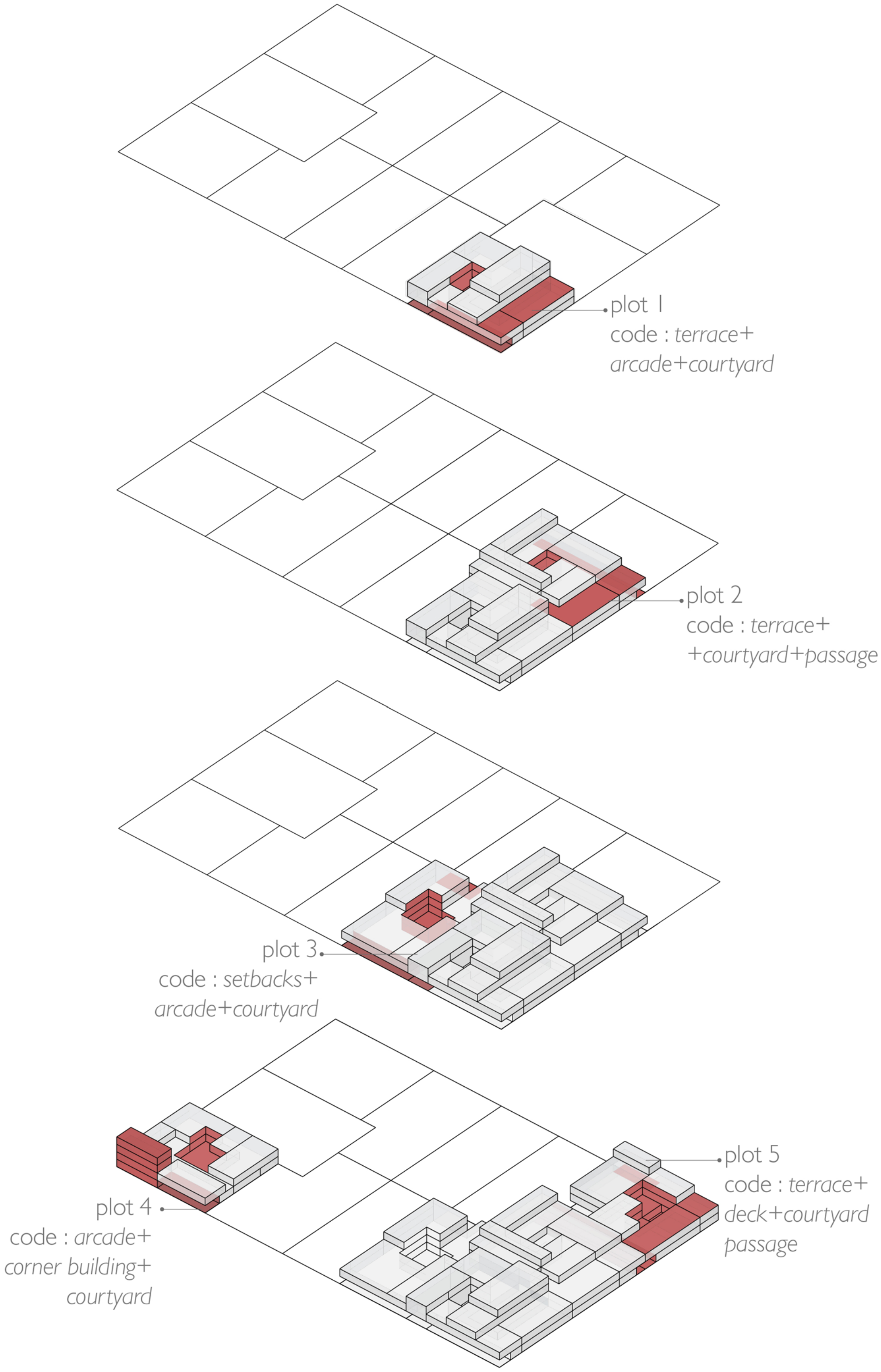


Fig. 7 The gradual development of the plot through environmental optimization

Fig. 8 Algorithmically randomized incremental form generation of the block fabric



algorithmic framework with a set of codes determined by the key parameters.

The model is run to utilize the specified architectural form elements. Consequently, the elements could act as livability factors responding to a series of performance criteria. They are generated parametrically in various forms to ensure morphological coherence through a series of local interactions between plots, streets, and buildings in a larger context (i.e., corner plot and the elevated building, main street and the arcade creating setbacks on the front line of the plots, etc.) The new block fabric generated by the parametric control model demonstrates greater diversity and coherence

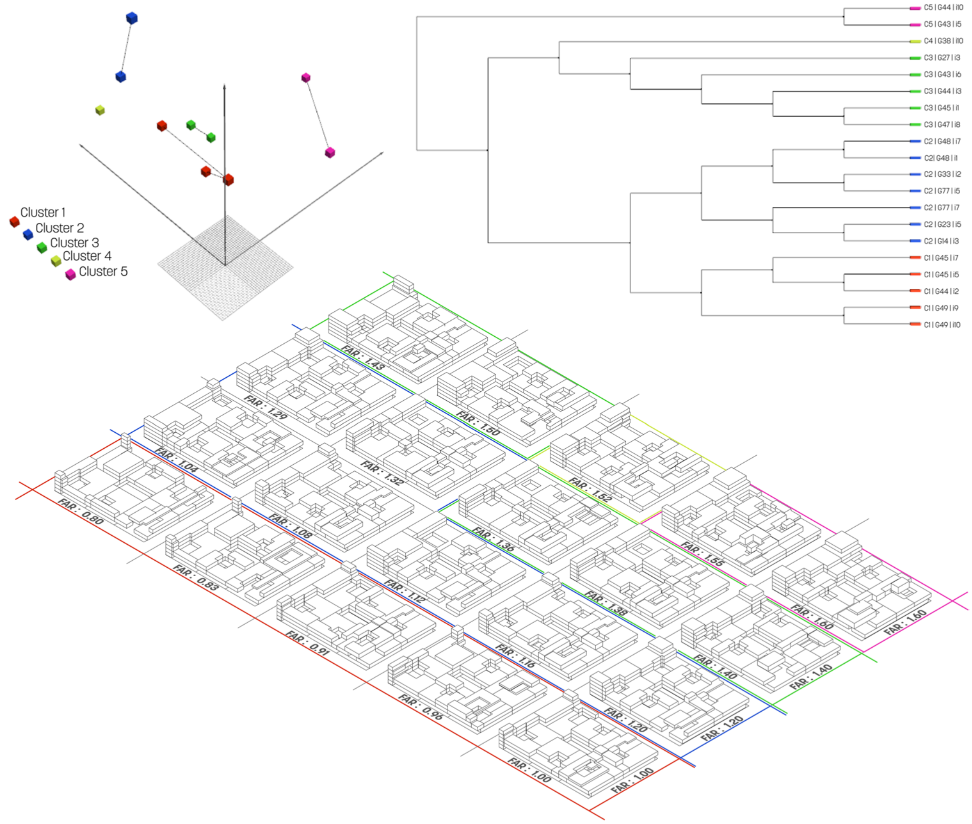


Fig. 9 Clustering results of the Pareto front solution (*above*) and the matrix of urban block formations with different floor area ratios (FAR) (*below*)

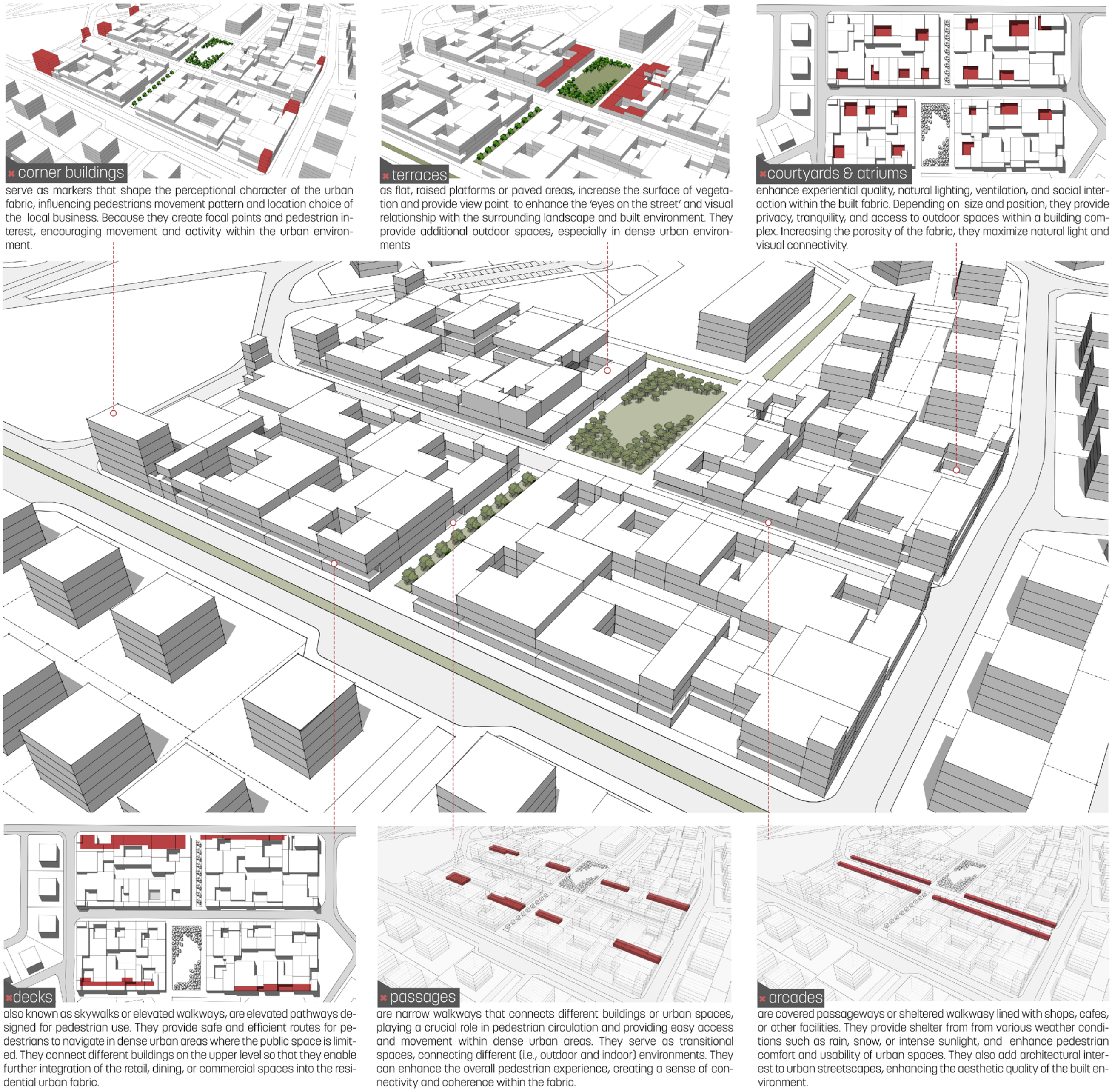
while maintaining the same development rights (FAR) as the surrounding plots and adhering to a standardized building typology (Fig. 10).

The key point here is that the exemplar illustration allows for alternative iterations. Then, the current arrangement of architectural elements that would be criticized for privacy concerns or the level of visual complexity can be modified into different configurations as a foundation for further design review processes.

The generative layout framework, in this context, established various building footprints within each plot using a generative grid that allowed flexible and diverse positioning of courtyards and setbacks, optimizing dimensions for daylight exposure and structural integrity. Thorough climatic analyses with a 1-m^2 grid on the building surfaces and the NSGA-II algorithm optimized outdoor thermal comfort and outdoor climate comfort, providing better environmental performance. Having such a high resolution for climate analysis also provides a robust basis for operating detailed environmental analyses while exploring spatial diversity.

The clustering algorithm, K-means, categorized the plots based on their FAR and climatic performance. This categorization facilitated efficient decision-making and comparative analysis, ensuring that each plot contributed to a cohesive urban block. Simulations of varying FARs demonstrated the model's capacity to generate diverse urban forms, enabling effective decision-making and fostering spatial synergies between plots, thus ensuring adaptability in the urban context.

In the future practice of the so-called *Parametric Plot-based Urban Design* (PPUD), several key contributions could be considered significant. The development of the 'generative grid' for building footprints allows for simulating potential 2D and 3D building layouts on a given plot. This approach integrates environmental performance indicators and utilizes multi-objective optimization algorithms, enabling designers to sift through numerous building form possibilities while considering neighboring plots. Furthermore, by leveraging data-driven insights, design decisions can be informed concurrently, leading to more efficient and optimized outcomes compared to traditional plot-based urban design (PUD) procedures. Another contribution is the simulation of solutions categorized as floor area ratio (FAR) through Pareto front clustering, which offers a deeper understanding of design alternatives. Pareto front clustering plays a vital role in evaluating typological diversity generated incrementally on plots and predicting urban form by analyzing how clustered typologies might combine to create specific urban patterns. This method also informs design decisions and guides the development of regulations based on plots, ensuring a more data-driven and responsive approach to urban design.



corner buildings serve as markers that shape the perceptional character of the urban fabric, influencing pedestrians movement pattern and location choice of the local business. Because they create focal points and pedestrian interest, encouraging movement and activity within the urban environment.

terraces as flat, raised platforms or paved areas, increase the surface of vegetation and provide view point to enhance the 'eyes on the street' and visual relationship with the surrounding landscape and built environment. They provide additional outdoor spaces, especially in dense urban environments

courtyards & atriums enhance experiential quality, natural lighting, ventilation, and social interaction within the built fabric. Depending on size and position, they provide privacy, tranquility, and access to outdoor spaces within a building complex. Increasing the porosity of the fabric, they maximize natural light and visual connectivity.

decks also known as skywalks or elevated walkways, are elevated pathways designed for pedestrian use. They provide safe and efficient routes for pedestrians to navigate in dense urban areas where the public space is limited. They connect different buildings on the upper level so that they enable further integration of the retail, dining, or commercial spaces into the residential urban fabric.

passages are narrow walkways that connects different buildings or urban spaces, playing a crucial role in pedestrian circulation and providing easy access and movement within dense urban areas. They serve as transitional spaces, connecting different (i.e., outdoor and indoor) environments. They can enhance the overall pedestrian experience, creating a sense of connectivity and coherence within the fabric.

arcades are covered passageways or sheltered walkwasy lined with shops, cafes, or other facilities. They provide shelter from from various weather conditions such as rain, snow, or intense sunlight, and enhance pedestrian comfort and usability of urban spaces. They also add architectural interest to urban streetscapes, enhancing the aesthetic quality of the built environment.

Fig. 10 The selected simulation of the ensembles as a model application within an actual urban context

Conclusions

The claimed novelty of the research could be considered threefold:

- The proposed parametric model incorporates morphological operations of plot subdivision directly into the development control process. Unlike standardized parcellation techniques seen in traditional master plans, this generative approach allows for controlled diversity in plot layouts in a generative manner.
- It facilitates the incremental control of interactions between buildings on adjacent plots, enabling the simulation of the collective fabric that would emerge over time to ensure effective design control and guidance.
- The model supports the creation of diverse plot-based configurations while simultaneously evaluating their environmental performance through an embedded test and selection tool.

Within this framework, the proposed model of *Parametric Plot-based Urban Design* (PPUD) contributes to plot-based urbanism through certain aspects. The mainstream plot-based urban design practice relies mainly on the master planning approach, rendering the subdivision of urban blocks into a fixed plot pattern from the early stage of the planning process. The implementation of an algorithmic framework within the plot-based urban design (PUD), therefore, would significantly enhance the effectiveness of the mainstream practice by responding to the lack of robust methodologies across various planning systems. This study, accordingly, proposes a parametric model for design control, using an adaptable algorithmic framework to guide any plot-based urban development even in an incremental manner. With the model application, the plot layout defined by master plans would not necessarily be taken for granted for any plot-based development. The subdivision, which was considered the 'lost art' in urbanism (Campbell 2010) could be an intrinsic part of the development control processes. In the generation of the block fabric, key contributions also include the expanded design codes and parameters tailored to individual plots, improving control over urban form through building footprints, setbacks, and massing concerning the buildings on the neighboring plots. Such a relational control applied incrementally would make the basic condition of coherence (Alexander et al. 1987) applicable in actual contexts. Moreover, integrating environmental performance indicators, within a multi-objective framework, enables the model to optimize numerous building form possibilities, toward more coherent and climate-responsive form typologies.

All in all, PPUD could be considered a design control tool in planning, enabling precise adjustments to various design parameters. Leveraging data-driven models allows urban planners to simulate and optimize different design scenarios in real time. This approach facilitates the creation of adaptable urban spaces that respond to different climatic conditions. Through PPUD, designers can achieve the desired level of control and flexibility, ensuring climatic comfort within an urban fabric.

Computational insights of the model would enhance decision-making processes, potentially providing more efficient outcomes. This approach is strengthened with simulation and Pareto front clustering to provide a comprehensive understanding of design alternatives, evaluate typological diversity, predict urban form patterns, and inform design decisions. It allows for the assessment of incrementally generated plot typologies and their contribution to urban diversity and functionality. Analyzing clustered typologies, the model can predict cohesive urban patterns and provide a regulatory framework for guiding plot developments.

In this regard, the simulation capacity of the parametric modeling would serve as a planning support system. It would allow diverse stakeholders to visualize and explore the impacts of various design decisions. By bridging the gap between technical expertise and public input, PPUD promotes transparency and consensus-building in urban development projects. Ultimately, this model enhances the practical application of plot-based urban design, enhancing the morphological integrity of piecemeal urban development patterns, which remain prevalent in many countries.

A practical limitation of the model is its reliance on a highly sophisticated visual interface for the parametric algorithms, making it challenging for local planning experts to use. This complexity poses a significant barrier to integrating the model into actual planning control processes. In this sense, there is a necessity for a simplified interface design that would make the model framework much more practical. Likely, for future work, the parametric modeling has the potential to enable designers to test some other sets of performance criteria, such as visibility, programmatic capacity (functional diversity), and/or visual coherence of urban form, which had to be excluded within the current framework of the paper.

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