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Research on the spatial boundary design of urban underground space for the composite use of urban green space

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ABSTRACT

As urban populations grow and cities become more densely populated, the need for sustainable and liveable urban spaces has become increasingly important. Urban green space, known as the "lung of the city," plays a critical role in shaping the ecological environment of cities and enhancing the quality of life for urban residents. However, the limited availability of aboveground space has prompted a growing interest in integrating urban green space with underground space, offering a solution for more sustainable and liveable urban environments. The spatial boundary, an essential medium for exchanging material, energy and information between buildings and the natural environment, directly impacts microclimate and indoor comfort. Besides, its direct connection with nature allows renewable energy sources to provide power, which is an efficient way to minimise environmental impacts. This study seeks to identify the commonly used forms of spatial boundaries and analyse their relationship with building performance. Specifically, the research focuses on relevant prototypes of spatial boundaries in the Yangtze River Delta's most densely populated cities (over 1,000 persons per sq. km), including Shanghai, Wuxi, Nanjing, and Suzhou. By examining spatial boundaries in selected cases, the study explores their impact on building performance and summarises the frequently used forms of spatial boundaries, highlighting their role in regulating building performance. The findings offer valuable insights for constructing modern urban green space systems and contribute to the advancement of three-dimensional urban planning, ultimately aiding in the creation of sustainable and liveable urban spaces and fostering a better understanding of the benefits of integrating underground space with urban green space.

1. Introduction

Urban Green Space (UGS), as an indispensable element of urban quality of life [1], provides a range of ecological ecosystem services, including air purification, temperature regulation, noise reduction, and stormwater management [2–5]. Beyond these environmental benefits, UGS also provides aesthetic experiences and diverse recreational opportunities for urban residents [6,7]. However, the rapid pace of urbanisation presents significant challenges for maintaining these green spaces. Increasing population density, scarcity of land resources, traffic congestion, challenging parking, massive energy usage, and severe environmental pollution are pressing issues confronting contemporary cities, making it increasingly challenging to ensure sustainability and equitable accessibility to UGS. As urbanisation continues, with the world's population lived in cities from 30% in 1950 to 56% in 2021 and predicted to exceed 68 % by 2050 [8], it is crucial to explore innovative solutions that can mitigate the negative impacts of urbanisation.

In this context, one promising solution is the compound use of UGS, which involves integrating Urban Underground Space (UUS) beneath the UGS. This approach can restore the natural landscape and ecology, thus protecting cultural and historical values above ground [9–12]. Besides, it can accommodate one-third of the urban functional space, including traffic, commercial or office, and municipal function space [13], which can aid in enhancing urban capacity and resolving urbanisation concerns such as traffic pressure, low land-use efficiency, and a poor ecological environment, ultimately meeting the growing living needs of urban residents.

Despite the potential of combining UGS and UUS to contribute to low-carbon cities, many sustainability issues remain. Compared with the ground space, UUS, surrounded by soil and rocks, is somewhat sealed off from the atmosphere, thus hindering underground buildings' ventilation and natural lighting. As a result, UUS often relies on an equipment-oriented active system to maintain a pleasant environment and to blur the boundary between the ground and underground space, which can lead to high energy consumption. Wu and Ji [15] measured the energy usage of the urban underground street in Xuzhou, China and concluded that lighting and ventilation consume 45% and 44% of energy, respectively, accounting for nearly 90% of total energy consumption, indicating there is still a gap in the existing research on underground space utilisation and the considerable potential for energy savings, especially in reducing the energy consumption for ventilation and lighting.

To bridge this gap, the pursuit of maximising the prospects for the sustainable development of UUS is increasingly rooted in several policies and initiatives. These efforts are sparking discourse on the energy-saving potential of UUS and the feasibility of utilising clean underground energy. Therefore, research on UUS is increasingly focusing on integrating energy-saving strategies as well as clean underground energy and building performance, alongside examining their interactions. Sustainable design is also an essential contributor to sustainable development [16]. Notably, over 40% of the energy-saving capacities come from the earlier planning stage [17], which stimulated a plethora of studies on the relationship between building performance and design consideration. Spatial boundary, a critical aspect of sustainable design, serves as a vital medium for exchanging material, energy, and information between buildings and the natural environment. It also has the most direct impact on microclimates and indoor comfort. Besides, its direct connection with nature allows for the utilisation of renewable energy sources to provide power, which is an efficient way to minimise environmental impacts.

This work seeks to identify the most commonly used form of spatial boundaries in current practice and to analyse their associations with building performance. There are several reasons why such a study is both essential and timely. First, architecture resides at the heart of the troubled relationship with energy [18]. In the effort to save energy, the first conventional response is often to improve the energy efficiency of equipment-orient active systems, such as mechanical and electrical systems. However, more substantial reductions in energy use can be achieved by reducing loads with passive strategies before improving system efficiency [19]. Besides, while the vital role played by the spatial boundary in building performance has been widely discussed, it has not been systemically studied, particularly in the context of UUS and UGS. The existing concepts, principles and technologies of environmental quality and energy efficiency management in ground space cannot be directly applied to UUS [13]. This study provides researchers and practitioners with an up-to-date understanding of the low-carbon design for UUS and the critical messages about difficulties and opportunities associated with its contribution to global sustainable development. This work aims to answer the following questions:

- What are the frequent spatial boundaries used in current practice and their role in building performance?
- How should decision-makers prioritise complex challenges to mitigate current sustainable issues?

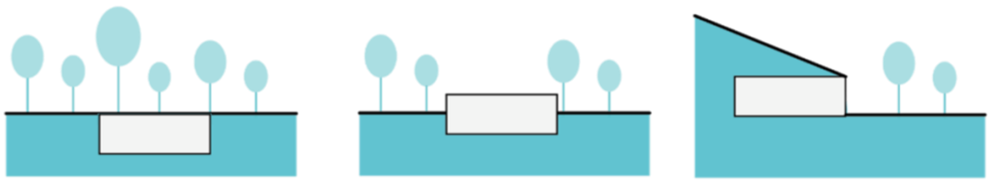
2. Methodology

This study seeks to collect and analyse relevant prototypes of spatial boundaries based on a set of precisely defined criteria to comprehend the development and present status of spatial boundaries. The study was conducted in the most densely populated cities (over 1,000 persons per sq. km) in the Yangtze River Delta, including Shanghai, Wuxi, Nanjing, and Suzhou (Table 1). The high population density makes these cities particularly vulnerable to urbanisation issues, thus exploring using UUS as an alternative means to accommodate inhabitants.

Table 1: The most densely populated cities in the Yangtze River Delta

City	Population (City proper)	Area (sq. km)	Population density (person/sq.km)
Shanghai	24,894,300	6,340.5	3926
Wuxi	7,479,500	4,650	1608
Suzhou	12,847,800	8,657.32	1484
Nanjing	9,423,400	6,587.02	1431
Jiaxing	5,516,000	3,915	1409
Changzhou	5,349,600	4,372	1224

Based on the relationship between structure and ground surface, the UUS for the composite use of UGS can be divided into three different types (Figure 1). Still, only the one whose structure is located totally under a sloped area (Figure 1-c) was excluded from the analysis, as the Yangtze River Delta is characterised by a plain river network, making this type less applicable. The spatial boundaries in each selected case were identified and analysed to understand their associations with building performance. Then, the frequently used forms of spatial boundary and their role in regulating building performance were summarised.



a. Located totally underground
b. Building having some floors above ground and some floors underground
c. Located under a sloped area

Fig 1: The classification of UUS for the composite use of UGS

3. Results

The present study included 21 related cases to collect the detailed forms of spatial boundaries. The frequent-use forms of spatial boundary and their role in regulating building performance are summarised below.

3.1 Vertical Spatial Boundary

3.1.1 Courtyard

The courtyard is one of the primary forms of architectural space, offering significant benefits for enhancing spatial quality, improving indoor environmental comfort, and reducing energy consumption. In summer, the shading effect of the courtyard space can limit the exposure of the inner surfaces of the east and west walls to direct sunlight, thereby effectively reducing the heat absorption by the structure. At the same time, courtyards provide the opportunity for natural ventilation, which effectively improves indoor air quality and thermal comfort, thus reducing the reliance on air-conditioning and leading to energy savings. In winter, courtyards make full use of solar radiation to warm space, minimising heat loss and lowering heating energy consumption. Moreover, courtyards allow natural light to penetrate indoors, thus reducing the usage of artificial lighting and further conserving energy. Beyond their functional benefits, courtyards serve as private outdoor spaces where people can rest and engage in recreational activities, fostering a deeper connection between people and nature as well as among individuals within the community.

Unlike the atrium (Tianjin) found in southern China dwellings, which primarily serve as passageways for lighting and ventilation, the courtyard discussed in this study is designed for occupants' activities. These courtyards, which can be either outdoor or semi-outdoor, maintain a direct connection with natural light and air, enhancing their utility and comfort. In the context of UUS, courtyards are typically categorised into sunken plazas and sunken courtyards.

A sunken plaza is to "sink" part of the ground space under the natural ground and integrate it with the UUS to form a multi-level space. This design approach effectively changes the character of the underground space, creating a relatively diverse spatial experience, such as positive or negative, bright or dark, noisy or quiet, closed or open. In addition, its surrounding underground buildings can often face the sunken plaza, utilising large light-reflecting glass doors, windows or transparent colonnades to bring in natural light and winds, effectively blurring the boundaries between the aboveground and underground space and weakening the psychological impact of transitioning to a subterranean space.

Traditional sunken courtyards can be traced back to countries such as China, Iran, and Turkey. For example, the sunken vernacular courtyard of Matmata, Tunisia, represents some of the earliest known subsurface structures. It was designed according to inhabitants' needs, local environment, and material availability to shield residents from the intense daytime heat and the chilly nights, particularly prevalent in this desert region [20]. As an essential feature in underground architecture, sunken courtyards offer the most convenient way for underground buildings to obtain natural light and natural ventilation, contributing to a reduction in energy consumption by about 25-35% [21]. They significantly enhance the comfort of underground structures by breaking the enclosed feeling of the underground environment and establishing a solid connection with the natural environment and indoor space. In addition, the integration of appropriate soil and plant mixes in the courtyard can provide varying amounts of sunlight or shade throughout the year, enhancing air humidity and making indoor space more comfortable.

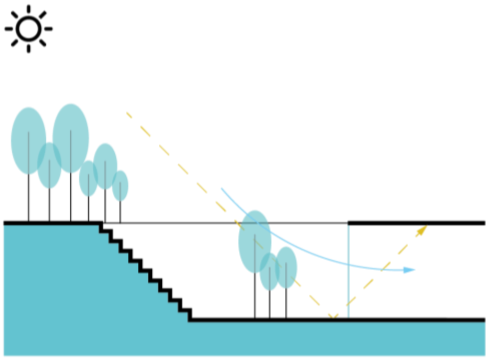


Fig 2: Sunken plaza

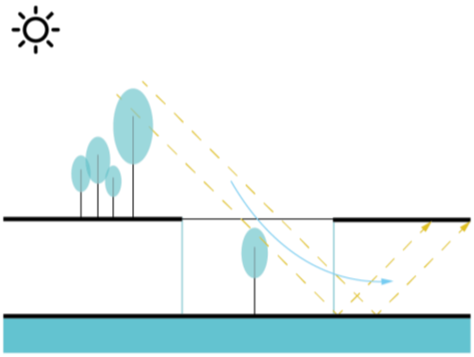


Fig 3: Sunken courtyard

3.1.2 Underground Atrium

The atrium, which originated from the central courtyard in the age of Rome, has evolved from a covered veranda to a covered courtyard within or between buildings, as defined by the Royal Geographical Society. These definitions reflect the development and evolution of the atrium over time. Today, an atrium is usually defined as a shared courtyard space within a covered building.

With the development of UUS and UUS, underground atriums become indispensable in regulating the environment within UUS, particularly in addressing insulation and ventilation issues. A large lighting dome at the top of the atrium, composed of various spatial grids and light-reflecting glass surfaces, allows natural lighting to enter while avoiding communication with the ground surface, effectively mitigating climatic influences. Besides, the openings of the underground atrium can be used as exhaust vents, which helps to improve the overall wind speed inside the building and promotes the underground space's natural ventilation. In some designs, combining two atria can further enhance natural ventilation within underground space. In such cases, the windward side opening of one atrium acts as an air inlet, while the leeward side opening of the other atrium acts as the building's exhaust, which introduces natural wind into the underground space. The rational design of the wind path guides the flow of wind, which helps to improve the air quality and environment of the underground space. In general, as a new architectural design concept, the underground atrium has a vital role in enhancing the indoor environment of underground buildings, making them more comfortable and energy efficient.

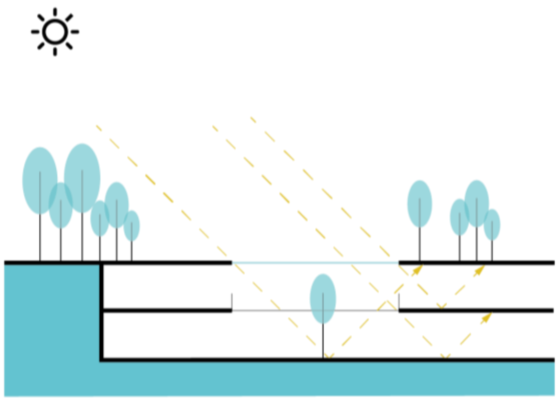


Fig 4: Underground atrium

3.1.3 Shaft Space

Unlike atriums, which are indoor spaces, shaft space functions as a direct pipeline connecting the building's interior with the exterior environment. These spaces play a vital role in reducing energy consumption by adapting to different climatic environments, such as using the chimney effect to promote ventilation and cooling in hot and humid climates or providing natural lighting while preventing wind and sand intrusion in cold regions.

Shaft spaces can be categorised into vertical or horizontal in terms of structural form. Vertical shaft spaces are the most common, and horizontal shafts include tunnel winds and other forms. Each of these designs aims to create a comfortable indoor environment by leveraging natural forces.

One of the earliest examples of shaft space is the wind tower, also known as the wind-catching tower, which is an ancient passive ventilation and cooling technology that originated from Islamic architecture in the Middle East more than 2,000 years ago. Wind towers utilise the combined effects of wind and heat pressure through longitudinal ventilation chambers to introduce air from above ground into the room, creating an indoor air flow that cools the building. Over time, various types of wind towers have been developed, including lighting wind towers and evaporative cooling towers. These structures can also be combined with modern technologies, such as solar photovoltaic cells or even light conduits, which can simultaneously provide ventilation and light functions to meet the energy-saving requirements of green buildings.

Light wells are another type of shaft space, designed as well-shaped light openings surrounded by retaining walls that allow natural light to enter underground space. When the building cannot light the indoor space, light wells can provide an essential solution, improving the overall quality of the indoor environment.

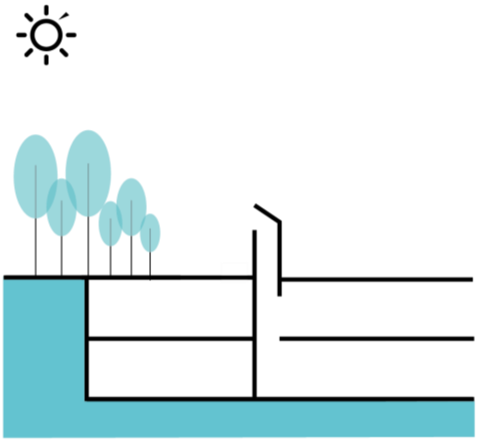


Fig 5: Wind tower

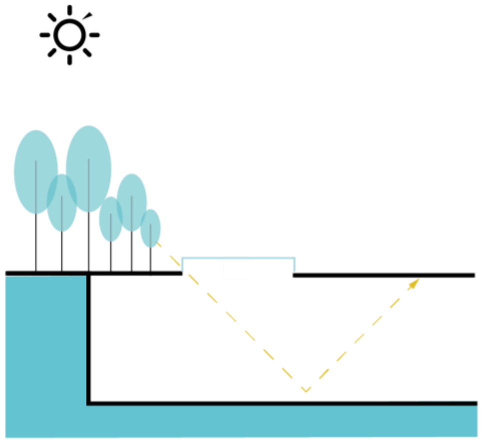


Fig 6: Light well

Solar chimneys are a more advanced form of shaft space designed to enhance the chimney effect. Typically constructed with one or more transparent chambers made of glass, Solar chimneys can utilise solar radiation to increase the temperature difference between the inside and outside of the chimney. This temperature difference creates buoyancy and thermal pressure, promoting airflow between indoor and outdoor spaces.

Another form of shaft space is the wind tunnel, which uses buried pipes as ventilation ducts, a common technique for leveraging shallow geothermal heat. In summer, outdoor air cools as it passes through these duct walls, providing sufficient cool and fresh air. In addition, wind tunnels also have the potential for humidity regulation in most climates other than dry areas because in-ground air cooling can involve a process of moisture reduction. In winter, when the outdoor air temperature is much lower than that of the layer in which the tunnels are located, the tunnel warm outdoor air as it passes through the soil, which helps to improve the thermal environment and air quality, and at the same time reduces the load on heating systems, thereby contributing to energy saving and environmental protection.

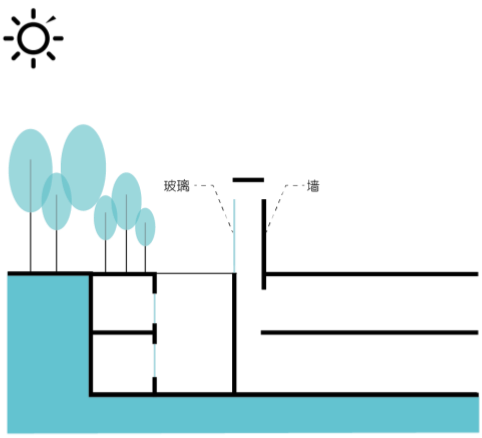


Fig 7: Solar chimney

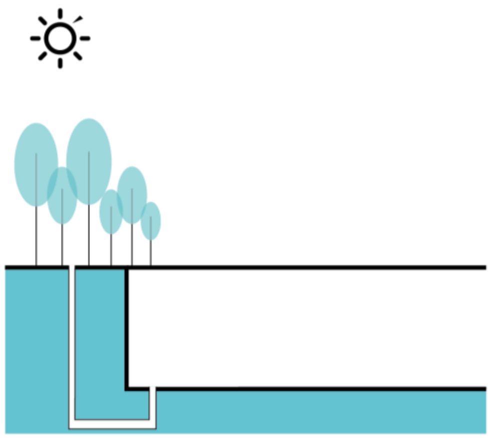


Fig 8: Wind tunnel

3.2 Planar Spatial Boundary

3.2.1 Roof

The roof is the spatial boundary at the top of the building, which needs to meet basic structural requirements such as waterproofing, windproofing, and heat insulation. Additionally, roofs are the primary platform for incorporating energy-saving technologies, harnessing natural resources like solar and wind energy to improve the indoor microclimate and realise the purpose of saving energy. One key method is the use of skylights, which are positioned at the top of the underground space to bring in natural light. At the same time, the chimney effect is created through the rise of hot air to promote natural ventilation. Some skylights are also designed to connect with small plazas, courtyards, gardens, and other outdoor open spaces, ensuring that sufficient light reaches the underground area while keeping the ground space open. This design not only brings light into underground spaces but also integrates aboveground views, enriching the visual and spatial experience within UUS.

Another vital roof design is the double-glazed roof, which features a climate-regulating buffer space between the inner and outer layers of glass. Fresh air enters the chamber through natural ventilation, absorbs heat from solar radiation, and then circulates into the building, improving indoor thermal conditions and air quality. The double-layer glass also has light transmittance, which introduces natural lighting and allows the building to gain heat directly, reducing the need for artificial heating in winter and lowering overall energy consumption.

3.2.2 Façade

Façade directly affects the effect of building energy saving since it can introduce not only natural light and ventilation but also serve as a receiver for the most natural resources such as solar energy and wind energy. One common approach is the installation of side windows, which are openings on the exterior wall above or along the basement wall that connect with the ground. High-side windows, an evolution of side windows, enhance air circulation, although they limit visibility and create a more enclosed feeling.

Double-glazed curtain walls, another advanced façade design, consist of two glass layers, forming a cavity buffer space. There are openings on the inner and outer surfaces of the cavity to allow air to circulate within the buffer space. Under the greenhouse effect, the air temperature inside the cavity rises and generates thermal pressure, and the hot airflow rises into the interior of the building, providing warm, fresh air for the indoor space. This system also brings in natural light and reduces the room's heat loss and the need for heating equipment in winter, contributing to energy conservation and improving the building's overall energy efficiency.

4. Conclusions

This study makes a timely and valuable contribution to advancing the understanding of the low-carbon design of UUS in the context of sustainability and the recent wave of urbanisation. By summarising the design considerations and analysing the role of spatial boundaries in regulating the indoor environment, the research offers insights that are particularly relevant as the urban population is projected to increase by 68% by 2050. The focus on spatial boundaries in this study highlights their significance in guiding future urban planning and architectural practices, particularly in high-density contexts like the Yangtze River Delta.

However, the limitation of the study lies in its regional focus, which primarily focuses on the Yangtze River Delta. While this region is representative of high-density urban areas in Mainland China, the findings may not be directly applicable to other regions with different climatic, cultural, and socio-economic conditions. Despite these limitations, the study's implications are profound. From an urban planning and architecture perspective, this study underscores the need for a longer-term research agenda that integrates performance-driven spatial boundary design into building-level architectural practices. Such an approach could provide actionable strategies to achieve Sustainable Development Goals (SDGs), especially "sustainable cities and communities" (Goal 11). By aligning architectural design with sustainability objectives, this research highlights the critical role of thoughtful spatial boundary design in creating more sustainable and liveable urban environments.

Looking ahead, future studies should explore the applicability of these findings across diverse regions, assess the long-term performance of UUS, and investigate the integration of advanced technologies to optimise sustainability. Through ongoing exploration and collaboration, the compound use of UUS and UGS can play a pivotal role in shaping the sustainable cities of the future.

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