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# Towards a pattern language for green space design in high density urban developments

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**ABSTRACT**

In the inevitable high-density urbanization process, existing urban green space (UGS) design approaches are ineffective in creating more green areas and combining multidisciplinary design principles to provide balanced sets of ecosystem services (ESs). This paper proposes a systematic framework for UGS design in the context of high-density urban development, results in spatial patterns, a pattern language, that combines specific design principles with a wide range of complementary ESs suitable for high-density environments. Such design approach can create more possibilities for UGS provisioning, deal with the complexity in high-density contexts, and provides consistency at different scale for UGS designs.

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Green space design; high-density urban environment; ecosystem services; pattern language

## Introduction

In the context of rapid global urbanization (United Nations 2019), high-density development is a potential way to promote sustainability through its mobility advantages and efficient land-use (Churchman 1999). However, many high-density cities have failed to provide a healthy and livable environment to maintain urban sustainability and have caused various urban problems, such as air pollution (Stone 2008), urban runoff (Hochrainer and Mechler 2011), loss of biodiversity (Collinge 1996), excessive mental stress and poor public health (WHO 2014). In this case, urban green space (UGS) has been considered fundamental to promoting quality of life and sustainability in high-density urban environments for their capacity as medicine for these 'metropolitan diseases' (Ramaswami et al. 2016). Following Taylor and Hochuli's (2017) suggestion, UGS means a type of land use mostly covered by green elements, providing notable contributions to urban environments in terms of ecology, aesthetics or public health. It includes both public and private greenery, natural and semi-natural, vertical and lifted greenery. UGS can offer many long-term benefits, in terms of ecology, culture, environmental regulation, and economics (Wolch, Byrne, and Newell 2014). These UGS-added values are critical to both human well-being and the natural environment beyond

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human society. Some studies summarize these values as ecosystem services (ESs) through a more 'human-centered' perspective, which means the benefits people obtain either directly or indirectly from ecological systems (Millennium Ecosystem Assessment 2003). Others argue that studies also need to consider a 'more-than-human' perspective (Apfelbeck et al. 2020). As urban design in high-density cities is difficult to place in a context detached from the residents' well-being, this article tends to agree with the ESs definition based on 'human perspective'. But this article also pays equal attention to the importance of UGS for environmental regulation and biodiversity, as they also indirectly impact social well-being and are fundamental for urban sustainability.

While the value of UGS has been widely recognized, UGS design still encounters many challenges and dilemmas in high density developments, mainly reflected in the following aspects:

***Inadequate provision.*** The inadequate provision of UGS is an inescapable and practical challenge for high-density developments (Haaland and van den Bosch 2015). In such cases the designer must consider the close integration of the UGS with the development of urban infrastructure or buildings. However, UGS design approaches, built on a strict typology and standards, lack flexibility and the possibility to create additional green elements (Wilkinson 1985).

***Complexity.*** Complexity consists of two aspects. Firstly, high-density cities are composed of many unique surfaces and spaces. With limited land provision, the UGS design in this context needs to be closely integrated with diverse infrastructures and building types. Such wide variety and complexity of urban information must also be incorporated into the UGS design process.

On the other hand, the social well-being of residents in high-density urban environments depends on the provision of ESs in many ways (Summers et al. 2012). UGS design in this context needs to consider multidisciplinary design principles to create a balanced provision of this variety of services. For example, urban ecology, urban resilience, microclimate, social behaviour and psychology (essential for recreation activities), etc. However, existing UGS design approaches often lack a systematic concern for such ESs (Jim and Chan 2016).

***Consistency.*** Existing UGS design approaches also lack the consideration of UGS quality at the local scale and in detailed design (Jim and Chan 2016; Zhu et al. 2019). Such limitation may have a significant impact on the overall effectiveness of the UGS system, especially in high-density cities with limited available land. In this case, the multidisciplinary design principles need to be consistent across different scales to maintain the provision of multiple ESs.

The above dilemma implies the requirement to seek more effective and adaptive UGS design approaches in high-density contexts. This study considers pattern language potentially valuable in this regard.

A pattern language is an organized and coherent set of spatial patterns, each describing a problem and the core of the solution that can be used in many ways (Alexander 1977). Pattern language has received much attention since it was first proposed but has

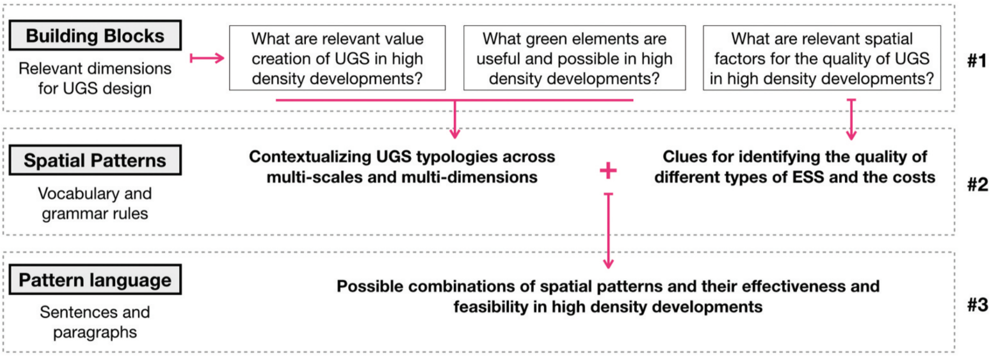


Figure 1. The structure of contextualizing pattern language in high-density developments.

also been criticized by many scholars. Pattern language is considered autocratic, bourgeois, romanticized, and mechanical (Dawes and Ostwald 2017). However, many studies acknowledge its value when used as a framework. Patterns can be combined and adapted in a variety of ways to create different building types and urban forms. Pattern language provides flexibility, possibilities, and the ability to tackle complexity by breaking down complex design problems into more manageable components that can be addressed through specific spatial patterns (Salingaros 2000). In addition, the linear, non-independently tight connection between patterns over different scales also provides a consistency of spatial quality in the solutions across scales (Alexander 1977). Such merits enable pattern language to serve as a practical design approach to address the above-mentioned challenges. Therefore, this article aims to propose a framework for UGS design, which results in spatial patterns and a pattern language, that combines specific design principles with a wide range of complementary ESs suitable for high-density environments. It considers both the possibilities of high-density environments and combinations of diverse aspects to reveal the evidence on how UGS values function optimally, then translates them into hands-on spatial patterns.

As shown in Figure 1, this article divides pattern language into three basic components and contextualizing steps. ‘Building blocks’ are the dimensions that UGS design must take into account, and they also correspond to specific problems. ‘Spatial patterns’ are visualized spatial solutions corresponding to the ‘Building blocks’. Ultimately, these spatial patterns on different scales and dimensions are organized into a practical design language (‘Pattern language’) following a specific order. Three main scopes of literature are reviewed as the research method in this article, including the value creation of UGS (ESs), the possible green elements in urban areas, and the relevant spatial factors of each ES. Then, the knowledge gained from the literature review is integrated to explore ways of developing pattern language in a high-density environment, based on the basic principles proposed by Alexander (1977).

## Dimensions for UGS design in high-density urban environments

High-density contexts are often accompanied by surging land values or urban renewal costs, meaning that developments need to generate enough benefits to balance their costs (Wang, Fan, and Yang 2022), as is the case with the UGS projects. On the other hand, UGS should also provide diverse services to alleviate the urban problems caused by high-density developments as mentioned above. In this case, the UGS design approach in high-density contexts has several premises: the essential values of UGS in high-density contexts, the potential green elements and their spatial costs, and the design principles of ESs provisioning. Therefore, these aspects come together in the following criteria for contextualizing the pattern language.

### *Value creation of UGS in high-density urban environments*

The concept of ESs is a systematic summary of the added value of green elements for human well-being, quality of life, and sustainability, including provisioning (e.g., drinking water, food), regulating & supporting (e.g., climate, flood regulation), and cultural (e.g., recreational, aesthetic) services (Berghöfer, Wittmer, and Gundimeda 2011). Many studies elaborate that UGS can improve social well-being and the urban environment by providing these services. Regulating and supporting services are the basis for other ESs. The UGS provides the habitat, food, energy, and gene pool necessary to maintain urban biodiversity, which shapes the sustainability of the ecosystem (Goddard, Dougill, and Benton 2010; Nielsen et al. 2014). In addition, the regulating services of the UGS are essential to a healthy urban environment in terms of improving air quality (Nowak 1994; Tallis et al. 2011; Bell, Morgenstern, and Harrington 2011), ameliorating noise pollution (Fang and Ling 2005; Gidlöf-Gunnarsson and Öhrström 2007), regulating urban microclimates (Dentamaro et al. 2010; Gill et al. 2007), enhancing urban resilience in extreme weather (Depietri, Renaud, and Kallis 2012; Zhang et al. 2012), and storing carbon (Davies et al. 2011; Strohbach, Arnold, and Haase 2012). For cultural services, the UGS provides opportunities for recreational activities for residents and integrates ecological or aesthetic value to promote social interaction (Jennings and Bamkole 2019; Maas et al. 2009; Peters, Elands, and Buijs 2010), improve social health (Ekkel and de Vries 2017; Jennings and Bamkole 2019; Maas et al. 2009), and bring tourism profits (Kothencz et al. 2017; Terkenli et al. 2020). In recent years, there has also been a growing interest in UGS provisioning services, particularly in urban agriculture (De Bon, Parrot, and Moustier 2010) and community gardening (Holland 2004). As a carrier of ecosystems, UGS can provide residents with a range of tangible natural resources such as materials, water, and food (Berghöfer, Wittmer, and Gundimeda 2011).

The social well-being of urban residents can benefit directly or indirectly from each of these ESs. However, limited space require UGS in a high-density context to prioritize those ESs that are urgently needed in high-density urban environments and that face serious threats. TEEB (The Economics of Ecosystems and Biodiversity) also elaborates such opinion in its report and provides an evaluation matrix based on demands and risks (Berghöfer, Wittmer, and Gundimeda 2011). The matrix shows which ESs with high demand in high-density contexts should be prioritized (see Table 1).

Christopher and Rachel, in their paper, provide a detailed review of the challenges that high-density development poses to cities (Boyko and Cooper 2011). As shown in Table 2 below, pairing various ecosystem services (Berghöfer, Wittmer, and Gundimeda 2011) with this checklist of high-density challenges is an effective way to identify which ESs are

Table 1. The evaluation matrix of how to prioritize ecosystem services.

| | | |
|---|---|---|
| **Local ecosystem services in high demand** | **Second priority**: Ecosystem services that are less challenged but essential to residents. | **First priority**: Ecosystem services that are confronted with significant challenges and have urgent demands. |
| **Local ecosystem services in low demand** | **Fourth priority**: Ecosystem services with fewer challenges and not directly related to the well-being of residents. | **Third priority**: Ecosystem services facing great challenges but not directly related to the well-being of residents. |
| | **Local ecosystem services at low risk** | **Local ecosystem services at high risk** |

Source: Based on Berghöfer et al. (2011).

Table 2. Identifying the relevant ESs in high-density contexts.

| The challenges of high-density developments[a] | Ecosystem services[b] |
|---|---|
| Limiting recreational opportunities.<br>Reducing the availability of public open space.<br>Causing psychological stress, cognitive overload, loss of control, anxiety, social withdrawal, physiological overstimulation and violations of personal space.<br>Leading to difficulty in supervising children in outdoor or play spaces and choice of friends. | Recreation & sense of nature |
| Reducing an area's capacity to absorb rainfall. | Moderation of extreme events |
| Exacerbating pollution, possibly because of reduced space for trees and shrubs that purify the air and cool the area. | Air quality regulation; Local climate regulation |
| Leading to loss of privacy and increases in noise, nuisance etc. | Noise reduction |

Sources: Adapted from [a]Boyko and Cooper (2011); [b]Berghöfer et al. (2011).

in high demand. According to this, this article sees the following five ESs as relevant in a high-density context: **Recreation & Sense of Nature, Air quality regulation, Local climate regulation, Noise Reduction, and Moderation of extreme events**. In addition, **Supporting urban biodiversity** is not included in this table, but should also be considered as it has a strong impact on other ESs in terms of ecosystem processes and functions (Schwarz et al. 2017).

The provision quality of these ESs is determined by different design principles and corresponding spatial factors. In order to address the complexity that results from the synergy and trade-offs of these spatial factors at different scales, it is necessary to understand the spatial principles behind them. Based on the review of mechanisms and relevant design principles on each of these ESs, the information within is systematically organized in the subsequent section (Section 2.3) to elaborate on the spatial factors that are critical to the ESs provisioning.

### *UGS inventory in high density urban environments*

UGS is a diverse concept that encompasses all vegetation in urban environments. Because of this diversity, as a prerequisite for understanding how green spaces can be connected functionally and with the built environment, an inventory of possible UGS elements is essential for the pattern language.

The traditional UGS typologies can accurately describe most green elements within cities (e.g (Bell, Montarzino, and Travlou 2007), (Byrne and Sipe 2010; Swanwick, Dunnett, and Woolley 2003). They identify and categorize the UGS that appear in cities from different perspectives. Among them, ownership, shape, size, and location are the basis for the classification. However, the demand of high density development and the application of new technologies have created many new UGS types, such as roof gardens and green façades (Rosenzweig, Gaffin, and Parshall 2006). Some informal green spaces or private green spaces are also starting to receive attention (Rupprecht and Byrne 2014). Due to the ESs potential of these UGSs to help address the challenge of inadequate UGS provision in high-density contexts, studies are continually updating the UGS inventory with new content. Some studies have systematically incorporated all of these UGSs into the UGS inventory to the extent possible, such as the GREEN SURGE report (Rall et al. 2015).

In high-density contexts, studies have recognized the importance of good inventories of existing and developable UGS (Jim 2004; Schäffler and Swilling 2013). But these UGS inventories are difficult to encompass all possibilities on the one hand and confusing in terms of typology on the other. For example, the GREEN SURGE report classifies parks by scale, but rooftop gardens by surface type (Rall et al. 2015). These green spaces can appear in cities at multiple scales or ownership, but are simply grouped together. Such a UGS inventory does not effectively provide information on the spatial factors mentioned above, thus making it difficult to handle the complexity of high-density developments. Therefore, this study is not intended to address this issue by a checklist-style UGS typology but rather to establish an inclusive framework for UGS inventory through the underlying spatial factors.

As shown in Table 3 below, the study categorizes these green elements according to three dimensions: the relationship of the UGS to the buildings or infrastructures, the morphological characteristics, and the land use characteristics. These three dimensions can basically cover the way UGS typologies are categorized in different UGS inventories. Morphological characteristics are the most commonly used and are often employed to categorize the various parks and streetside greenery. This study considers them to represent the basic spatial factors of UGS. Land-use characteristics indicate the way in which residents use these green spaces (for public or private use), which is crucial for recreational activities. The spatial relationship between UGS and buildings or infrastructures is another area of interest after new UGS typologies such as rooftop gardens, have also been included in the UGS inventories. As in high-density contexts, the integration of such two elements is needed be considered to save space.

Table 3. Spatial elements for UGS design in high density urban environments.

| Relationship with buildings and infrastructures | Morphological characteristics | Land-use characteristics |
|---|---|---|
| Traditional UGS<br>UGS dependent on building or infrastructure | Scale<br>Shape | Public UGS<br>Private UGS |

**Public UGS** also includes UGS that are owned by private individuals or institutions but are open to the public, or are open to the public at certain hours.

## *Spatial principals and organizations of green elements in high density urban environments*

### *Total amount of UGS and spatial cost*

The total amount is the most basic quantitative property in UGS planning and design. It is essential for all relevant ecosystem services in high-density urban environments. A greater total green area and green area percentage mean more vegetation in urban areas to enhance the capacity of air purification (Cook-Patton and Bauerle 2012), lesser sealed surface to enhance resilience in extreme climates (Yao et al. 2015), more shading coverage and more vegetation for evaporation (Ng et al. 2012), and more habitats for urban species (Alvey 2006). On the other hand, green area per capita is a more critical indicator for recreation services, which reflects the UGS provisioning for residents in a high-density context. Therefore, many studies use this indicator to assess the general quality of recreation services (e.g., studies from WHO (2010) and Dagmar Haase et al. (2012)).

However, the lack of UGS provision in high-density urban environments is an unavoidable reality (Ng et al. 2012). It was mentioned above that spatial costs are an unavoidable topic for any developments in high-density contexts, and that the UGS design cannot simply focus on providing a massive amount of green area, but should also consider how to save space whilst providing enough greenery. In such contexts, UGS design needs to fully consider the possibility of integrating green elements with other buildings or infrastructures to increase the green area (Haaland and van den Bosch 2015). In addition, spatial elements such as quality, equality, and accessibility of UGS are more important factors in this case (Byrne and Sipe 2010; Jim 2004).

### *Morphology, size and shape of UGS in high density urban environments*

On a landscape scale, the morphology of UGS can be defined by two dimensions in landscape metrics: dispersion and diversity (see Figure 2). Generally, it represents the two spatial forms of aggregation and fragmentation. A more aggregated morphology means larger patches, which can accommodate more urban species (Alvey 2006) or facilitate more recreational activities (Coles and Bussey 2000). Therefore, some studies suggest that this is a more efficient UGS layout (Dramstad, Olson, and Forman 1996). However, more fragmented morphologies can benefit some ESs on a broader range of urban spaces with less spatial cost. It can be proven that clusters of small UGS are equally attractive for recreation as large urban parks (Burgess, Harrison, and Limb 1988) and can significantly increase the possibilities of seeing green elements (Xiao and Min 2015). In this case, the fragmented morphology with higher diversity is a way of combining for searching synergies. Moreover, such layout can also enhance the ESs of microclimate regulation

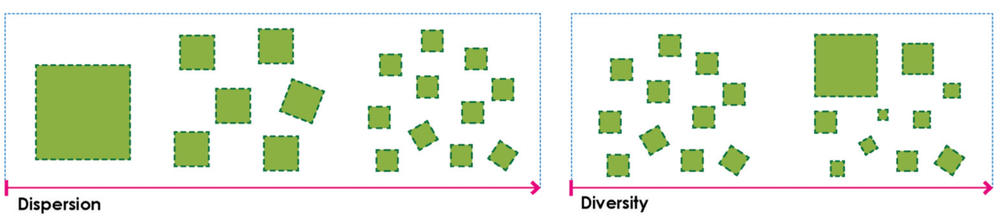


Figure 2. The two dimensions of the UGS morphology on the landscape scale.

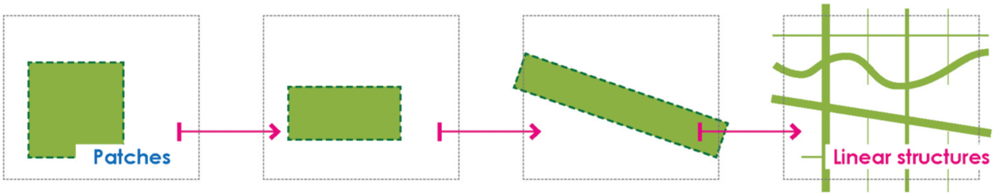


Figure 3. The shape of UGS on the local scale.

(Lin and Lin 2016) and runoff mitigation (Yang and Lee 2021). Therefore, more emphasis should be placed on the benefits of fragmented morphology in high-density contexts and the possibility of more diverse layout.

On the local scale, the shape of UGS is diverse, ranging from patches to linear structures (Figure 3). Green patches can usually accommodate more urban species and recreational facilities (e.g., football courts and large lawn areas) than linear UGS. However, linear UGS can provide services for more urban spaces in the same area because it has a longer perimeter. In addition, a linear UGS can serve as a corridor, constituting an essential element in connecting the UGS to a network. Therefore, the value of linear green elements cannot be ignored in high-density contexts.

### *The importance of distance, connectivity, and accessibility*

The distance of UGS has two dimensions (see Figure 4): the distance between UGSs and the catchment area (distance for providing services). The distance between the green elements is a crucial spatial factor for their biological value. Some studies suggested that 100-500 m is the appropriate distance for the movement of urban species (Hüse et al. 2016). In addition, it is also important for local climate regulation. Evidence shows that the cooling effect of green areas will lessen with increased distance (Zhang et al. 2009). On the other hand, the catchment area is a quantitative factor that is crucial to the recreation value of UGS. Residents' recreational needs can be very different for various types of UGS. Such different demands for recreational activities often determine the amount of time users are willing to dedicate in parks, which in turn determines the commuting time they are comfortable spending towards the parks. Then, these different commuting times can be translated spatially into effective service distances for UGSs, with smaller UGSs typically 200-400 m and larger parks can reach 1600–2000 m.

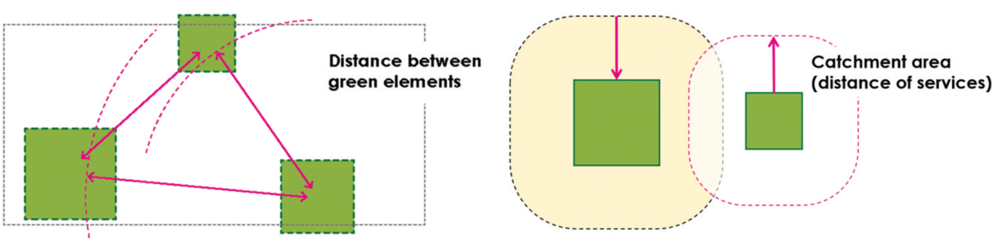


Figure 4. The two dimensions of distance.

As mentioned above, a more fragmented UGS system morphology is often more practical and effective in high-density urban environments. In this case, UGS connectivity is crucial to constructing the network system. In addition to distance, the physical connection between UGSs is another decisive factor, which usually refers to corridor connections, an essential element for low-mobility species (Bennett 1999). It also reflects the value of linear UGS in high-density contexts. On the other hand, well-connected UGSs with more transport infrastructure means residents can use it more efficiently. In this case, accessibility is an important qualitative property of UGS design. Nevertheless, in addition to distance and connectivity, UGS land-use characteristics are also crucial for accessibility. For example, some private or semi-private UGSs do not serve all residents, even if they are easily accessible. Another noteworthy aspect is accessibility in the vertical dimension. Roof gardens on top of high-rise buildings are often more difficult for nearby residents to access than lower ones (e.g., on the second floor), even if they have a good location and are completely public.

### *The proper location of UGS in high-density contexts*

The location of the UGS describes the spatial relationship between the UGS and other elements in a high-density context, mainly containing two aspects. The first is the relationship between the UGS and other infrastructures or elements. As mentioned above, large scale UGS should be closely linked to public transport nodes (e.g., metro stations) to enhance accessibility. Placing a UGS along a primary road in the form of streetside greenery or boulevards will maximize its ability to absorb pollutants and noise, as roads are often the most important sources of pollution and noise in the city (Tallis et al. 2011), (Chaparro and Terradas 2009). The other aspect is the relationship between the UGS and the natural or geographical elements. Positioning large-scale UGS upwind will help mitigate the heat island effect (Lin and Lin 2016). Combining large-scale UGS with main flooding threats (e.g., rivers and canals) and locating them downstream in the direction of runoff will facilitate their services in extreme weather (Yang and Lee 2021).

### *The quality of UGS on the local scale*

The high spatial cost in high-density contexts requires UGS to effectively provide their due services to yield profits. With the proper spatial organization, UGS still needs effective detailing on the local scale, including planting design, surface cover, and other artificial features. Denser vegetation generally results in higher quality habitats (Bräuniger et al. 2010), more efficient absorption of noise (Van Renterghem, Botteldooren, and Verheyen 2012) and pollutants (Cook-Patton and Bauerle 2012), more shading and evaporation (Armson, Stringer, and Ennos 2012), and less runoff (Armson, Stringer, and Ennos 2013). However, excessive plant densities can also negatively affect recreational activities by taking up space, obstructing sightlines, and compromising the sense of security (Zhang et al. 2013). In this case, the planting composition is the more influential factor. In addition, the type of surface of the UGS and other detailed design also significantly affect its quality. For example, UGS as a rain garden must be lower than the surrounding hard surface, allow the smooth inflow of surrounding rainwater, and have enough unsealed surface (see Figure 5) (Sadik-Khan 2012). In general, the quality of UGS is a comprehensive concept that cannot be judged solely by its density and amount of vegetation.

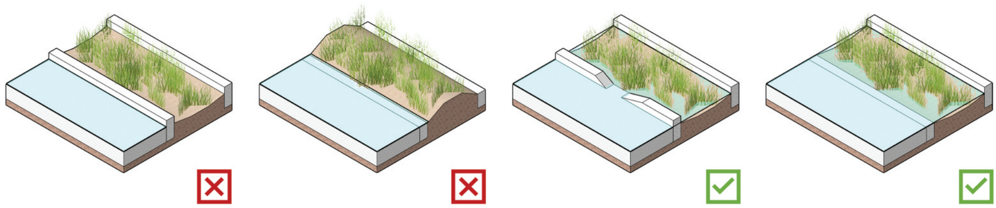

Figure 5. How detail design affects the effectiveness of bioswales.

## Contextualizing the pattern language of UGS design in high-density contexts

The building blocks described above reflect pattern language's complexity in high-density contexts. It comprise three components: the problems of UGS design in high-density contexts (relevant ESs), the green elements available in UGS design, and the design principles for different ESs. Contextualization is a process of translating these parts into practical spatial patterns and composing these spatial patterns into a diverse pattern language. It consists of the following steps.

### *Understanding the UGS inventory and spatial costs*

The UGS inventory refers to the green elements that can be used in UGS designs in high-density urban environments. Based on the UGS inventory framework mentioned above, the possible green elements that can be used to build up the UGS system are known. Two dimensions that need to be focused on first are morphological characteristics and land use characteristics, as they determine the fundamental role of the UGS in the ESs provision. As shown in Figure 6, the matrix based on these two dimensions can effectively describe all possible green elements in high-density contexts. The spatial morphology of green elements is determined by two variables: size and shape. Then, these elements can be classified into two categories in terms of land use characteristics: private or public UGS.

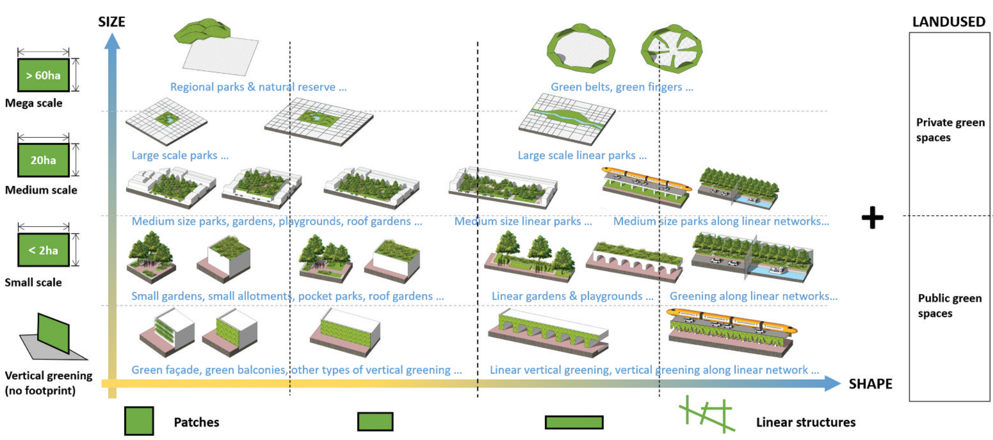


Figure 6. Spatial morphology and land-use characteristics of green elements.

The definition of the different scales of UGS can be referred to some commonly used green space standards. For example, the London Plan report considers small UGS to be less than 2 ha, 20 ha for medium scale, and 60 ha for mega scale (Greater London Authority 2016). But it is worth noting that these values are often localized; UGS design needs to be considered in the specific context.

On the other hand, the importance of spatial cost is the most significant difference between UGS planning and design in high-density and general contexts. However, the existing UGS inventory lacks a dimension to evaluate the spatial costs. Therefore, classifying green elements by spatial costs is necessary to optimize the use of limited land resources. In this case, UGS can be divided into three types. Among them, the first and second approaches can be collectively referred to as limited-footprint approaches because they do not occupy additional land resources or can provide services for a larger area with a smaller footprint. Taking this as a starting point in the case of limited space can create possibilities for more UGS and other infrastructures.

#### *No footprint approaches*

This type of UGS is often combined with buildings or infrastructure in high-density urban environments, as the UGS itself does not occupy any additional urban space (e.g., green façade, green roofs). Or the space above or underneath the UGS could still be used for the development of other projects.

#### *Moderate footprint approaches*

This type of UGS needs to occupy a certain amount of urban space, but these spaces are often small or fragmented and are easily realized in the existing high-density urban environment. These UGSs are usually small in size (e.g., pocket parks, community parks), or can cover a large area of urban space with low spatial cost (e.g., street side greenery).

#### *Large footprint approaches*

This type of UGS often takes up a lot of urban space, and these spaces are often continuous and concentrated (e.g., municipal parks, local parks). This means that these UGSs are impossible or require extremely high spatial costs to achieve in high-density cities.

### *Contextualizing spatial patterns across multi-scales and multi-dimensions*

The pattern language needs to be composed of some basic spatial patterns according to the corresponding design principles. These spatial patterns should provide core solutions to the problems in high-density contexts at multiple scales and dimensions. The process of contextualization can start at the landscape-scale. The various green elements of the UGS inventory described above can be combined to form a variety of spatial layouts. In this case, for each relevant ESs, a specific spatial layout optimizes their provisioning. By integrating and translating the design principles for UGS morphology and distribution in Section 2.3 into spatial patterns according to the different ESs perspectives, several UGS layouts could be derived, as shown in Figure 7. As an example, a decentralized and diverse UGS system intended for cooling effects requires both widely distributed small UGSs and a few large UGSs.

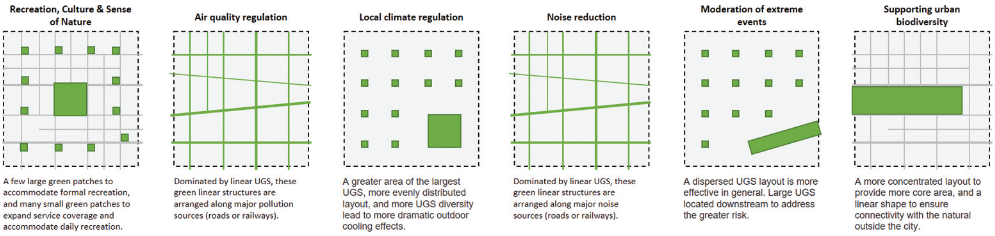


**Figure 7.** The optimal UGS layout for each relevant ESs.

However, UGS design needs to seek a balanced provision of such relevant ESs to cope with the various urban problems of high-density developments, and therefore, these UGS layouts cannot be directly applied. In this case, a framework needs to be built to evaluate the quality of ESs provision in different UGS layouts based on the spatial factors that are important in them. For UGS layouts, three of the spatial factors elaborated in Section 2.3.2 (morphology, size, and shape) determine their fundamental patterns. Based on these spatial factors, a matrix of two variables (shape and dispersion) can be applied to describe the underlying spatial layouts of the UGS system in urban environments (see Figure 8). Layouts with a low degree of dispersion tend to be composed of large UGSs, while those with a high degree of dispersion are dominated by small UGSs. The diversity of the UGS system, on the other hand, depends on the combination of the different layouts in this matrix. Within the matrix, the ESs provision of diverse UGS layouts can be evaluated based on the design principles elaborated in Section 2.3.2.

With an understanding of the UGS layout, it is possible to combine these patterns by referring to the optimized UGS layout above to balance the supply of diverse ESs in high-density contexts (Figure 9). Notably, this combination is diverse and flexible, with different ESs qualities and spatial costs, offering a viable alternative to design practice. Of course, the optimal spatial pattern as the 'perfect answer' to a particular need can only be achieved if there is enough space, meaning that it is often necessary to make 'smart sacrifices' in high-density contexts.

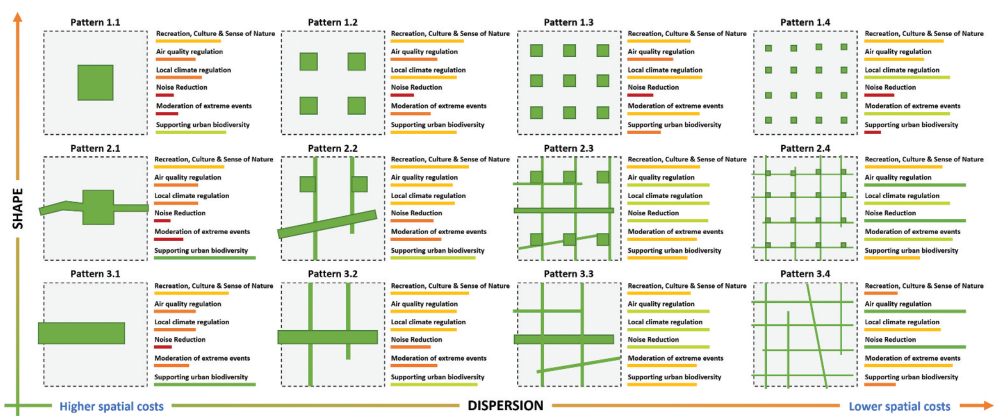


**Figure 8.** The diverse spatial patterns of UGS layout and their ESs quality.

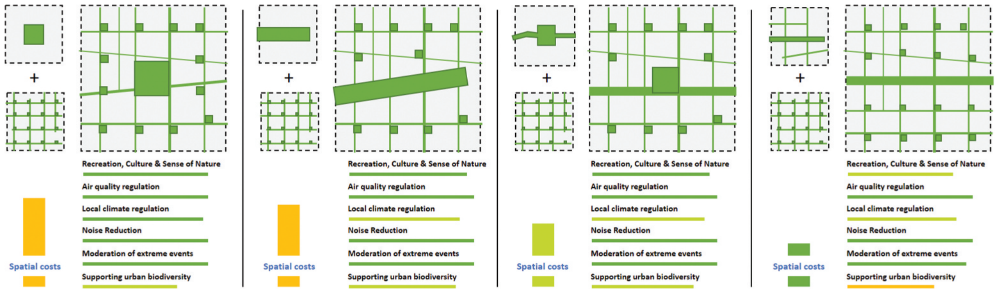


Figure 9. Optimal layout pattern and alternatives with their corresponding ESS quality and spatial costs.

In addition, the spatial factors involved in the previous Sections 2.3.3 and 2.3.4 (location, distance, connectivity, and accessibility), are also essential for UGS layouts. Based on the design principles mentioned above, the optimal UGS spatial organization pattern for each relevant ESs can also be derived. Figure 10 illustrates these optimal spatial patterns based on one of the spatial patterns in Figure 9. These patterns can be overlaid to contextualize a combined pattern, which complements the missing information (e.g., distribution, location, distance) in the layout patterns above to determine the skeleton of the UGS system in high-density contexts.

As mentioned above, the overall quality of the UGS system is determined by the units' quality. On the other hand, many of the green elements in the UGS inventory can be placed in the same position in the spatial morphology matrix. Thus the pattern language should also be multi-scale, which requires diverse possibilities on the local scale and attention to the individual quality and spatial cost of UGS. In this case, deconstructing these green elements into a set of patterns based on different variables is an effective way of creating more possibilities and identifying their quality. Several aspects critical to ESs provision on a local scale are described in Section 2.3.5: plantings and surface types, patterns of use and facilities, and detailed design. Using them as variables in the evaluation matrix on the local scale is a valid approach (see Figure 11). 'Surface cover' encompasses plantings and surface types in the UGS with higher naturalness, meaning denser plantings and more permeable surfaces. 'Functionality' summarizes the patterns of use by residents and the facilities available within them; for example, more formal recreational activities often require specific sports facilities, which do not allow for more vegetation. Furthermore, in high-density contexts, UGS design must take into account the spatial

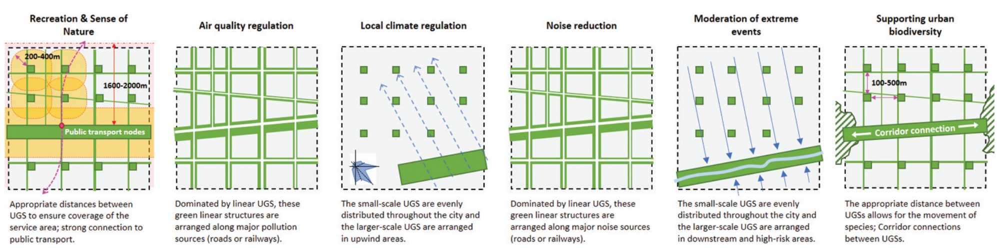


Figure 10. The optimal UGS distribution and location for each relevant ESs.

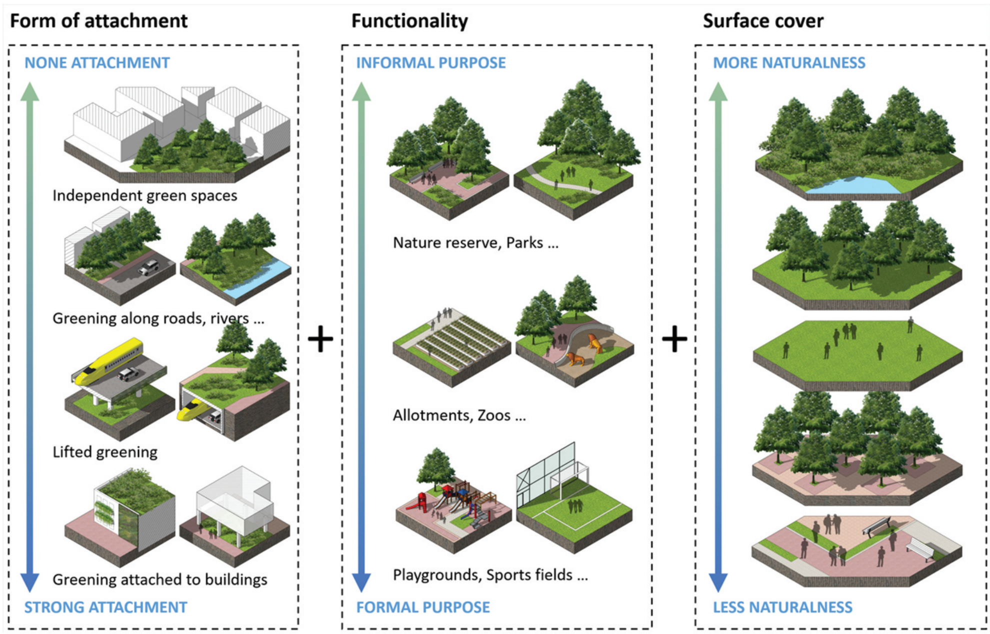


Figure 11. Multiple patterns of UGS on the local scale.

costs. So, in addition to such two variables, 'Form of attachment' is also a key factor that represents the spatial relationship between the UGS and the buildings or infrastructures (whether or not the UGS occupies footprints). As detailed design is based on these three variables and determines the effectiveness of the UGS pattern in delivering the relevant ESs, this factor will be considered after this framework.

The combination of these three dimensions of spatial patterns determines the essential characteristics of the UGS at the local scale. However, other dimensions of UGS design can also significantly impact the quality of ecosystem services, such as roof gardens' height, planting design, facility types, etc. Therefore the design principles of each relevant ES in terms of detail design should also be translated into spatial patterns. At this point, there is a set of spatial patterns covering different scales and disciplines, which will be the 'dictionary' of UGS design in a high-density context.

## *Looking for smart combination of spatial patterns in high-density contexts*

The above spatial patterns can be combined to create a variety of pattern languages. In high-density developments, different combinations imply different ESs qualities and spatial costs. It means a method by which efficient languages can be found is needed.

### *The linear order of a pattern language*

Pattern language is a systematic design toolbox with multiple scales and dimensions. In this case, 'order' is essential to the pattern language, which is presented as a straight, linear sequence. Each pattern is connected to certain 'larger' patterns that come above it in the language and to certain 'smaller' patterns that come below it in the language

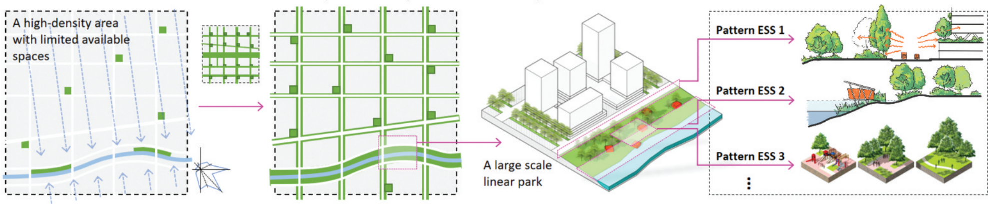


**Figure 12.** The linear structure of contextualizing a pattern language.

(Alexander 1977). This means that each spatial pattern cannot function independently; they need to be considered in a broader context. Following the above order, this study begin to contextualize spatial patterns in a larger dimension. Other smaller spatial patterns are then integrated according to the characteristics and roles of each of these green elements. Figure 12 below shows how this order works. At first, depending on the characteristics of the high-density area and the geographical information, an appropriate and practical layout pattern is assigned. Then, suitable spatial patterns are selected for each green element on a local scale according to their role (ESs provisioning).

### *The diverse possibilities of pattern combinations*

A pattern language in high-density contexts has two premises: more diverse and flexible pattern combinations and grammatical rules for combining these spatial patterns into valid languages. Firstly, the linear order does not imply a solid decision-making approach. The diverse and flexible combination of spatial patterns can create more decision-making possibilities for UGS design, which is crucial in high-density contexts with many constraints and limited space. As shown in Figure 13, pattern language can generate diverse possibilities, from the green system strategy to the spatial patterns of UGS on the local scale. In this case, the larger pattern in the linear order does not determine the choice of smaller patterns but allows for the creation of different pattern languages through

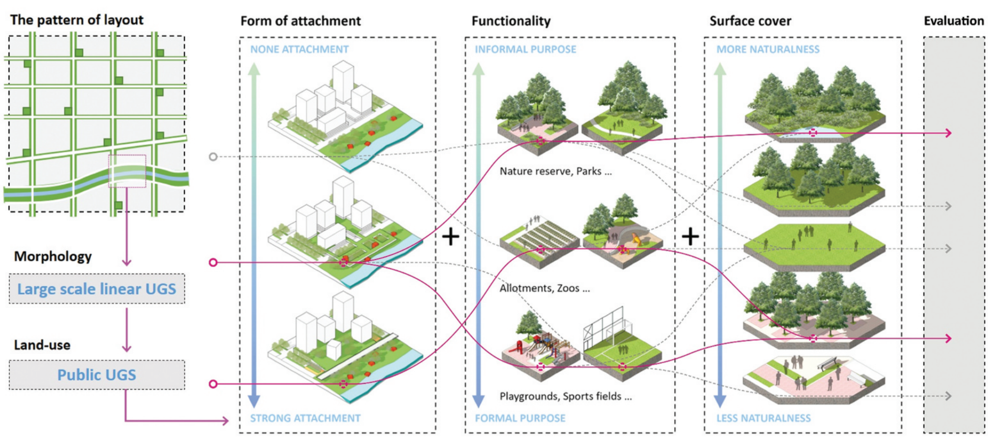


**Figure 13.** The diverse combinations and decision paths of spatial patterns on the local scale.

multiple paths. On this basis, the spatial principles of relevant ESs are the benchmarks for evaluating the efficiency and feasibility of these various combinations. Combined spatial patterns endow UGS with specific spatial characteristics reflected in ESs quality and spatial costs.

## *Exploring the smart alternatives and "sacrifices"*

The linear structure of pattern language shows the interrelationship of spatial patterns at different scales. This relationship is not unidirectional; smaller spatial patterns on the local scale also critically impact the UGS layout's overall quality. In this case, the process of contextualizing pattern language should be a circular, linear structure in which the selection of each smaller pattern feeds back into the larger pattern rather than a one-way order. This circular structure offers more possibilities for UGS design to cope with complex high-density environments. Figure 14 illustrates this process of exploring alternatives. The selection of smaller patterns on the local scale can create more UGS area to provide a higher quality alternative to the larger patterns.

On the other hand, combinations between spatial patterns are not only synergies but sometimes trade-offs, which often occur between spatial patterns on different dimensions. In such cases, a combination of spatial patterns may be beneficial to some ESs but detrimental to others. Figure 15 illustrates a situation where the location of a large area of UGS cannot facilitate both microclimate regulation and runoff mitigation due to geographical factors. It means that the UGS should be designed in such a way as to gauge which ES is more important. For example, in a hot and dry city where rainfall is not a significant threat, a large UGS should be placed upwind to enhance the cooling effect, but in a city with constant rain and high flood risk, a different layout should be assigned.

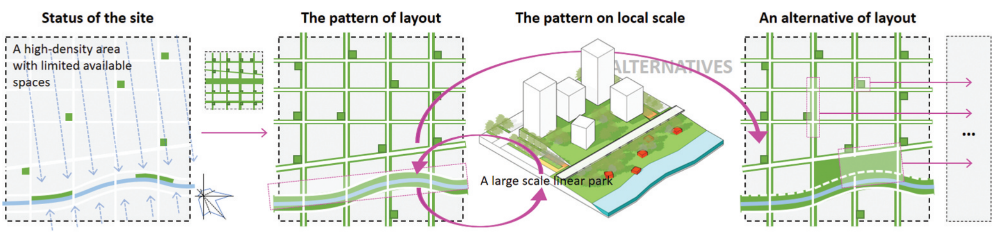


**Figure 14.** The circular linear structure of decision paths for exploring alternatives.

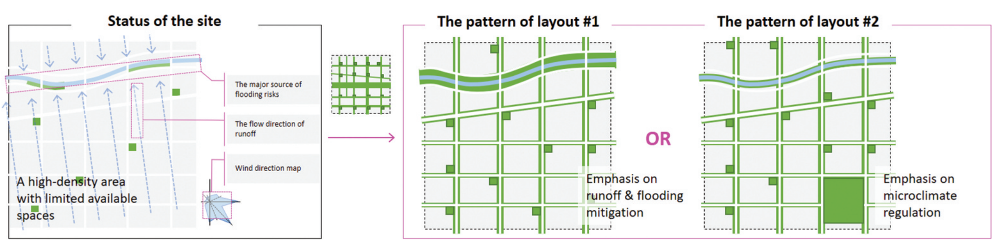


**Figure 15.** The choice of different pattern combinations in the context of trade-offs.

## Discussion – towards a systematic framework for integrating spatial design throughout the UGS development in high-density contexts

Pattern language is a design approach based on providing spatial solutions to specific problems at different scales. It implies that the process of contextualizing pattern language is also a process of performing spatial design in response to specific problems or scenarios. Therefore, how pattern language integrates the design process with UGS development is a relevant topic.

Throughout the above, pattern language continuously breaks down the complex issues of UGS design in high-density urban environments into a set of manageable problems at different scales, including the form of UGS, ownership, spatial principles, spatial costs, etc. Then, these issues are combined within a systematic framework on ESs in various ways, resulting in many decision chains across scales. In such a process, spatial design is seen as a way of knowing what works considerably to address a research question and be incorporated into the development of UGS by pattern language. In this process, conducting spatial design provides pattern language with the ability to address the challenges of inadequate supply, complexity, and consistency faced by UGS in high-density developments.

In addressing the challenge of complexity, it first provides a way to understand and process complex information within the framework of the pattern language based on spatial perspectives. The high concentration of social activity in compact cities results in a large number of unique surfaces and urban spaces being covered. The framework of ESs can be applied in the design process to help understand the spatial characteristics of these urban elements, seeking commonalities in them, and the relationship to ESs provisioning. It provides the basis for UGS designs that can be embedded into complex urban spaces or integrated with diverse buildings and infrastructures. In addition, spatial design is also a process of transforming qualitative and quantitative indicators into spatial language. This is essential for dealing with the complex spatial principles of different ESs provisions, as it can help to understand the synergies and trade-offs between these spatial patterns.

Contextualizing pattern language is a way to create possibilities of combinations through the spatial design process. The diverse urban elements of high-density development and the spatial principles associated with ESs quality are combined in a framework provided by pattern language to form a diverse chain of cross-scale decisions. In this process, urban parks may appear on roofs, at street level of buildings, or under highways, and they may be covered by dense forests or provide public farmland for residents. The process of spatial design expands the possibilities of UGS in high-density contexts, helping us to make more efficient use of limited urban space. Then, pattern language provides an evaluation framework based on ESs provisioning. Spatial design is applied, where different possibilities are systematically considered (based on site conditions and the quality of multiple ESs provisioning) in search of reasonable and feasible combinations or decision chains. This process makes spatial design a connector of spatial patterns at different scales, and the evaluation framework brings consistency to the UGS system.

Pattern language is a way to use design exploration to identify the effectiveness and efficiency of design principles. Pattern language has the potential to serve as a tool for integrating opinions from designers, users, stakeholders, and related agencies. Their voices can be translated into spatial language within this framework, and spatial solutions can be proposed accordingly. For example, ecologists tend to expect denser plantings along street corridors, while developers do not want trees hiding their well-designed façade. Each of these views can be translated into specific spatial patterns within the framework. Pattern language then offers the possibility of integrating these views, dealing with conflicts and seeking alternatives (e.g., placing the more iconic façade on the side where trees are not required or using trees as part of the façade iconicity). Applying spatial models in real-world circumstances can also provide opportunities to discover the possibilities and limitations.

## Conclusion

High-density development is not just a concentration of population and traffic, but requires more sophisticated and 'smart' design. Even though almost the importance of UGS for urban sustainability is well recognized, three important issues still need to be addressed to design UGS in high-density contexts: inadequate supply, complexity, and consistency. As a design approach based on practical spatial models, pattern language brings features of spatial design process that can effectively address both of these issues to urban design, which is evidence of its effectiveness and necessity as a UGS design approach in high-density contexts. However, pattern language also has limitations. The most typical of these is that they cannot contain all the possibilities of UGS design. The complexity of various spatial variables and users' activities may produce defects. In this case, pattern language should be an open system that can be tested, adjusted, and expanded through design practices in the future.

## Disclosure statement

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