19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 8.6.74
DOI: 10.46793/ACUUS2025.8.6.74

RESEARCH ON THE PERFORMANCE-DRIVEN SPATIAL INTERFACE DESIGN FOR CLIMATE-ADAPTIVE URBAN UNDERGROUND SPACE

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Abstract: Rapid urbanisation is placing immense pressure on modern cities, with escalating issues such as increasing population density, scarcity of land resources, traffic congestion, challenging parking, massive energy usage, and severe environmental pollution[1–3]. In 1950, only 30% of the world's population lived in cities, but this number has grown to 56% in 2021 and is predicted to exceed 68 % by 2050[4]. Traditional vertical expansion, such as skyscrapers, while effective, is increasingly insufficient to addressing these challenges. Urban underground space (UUS) offers a viable alternative. By accommodating one-third of the urban functions - including traffic, commerce or office, and municipal facilities – below ground[5], UUS not only enhances urban capacity, but also contributes to restoring the natural landscape, improving ecological conditions and protecting cultural and historical values above ground.

Despite its recognition as a potential contributor to low-carbon cities by academics, UUS still faces significant sustainability challenges[6]. Unlike ground-level buildings, UUS is surrounded by soil and rocks, creating semi-sealed environment that hinders natural ventilation and lighting. This necessitates reliance on energy-intensive mechanical systems to maintain a pleasant environment. Lighting and ventilation in an underground street in Xuzhou, China, consume 45% and 44% of energy, respectively, accounting for nearly 90% of total energy consumption[7,8]. This underscores a substantial need for energy-efficient solutions, particularly in terms of reducing the energy required for ventilation and lighting.

To address these challenges, the pursuit of maximising the prospects for the sustainable development of UUS is increasingly rooted in theoretical science and architectural practice, sparking discourse on the relationship between architecture and climate. The introduction and adoption of air-conditioning in the early 1910s marked a significant shift from passive climate adaptation to active environmental control, gradually isolating buildings from their external environments. During the energy and environmental challenges of the 1970s, interest in the integration of active and passive control technologies intensified, aligning with the growing emphasis on green and ecological development. This integrated approach became a defining paradigm in the architecture–climate relationship.

Within this context, spatial interface, a key element in sustainable design, assumes a crucial function in facilitating climate adaptation mechanisms through enabling buildings to regulate the exchange of material, energy and information between buildings and the natural environment. By guiding natural ventilation and optimising lighting conditions, spatial interfaces directly influence both microclimate and indoor comfort, as well as reduce energy consumption. Natural light not only fulfils visual requirements but also positively influences psychological well-being, circadian rhythms, productivity, and emotional health. It reduces the reliance on artificial lighting, lowers heating demand in winter, and mitigates the psychological discomfort commonly associated with underground environments. Likewise, natural ventilation enhances indoor air quality, regulates temperature and humidity, and improves occupant comfort. It enables higher thermal tolerance, reducing dependence on mechanical cooling and contributing to energy conservation. Besides, spatial interfaces, due to their close interaction with natural systems, enable the incorporation of renewable energy sources to provide power, substantially reducing environmental footprint. This approach fosters a balance between the performance of natural lighting, natural ventilation, and energy usage. Considering this increased interest in UUS, as well as the importance of sustainable UUS development and the pertinent role of spatial boundary, the focus should be expanded to the spatial interface design.

Based on this premise, this study adopts a "Identification of building performance metrics - Investigation of spatial interface typologies - Implementation through empirical validation (3I)" framework to conduct a quantitative analysis of spatial interfaces from a performance-oriented perspective. This framework facilitates a more precise and holistic understanding of the influence of spatial interfaces on environmental performance.

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Key performance evaluation metrics—including daylight autonomy (DA), daylight glare probability (DGP), ventilation rate, air changes per hour (ACH), and annual energy load— are utilised to construct mathematical models that theoretically explores the intrinsic connection between the design variables, such as window-to-wall ratio, and building performance The analysis reveals the existence of optimal thresholds or selection ranges that balance natural lighting, ventilation efficiency, and energy consumption, underscoring the need for performance-based decision-making in UUS design. Furthermore, by analysing 30 relevant cases in subtropical monsoon climate zones with hot and humid summers, and cool to mild winters, the form of spatial interface was identified from the perspective of performance, and matched with the natural element such as sun, wind, soil, water and vegetation to complete the identification. This performance-oriented spatial interfaces are visualised as a spatial interface design atlas tailored to UUS in subtropical monsoon climates, offering a comprehensive framework for performance-oriented UUS design in these climatic conditions. To validate the effectiveness of the proposed design strategies, physical environmental monitoring of the Suzhou Bay underground space was conducted. This empirical data provides a practical basis for assessing the impact of the proposed design solutions on building performance. Ultimately, this research aims to shift underground space environmental regulation from "passive adaptation" to "active response". By offering systematic and practical design guidelines for low-carbon, comfortable underground environments, it provides both theoretical insights and actionable solutions for advancing sustainable UUS development.

Looking ahead, future research efforts should focus on the development of climate-specific low-carbon design guidelines that identify strategies with the greatest impact on energy conservation across diverse climatic zones In addition, an integrated design platform capable of integrated modelling, simulating, evaluating, optimising, and generating should be further developed and incorporated into the design workflow to enable rapid and accurate performance analysis, making performance-based architectural design possible. Finally, a standardised, scientific evaluation system for UUS sustainability is essential to guide industry adoption and fully realise the energy-saving potential of underground development.

Keywords: Urban underground space, Spatial interface, Building performance, Sustainable development

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