CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (3): 0033-0047
DOI: 10.59440/ceer/204090
Original Research Article

UNDERGROUND SPACES AS PART OF SUSTAINABLE URBAN DEVELOPMENT - FUNCTIONAL AND SPATIAL ANALYSIS

Inna ABRAMIUK[1], Olena OLIYNYK [2], Oleh HUBANISHCHEV[3]
[1]Department of Architecture and Urban Planning, University of Zielona Gora, Zielona Gora, Poland
[1]Department of Architecture, National Academy of Fine Arts and Architecture, Kyiv, Ukraine
[3]Architectural Design Department, National Academy of Fine Arts and Architecture, Kyiv, Ukraine

A b s t r a c t

In many countries of the world, there is a growing interest in underground construction, which is considered an effective solution for improving the efficiency of urban infrastructure and public transport. In addition, it allows the increasing of limited spaces in cities, enables the development of public spaces, and also contributes to solving air and groundwater pollution problems. In the context of the current war situation in Ukraine, there is growing interest in the adaptation of existing underground spaces, in particular those related to urban transport, for educational, cultural, commercial and tourist purposes. This article provides a spatial analysis of selected underground urban structures as an alternative solution in urban design, with a special emphasis on the integration of functions and spatial configuration in the context of sustainable development goals. A spatial analysis based in particular on Space Syntax theory was used to understand the compositional structure of the underground facilities and to identify the relationships between different spaces, including those that shape user movement patterns. Spatial analysis of selected underground objects shows that the design of spaces with cultural and educational functions in an underground context should take into account the appropriate balance between stationery and transit zones. The article also discusses the compatibility of the development of underground urban structures for cultural and educational functions with sustainable development goals, such as resource efficiency, reuse of materials and construction, reducing negative environmental impacts and improving the quality of life of people.

Keywords: urban underground spaces, spatial analysis, Space Syntax, sustainable development goals, spatial configuration

[1]Corresponding author: Inna Abramiuk, University of Zielona Góra, Faculty of Engineering and Technical Sciences, Department of Architecture and Urban Planning, Professor Szafran Street 1, 65-516 Zielona Gora,
e-mail: iabramiuk@aiu.uz.zgora.pl, phone: +48 (68) 328 23 08

1. INTRODUCTION

In many countries around the world, underground construction is regulated by engineering and construction regulations, based on balancing the interests of investors with community interests and principles of city development. The prerequisite of this legislation is the protection of rights, ensuring the safety and well-being of citizens, as well as the protection of the natural and cultural environment. In many large cities, in different countries of the world, more and more attention is paid to the intensification of the processes of using underground parts of buildings and developing underground spaces. The reasons for this process lie not only in the need to improve the efficiency of urban infrastructure and public transport, but also in connection with the rapid growth of the population in cities, the lack of available land within the administrative boundaries of cities for the creation of public spaces and recreation, and climate problems [1]. In the contemporary circumstances of the war in Ukraine, the security of the population, the need to create a well-developed system of convenient shelters for educational, communication, commercial and security functions also add to the above-mentioned list.

In Ukrainian cities such as Kyiv, Kharkiv, Lviv and Odesa, there is an increased interest in adapting existing underground public spaces for educational, cultural, commercial and tourist purposes. Since the beginning of 2023, a primary school has been operating in Kharkiv on the platforms of five metro stations, starting from the 'Universitetska' station, with classrooms located three meters underground and distributed in existing spaces formerly used for metro administration. In 2023, the Safe Education Offline initiative was launched and is currently being implemented in Zaporizhzhia and Zaporizhzhia region. In 2024, construction began on 11 such schools, two of which are already receiving students. Although concrete is the main construction material and the buildings have been equipped with modern plumbing systems and adapted to the needs of children with special requirements, the educational facilities do not take into account the principles of sustainability - they do not minimise the negative impact on the environment or the energy intensity of operation. However, the process of adapting or constructing new underground spaces is complicated by the need to adapt the spaces to modern usage requirements while preserving their historical and functional value [2]. No less importance is attached to solutions related to ecology, energy use and effective spatial planning that is safe for users when constructing underground structures. This new challenge of designing and constructing underground infrastructure with cultural and educational functions requires a combination of functionality, aesthetics and adaptation to changing environmental conditions and catastrophic climate change. More importantly, the potential of urban underground space (UUS), which can bring numerous benefits to urban areas and users of urban space, is still underestimated and underutilized [3]. The most common functions of modern urban underground spaces include storage, industry, energy generation, transport, utility supply, and to a lesser extent public or private utility spaces [4].

Urban underground space should ensure the realization of users' needs, correlate their behavioural perceptions with other public spaces in the neighbourhood and respond to sustainability issues. From the perspective of the attractiveness of UUS to the public, it is important to understand that behavioral features and benefits are intrinsically linked to the configuration of space [5]. In order to understand the configuration ofurban public space, its significance in the structure of the city and also to understand how patterns of people movement are created in this space and how its users interact, it is useful to turn to Space Syntax theory [6]. This approach allows for a detailed analysis of the related elements of the spatial configuration, taking into account the function and interconnection of underground spaces, which enables a deeper understanding of the dynamics of the development of underground architecture and its impact user behaviour.

This study focuses on identifying a spatial analysis of the underground spaces in an urban context as alternative solutions of potential urban challenges. It also highlights the need to develop subterranean spaces that can perform adaptive functions in the face of rapid climate change and provide the sustainable development goals. The article examines selected examples of the use of underground spaces in the 20th and 21st centuries, presenting good practices and successful solutions. In addition, it assesses whether the studied underground spaces are capable of providing security in the face of climatic and military threats.

2. STATE OF RESEARCH

Underground architecture and urbanism have been the subject of active interest of researchers for more than three decades and covers a wide range of issues. The priority issue is the use of underground spaces as transport systems, such as subways, energy facilities or industrial areas. This study focuses on understanding how public functions are combined with the configuration of underground spaces and their interaction with the public, as well as their compatibility with sustainability issues.

One of the topics devoted to aspects of underground spaces design is risk forecasting by conducting morphological analysis and taking into account the specifics of the geological environment and underwater areas [7]. The studies of Trigub R. [2] and Ryndiuk T. & Maksymenko M. [8] are devoted to the preservation of the historic environment through the use of underground spaces. In turn, T. Zhidkova and O. Shelkovin focused on the systemic development of the underground space of Kyiv [9].

Bobylev and his team have paid -great attention to the functions of underground spaces and their importance for people, as well as the benefits for the development of urban infrastructure [4]. This research is also closely linked with the issue of implementing sustainable development goals in the reconstruction of underground spaces. An overview of the use of underground space and an analysis of the underground urban plan in Helsinki was done by Ilkka Vähäaho [10], also presenting its role for creating a sustainable environment, maintaining the city's capacity for future generations and an aesthetically acceptable landscape. She also discussed an example of the possibility of an underground connection between Finland and Estonia [10]. The positive impact of urban underground infrastructure development also manifests itself in meeting the needs of the population [11], in reducing the rate of resource consumption [12], in reducing internal temperature fluctuations and in reducing the cost of living [13, 14].

Other scientific work is devoted to understanding the relationship of different areas of underground space to each other, the effects of space on the user and their behaviour and well-being, and the organisation of underground traffic to achieve the highest level of human-space interaction [5, 6, 15]. To date, no attempt has been made in scientific sources to analyse underground architectural facilities in terms of their compatibility with sustainable development objectives, simultaneous with an examination of the functional and spatial relationships between the different areas of these spaces. This gap is filled by this article.

3. MATERIALS AND METHODS

A meticulously designed and organized high-quality urban underground space stands out for its significant potential to support social integration processes. In order to analyze the UUS as a complex space, creating patterns of user movement and movement behavior, as well as to understand the mechanisms of communication of its elements and their social meanings, the theory of spatial syntax,

which explores the relationship between the configuration of the space and its audience [15], was applied.

Spatial analysis, based on the theory of Spatial Syntax [16], was used to discuss the compositional structure of the UUS and to understand the connections between different spaces, including those that create user movement patterns. This theory enables the identification of community behavior and allows a better understanding of how the space is used and interpreted.

This study focuses on analysing global best practice in the realisation of underground spaces with an educational and cultural function, erected in accordance with sustainable development principles. However, these facilities have not been adapted to serve as shelters to protect against climatic or military threats. Five examples covering museums, cultural centres, academic facilities and public spaces were selected for analysis. The cases presented are from different countries - Denmark, China, South Korea and the Netherlands (Opera Park, Copenhagen, Denmark; concept design for the extension of the Danish Parliament courtyard, Copenhagen, Denmark; Floating Courtyard - underground entrance plaza, Suzhou, China; Ewha University for Women, Seoul, South Korea; Fort Vechten Museum, Utrecht, the Netherlands). This allows a comparison of the various approaches to integrating underground spaces in the context of sustainable development.

The facilities analysed are located in urban areas and not only have educational and cultural functions, but also constitute important elements of transit infrastructure, enabling the free movement of residents and users of public spaces. Thanks to their location and open character, they integrate into the urban fabric, supporting both daily mobility and the multifunctionality of underground spaces.

Each of these facilities represents a different approach to the design of underground spaces in large cities, which play a role not only in the context of education but also in facilitating access to various public functions. The selection of these facilities allows a comparison of diverse design solutions and spatial layouts that respond to the needs of sustainability, functionality and integration with the urban environment.

In order to understand how the space of underground structures should be organised and planned to ensure user comfort, an attempt was made to spatially analyze five architectural objects - examples of urban underground spaces located in different countries. The main criterion for choosing underground structures is compliance with the principles of sustainability and the cultural and educational function they perform. Next, the main types of spatial syntax in specific examples of underground architecture are distinguished: permanent (stationary) space, i.e. areas where people stay, gain knowledge or develop their personality; movement (transit) space, movement zones [15] and auxiliary-spaces (recreational, technical, economic). At the next stage of the study, underground spatial objects were presented in graphic form, with subsequent analysis of configurational relationships between different spatial areas, which made it possible to identify the patterns of spatial organization and its impact on the movement of users (fig.1).

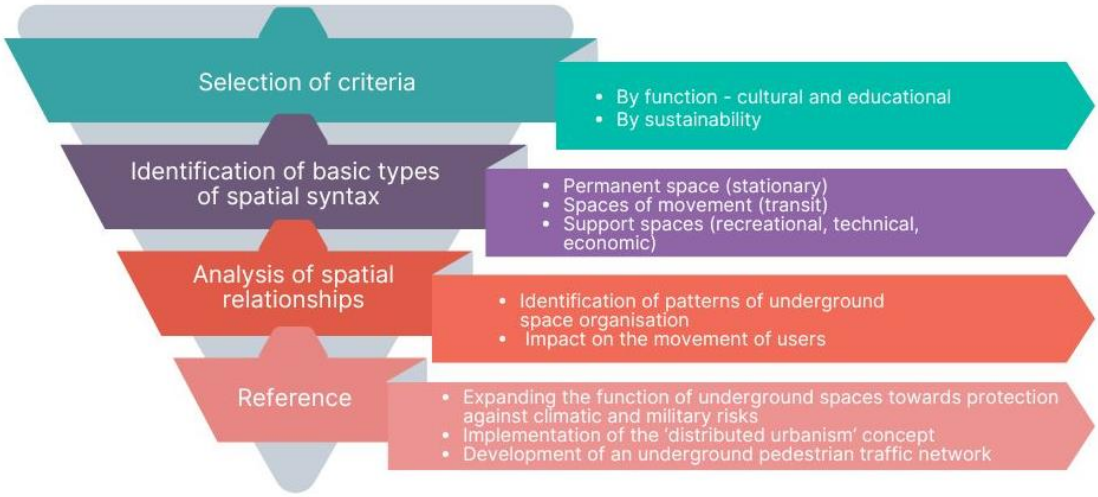

Fig. 1. Methodology of the study

4. RESULTS AND DISCUSSION

As urbanization becomesa global trend [17], the sustainability of the urban environment is becoming an increasing concern. A critical factor to consider is the increase in population density, which is closely linked to the deterioration of the quality of urban life,leading to a change in the landscape of most modern cities and an increase in height. In addition to the obvious advantage of reducing pressure on urban outskirts and natural areas, which limits environmental degradation outside central areas, vertical urban development also has some disadvantages. These include the restriction of airflow, leading to the accumulation of pollutants, and the use of materials and construction technologies that can contribute to the increase in temperatures in cities. Faced with the limitations of high-rise capacity, the need to develop underground complexes that can effectively meet the needs of large settlements is increasingly recognised [11].

Underground space is characterised by high energy efficiency, due to the thermal properties of the soil, which acts as a natural thermal buffer with stable temperature levels throughout the year. This allows for-reduced internal temperature fluctuations, which leads to a reduction in the need for fossil fuel energy [18, 12]. For example, in desert climates, where daily temperature amplitudes can exceed 35°C, this effect plays a key role in maintaining optimal thermal conditions inside facilities [13]. Soil plays an important role in protecting against extreme climatic conditions and natural hazards. In addition, underground spaces have low maintenance requirements, which leads to lower life-cycle costs and lower consumption of renewable and non-renewable resources [14]. After 1970, many countries began to show more interest in the properties of soil as a natural insulator. An example is Finland, which became one of the leaders in Europe in the use of underground spaces for various purposes, such as sports facilities, religious centres, restaurants, shopping centres and transport tunnels [10]. Meanwhile, in France, there is growing interest in designing underground spaces for educational and infrastructure purposes.

A preliminary analysis of the United Nations' 2030 Agenda for Sustainable Development [19] and the 17 Sustainable Development Goals (SDGs) defined therein has shown that architectural solutions can significantly support the achievement of almost all of these goals through appropriate design and planning. In particular, underground architectural facilities have the potential to contribute

to many of these goals. For example: SDG 3: Good health and quality of life - Underground shelters and spaces provide protection from air pollution, noise and the effects of armed conflict; SDG 5: Gender equality - In the context of underground spaces, the empowerment of women and girls in all aspects of life is strengthened; SDG 6: Clean water and sanitation - Underground infrastructure systems can support water and sanitation management; SDG 7: Clean and accessible energy - Such structures promote efficient energy management and storage; SDG 9: Industry, innovation and infrastructure - Underground architecture promotes the development of modern technology and sustainable infrastructure; SDG 11: Sustainable cities and communities - Underground spaces enable more efficient use of limited urban resources, such as space and infrastructure; SDG 12: Responsible consumption and production - Underground architecture reduces the need for urban expansion, reducing resource and space consumption; SDG 13: Climate action - Underground facilities support adaptation measures and mitigate the effects of climate change; SDG 15: Living on land - Underground spaces preserve green spaces and natural areas on the surface. For example, contemporary underground projects are increasingly focusing on sustainable resource management, including the reuse of waste materials such as silt. This process, referred to as resource recovery, involves the use of modern processing and reclamation technologies to transform silt into useful materials, such as for concrete production, land reclamation or as an ingredient in engineering processes. This approach not only minimises the negative impact on the environment, but also increases the efficiency of the use of natural resources in underground developments [13].

To further analyse and understand urban resilience, the 100 Resilient Cities organisation has also created a ‘City Resilience Framework’, which describes four dimensions through which a city can be examined. Each dimension - health and wellbeing; economy and society; infrastructure and environment; leadership and strategy - consists of three factors that relate to actions cities can take to become more resilient. The three factors are: ensuring and enhancing the protection of natural and man-made resources, ensuring the continuity of critical services and ensuring reliable communication and mobility [20]. To explore this issue further, one of the key aspects of the city's resilience system - economy and society - will be analyzed. In the context of understanding design principles and organization of urban underground space, a comprehensive spatial analysis and functional analysis of the selected architectural objects were carried out (fig. 2).

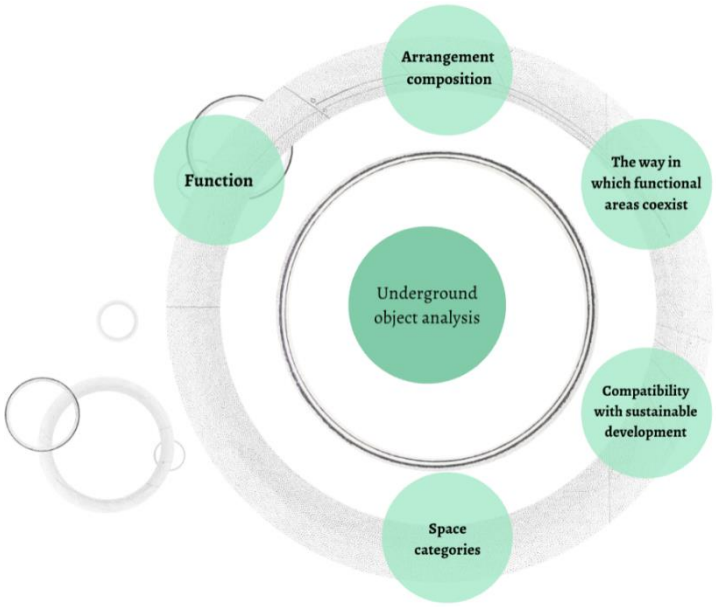

Fig. 2. Analysis of the urban underground space. Source: Author's study

The underground facilities surveyed between them combine cultural, educational and public functions, while fulfilling sustainable requirements. Five underground spaces were selected for analysis: Opera Park, Copenhagen, Denmark; concept design for the courtyard extension of the Danish Parliament, Copenhagen, Denmark; Floating Courtyard - underground entrance plaza, Su Zhou Shi, China; Ewha Women's University, Seoul, South Korea; Fort Vechten Museum, Utrecht, the Netherlands (tab. 1).

Table 1. A collection of underground facilities analysed. Source: author's study

Object	**Country of implementation**	**Architects**	**Function**	**Integration into the landscape**	**Urban function**	**Location**
Opera Park	Copenhagen, Denmark	Cobe	public, cultural	semi-underground form	transit	downtown
Danish Parliament building (concept)	Copenhagen, Denmark	Cobe, Arcgency & Drachmann	public, cultural	underground form	transit	downtown
Floating courtyard	Su Zhou Shi, China	Deep Origin Lab	cultural and educational	underground form	transit	downtown
Fort Museum Vechten	Utrecht, Netherlands	Anne Holtrop	cultural and educational	semi-underground form	stationary	suburb
Ewha Women's University	Seoul, South Korea	Dominique Perault Achitecture	cultural and educational	semi-underground form	transit	downtown

Table 2. Compatibility of the analysed underground facilities with the assumptions of sustainable development. Source: author's study

Object	Sustainable development objectives								
	SDG 3	SDG 5	SDG 6	SDG 7	SDG 9	SDG 11	SDG 12	SDG 13	SDG 15
Opera Park	+		+	+		+	+	+	+
Danish Parliament building (concept)	+	+				+	+	+	
Floating courtyard	+		+			+	+		+
Fort Museum Vechten						+	+	+	+
Ewha Women's University	+	+		+		+	+		+

From a sustainability perspective (tab. 2), the Ihwa campus in Seoul most closely meets the demands of gender equality and ensuring women's right to thrive in a safe and supportive academic environment. Its spatial and functional form is in line with the ideas of inclusive architecture, emphasising the integration of the academic community into the surrounding city. A key aspect of the project is the creation of a new urban topography that harmoniously interacts with its surroundings and transforms the landscape in a multidimensional way. The campus acts not only as a new gateway to the University, but also as a space that connects the urban fabric to the academic area, fostering interaction between students and Seoul residents. Formally and ideologically, the Ihwa campus is an example of contemporary democratic, open and inclusive architecture, whose spaces not only attract users but also emphasise equality values. In this context, it can be compared to the design of the Chanel mobile exhibition pavilion by Zaha Hadid, which was presented in Hong Kong, Tokyo and New York. Hadid, opposing the masculinisation of architecture, created the concept of a fluid, organic space, symbolising a democratic and inclusive femininity [21]. Similar ideas are evident at the Ihwa campus, where the shape and organisation of the space not only conforms to functional and aesthetic objectives, but also manifests the values of equality and openness in architecture.

Spatial analysis involves a comprehensive study of the location, organisation and functioning of spatial elements in different urban and architectural contexts. Its primary objective is to identify the ways in which functional areas and architectural objects coexist in space and to determine their interrelationships, intensity of use and impact on wider social, economic and environmental processes. The compositional arrangement of the analysed spaces is based on two main spatial configurations: centric and line-axis, which determine the organisation and functionality of these structures. In the analyzed underground structures, five main categories of space, have been identified, which have clear utilitarian and organisational functions: stationary spaces (permanent stay spaces) - areas intended for long-term stay, including places for meetings, rest and social activities; secondary stationary spaces (short-stay spaces) - zones of temporary use, such as places of temporary rest or landmarks; transit spaces (traffic spaces) - traffic routes that enable the movement of users, shaping traffic dynamics and the organisation of the flow of people; utility spaces (support spaces) - areas with technical and logistical functions, necessary to ensure the smooth operation of underground infrastructure; screening spaces - zones of a light or ventilating nature, crucial for the comfort of users and the quality of the indoor environment (fig. 3).

Fig. 3. Basic categories of public spaces in underground facilities

The designs for the Opera Park pavilion in Copenhagen (fig. 4), the Fort Vechten Museum in Utrecht and the courtyard in the Science and Technology Park in the Hutsu district of Seoul (fig. 5) show common features in terms of the composition of the transit space. A key element of their layout is the integrated central space - the core of the atrium - which acts as the centre of the composition and a meeting place for visitors. The organisation of space in these facilities directs the flow of users around an atrium or in the form of a spiral movement, depending on the spatial configuration adopted. The stationary service and leisure zones are distributed evenly around the central core to ensure optimum accessibility for users. Depending on changing spatial needs, they can be flexibly extended to neighbouring transit areas, allowing for dynamic reorganisation of functions and adaptation of spaces to current user requirements. This solution not only emphasises the visual coherence of the entire site, but also reinforces its openness and multifunctionality.

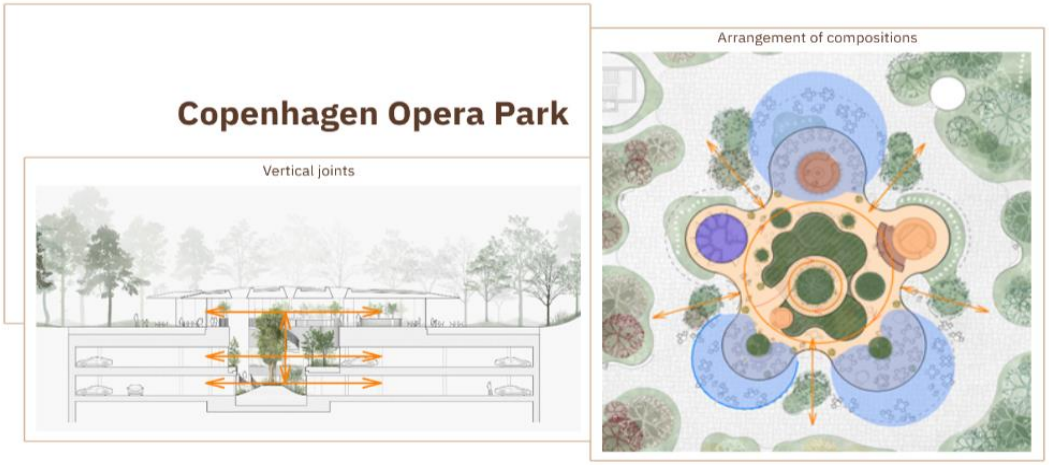

Fig. 4. An analysis of the interconnectedness of the compositional layout and function of the different spaces in Opera Park in Copenhagen. Source: author's study

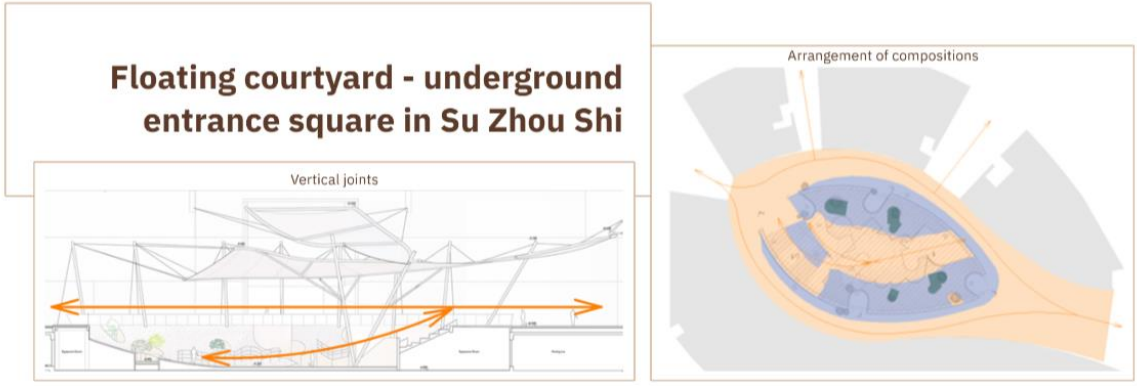

Fig. 5. Analysis of the linkage of the compositional layout and the functions of individual spaces in the territory of the Floating Courtyard - underground entrance square in Su Zhou Shi. Source: author's study

In contrast, the design of the Ewha women's college campus in Seoul (fig. 6) and the design-concept for the extension of the Danish Parliament Square (fig. 7) are characterised by a linear-axial layout, which envisages that the traffic vector of users will be directed along one or two main lines as a traffic artery. Both the design of the Ewha University campus and the Copenhagen Parliament courtyard assumed the use of a linear-rectangular model, which not only organises the movement of users, but also provides functional links between zones of the space in order to integrate above- and below-ground levels. By using this approach, it is possible to increase the use of underground space by users and to accentuate attention to transit traffic.

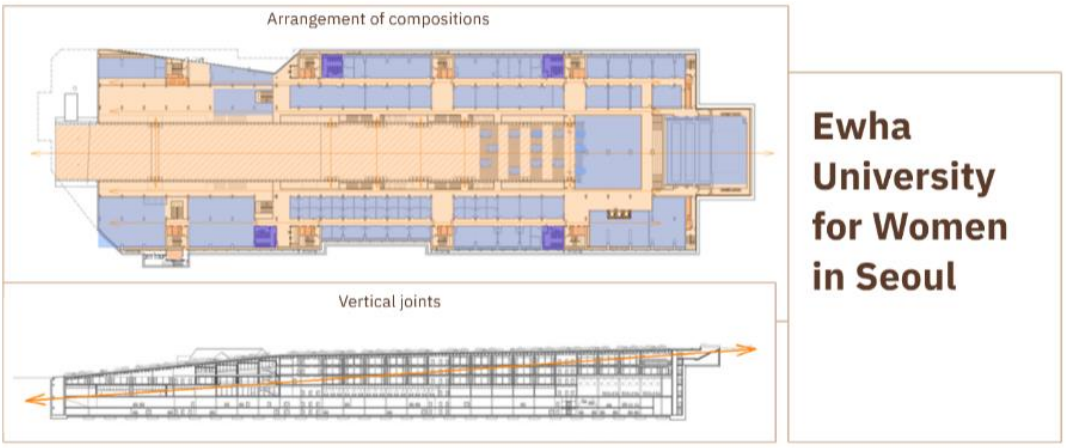

Fig. 6. Analysis of the relationship between the compositional layout and the functions of the different spaces on the territory of the Ewha University Campus in Seoul. Source: author's study

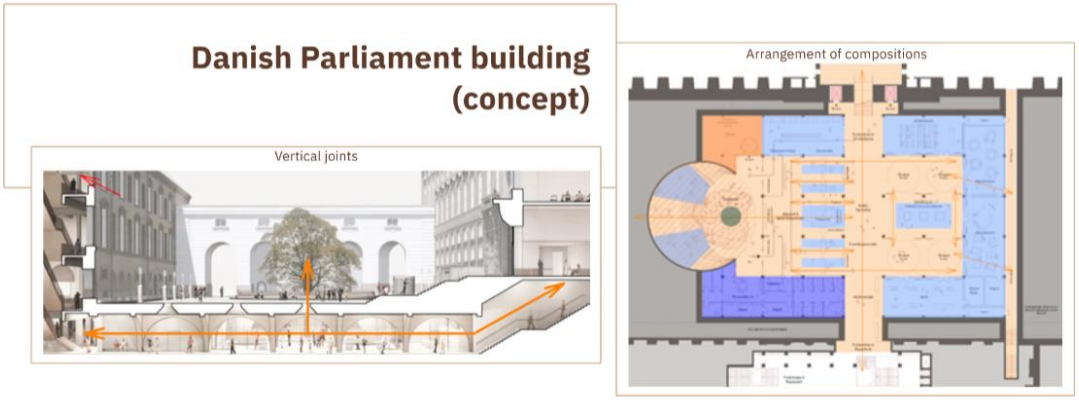

Fig. 7. Analysis of the relationship between the compositional layout and the function of the different spaces in the design of the Danish Parliament in Copenhagen. Source: author's study

Based on the theory of Space Syntax, in the process of configuration analysis of the specified urban underground spaces, their arrangements were modelled, which made it possible to identify the relationships between individual spaces that are combined into a common structure. It was noted that spaces with a central type of configuration, such as Opera Park and the Fort Vechten Museum, are characterised by a balance between stationary and transit areas due to their location in the fabric of the city. In contrast, linear-axial layouts such as the Ewha University Campus and the courtyard of the

Danish Parliament show a higher percentage ratio in favour of transit spaces. The increase in transit space in these UUS has resulted in their importance as traffic corridors between ~~the~~ urban areas and the centre, which contributes to the revival of pedestrian traffic (fig. 8).

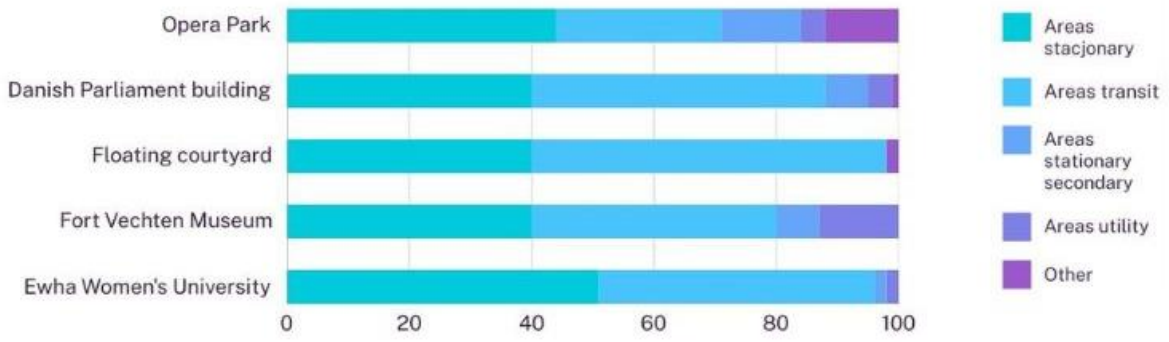

Fig. 8. Degree of relationship between spaces in the underground facilities analysed.
Source: author's study

Based on the spatial analysis of the studied underground facilities~~,~~ a pattern can be observed: the percentage of transit and stationary areas in all projects, regardless of their priority function, remains similar in value and significantly outweighs that of secondary areas. The configuration of ~~the~~ spaces, its layout and connectivity of the different areas depend on the nature of the use and have a significant impact on people movement directions.

The future of underground architecture is inextricably linked to building technology development. As underground architecture is a means of mitigating the effects of climate change, optimal conditions for sustainable development and comfortable living in urban areas can be achieved when underground structures occupy around 20-25% of the total urban square. The design of urban underground spaces is closely linked to the functioning of life on the surface. For it to be effective, sustainable and useful in the future, it is worth treating it as a key resource to support life on the surface, rather than simply as an inexhaustible raw material to be exploited for development [23]. The main challenge remains to identify the interconnections between all elements of UUS and to identify potential vulnerabilities that may arise in the future [4]. Both technological and social factors - including public attitudes and behaviour towards underground spaces - can both encourage and constrain their development [25].

According to spatial analysis of underground facilities and space syntax theory, it can be assumed that underground structures can form an alternative to above-ground urbanism, due to the fact of primary and complementary functions through the correct placement of accents and the orientation of pedestrian traffic. Unlike traditional above-ground buildings, subterranean structures can be interconnected to each other, allowing them to be distributed over extensive areas. Such spatial organisation will increase an efficiency of their use [2]. The cultural and educational function of analysed underground facilities is complemented by the transit corridors as ‘neighbourhood’ space to provide needs of users without restricting their movement. A person moving in a fixed direction always understands that he or she can leave the path at any time. This certainty is based both on visual clarity, as on the actual easy accessibility of neighbouring spaces [22].

5. CONCLUSIONS

The carried out spatial analysis achieved the stated aim of understanding the need to develop underground spaces that support the principles of sustainable development. In addition, an assessment was made as to whether the investigated underground spaces provide security in the context of climatic and military threats.

The spatial analysis of the selected underground facilities indicates that the design of underground spaces with cultural and educational functions in the context of safety is based on an appropriate balance between stationary and transit zones. As has been shown, soil is an effective protection against climatic (floods, windstorms, earthquakes) and military threats. It is therefore worth expanding secondary spaces to 3-5 m² per person, with the possibility of increasing to 10 m² in the event of long-term crises (tab. 3). Such changes will affect the relationship and layout of the various internal spaces, requiring a flexible approach to the planning of underground structures and taking into account the behavior and movement directions of users. Under the conditions of war in Ukraine, it is recommended to implement the concept of 'dispersed urbanism' instead of concentrated development in strategic areas of cities. It is also crucial to ensure efficient access to underground spaces through their integration with above-ground infrastructure and to develop the underground communication network as transit corridors that can act as safe routes for population evacuation, supply logistics and emergency services. In this context, it is recommended that existing and new underground spaces be integrated into a unified network, enabling rapid movement between key urban areas. In addition, an important aspect is the introduction of modular spatial solutions that allow underground facilities to be adapted to different use scenarios - from everyday educational and cultural functions to temporary shelter in emergency situations.

Table 3. Recommended areas to ensure safety function

Function	**M^2/ person**	**Requirements**
Short-term shelter	1-2 m²	not available
Longer stay (3-7 days)	3-5 m²	Provision of basic living conditions (hygiene, food, accommodation)
Long-term stay	5-10 m²	Ensuring autonomous operation, storage, ventilation

In the context of the post-war reconstruction of Ukraine's cities, it is important to take into account long-term risks of both a military and climatic nature. Accordingly, urban development should take into account the intensification of underground space development, especially in city centres and densely urbanised areas. A key element of this approach is the realisation of multifunctional transit corridors that can be integrated with educational spaces (e.g. teaching halls, language schools, post-secondary and higher education facilities) and cultural spaces (e.g. art galleries, avant-garde theatres, music spaces).

The implementation of such solutions, in accordance with the standards for the design of protective facilities and the principles of sustainable development, will contribute to increasing the safety of users, as well as improving the transport accessibility of cities. In addition, the transfer of selected functions to underground structures will enable the rationalisation of above-ground space through its adaptation to landscaped green areas, which may have a positive impact on microclimatic conditions and the quality of life of residents.

Importantly, transit-education spaces, due to their functionality and integration with urban infrastructure, will play a key role in the long-term urban structure. Their multifunctional nature will ensure a continued demand for their use, which will translate into their sustainability, profitability and economic viability. Investment in this type of development will not only contribute to making cities more resilient to crises, but will also provide a stable source of income and social benefits, enhancing long-term urban development.

As well as ensuring the safety of UUS, they should fit in with the key tenets of sustainability. These include resource efficiency, reuse of materials and constructions, reducing environmental impact and improving quality of life for users. A good illustration of this approach is the following examples, including the museum in Utrecht, which has been harmoniously integrated into the natural topography of the site, thus minimising interference with the historical heritage. In contrast, the Danish underground Parliament Square project used recycled building materials, using them for the load-bearing arches. The location of the analysed underground facilities within the urban structure is also an important aspect, as they are mostly located in central parts of cities, acting as transit spaces (with the exception of the Fort Vechten Museum). This location enhances their potential as safe places that provide easy and quick access.

It is also worth noting that in many large cities there are still disused underground railway stations that remain abandoned, although they are sometimes used as outposts for alternative taps because they have a unique atmosphere. However, their potential is not limited to being unique spaces for creativity - they can be transformed into spaces of social significance, acting as educational, cultural or exhibition facilities. Adapting these spaces into museums, art galleries, science centres or coworking spaces would not only bring them back to life, but would also have a positive impact on the revitalisation of the urban fabric, fostering social integration and preserving the architectural heritage.

The study presented here is a preliminary step in analysing the impact of integrating transit and educational/cultural functions in underground spaces on the development of urban structures. Identifying the relationship between urban mobility and the adaptation of underground spaces for social purposes allows a better understanding of the potential of such solutions in the context of sustainable development. In particular, the study highlights how multifunctional underground spaces can contribute to optimising urban layout, increasing accessibility to education and culture, as well as improving safety and urban resource efficiency. The results of the analysis can provide a starting point for further research into models for planning and implementing such structures in a dynamically changing urban environment.

REFERENCES

1. Kirichkov, I, Levoshko, S and Oliynyk, O 2017. Cultural development of the underground urban spaces on the experience of Saint-Petersburg and Harbin, *MATEC Web of Conferences* **106**, Article 01045. Available at: https://doi.org/10.1051/matecconf/201710601045 (Accessed: 12-01-2025).
2. Trygub, RM 2019. The role of underground space structures in a modern city, *In Modern Technologies and Calculation Methods in Construction* **12,** 207-212. Available at: DOI: https://doi.org/10.36910/6775-2410-6208-2019-2(12)-25
3. Sterling, R and Nelson, P 2013. City resiliency and underground space use. *Advances in Underground Space Development*, **7**, 43-55.
4. Bobylev, N, Hunt, DVL, Jefferson, I and Rogers, CDF 2013. Sustainable infrastructure for resilient urban environments. In: Advances in Underground Space Development – Zhou, Cai & Sterling (eds) *The Society for Rock Mechanics & Engineering Geology (Singapore).* Available at: https://surl.li/dtghli, (Accessed: 03-02-2025)
5. Dursun, P and Saglamer, G 2003. Spatial Analysis of Different Home Environments in the City of Trabzon, J. *Hanson (Ed.) Proceedings, 4th International Space Syntax Symposium*, University Collage London, 17-19 June 2003, **II**, 54–54.18.
6. Dursun, P 2007. Space Syntax in Architectural Design *Proceedings, 6th International Space Syntax Symposium.* İstanbul, **56–56.12**.

7. Gayko, G, Matviichuk, I, Biletskyi, V and Saługa, PW 2018. Forecast assessment methods of geological environment promotion for the construction of urbanistics subjects *In Visnyk of V N Karazin Kharkiv National University series Geology Geography Ecology* **48**, 39-51. DOI:10.26565/2410-7360-2018-48-03
8. Ryndiuk, S and Maksymenko, M 2021. Development of underground space as a solution to the problems urbanization of cities, *In Modern technology materials and design in construction* **29** (2), 101-107. Available at: DOI:10.31649/2311-1429-2020-2-101-107
9. Zhidkova, TV and Shelkovin, OA 2009. Vertical zoning of the territory as a method of preserving the historical environment of the city. *Municipal Economy of Cities* **90**, 148-151.
10. Vähäaho, I 2014. Underground resources and master plan in Helsinki. *Journal of Rock Mechanics and Geotechnical Engineering* **6**, 387-398. Available at: DOI: https://doi.org/10.1016/j.jrmge.2014.05.005, (Accessed: 03-02-2025)
11. Li, X, Li, C, Parriaux, A, Wu, W, Li, H, Sun, L, et al. 2016. Multiple resources and their sustainable development in Urban Underground Space. *Tunn. Undergr. Space Technol* **55**, 59–66. Available at: https://doi.org/10.1016/j.tust.2016.02.003
12. Grodecki, W 2004. Budownictwo podziemne jednym z czynników zapewnienia zrównoważonego rozwoju [Underground construction one factor in ensuring sustainable development]. *Budownictwo Górnicze i Tunelowe* **4**, 14–21. Available at: https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BPS1-0017-0002, (Acessed: 03-02-2025)
13. Parker, H 2004. Underground Space: Good for Sustainable Development and Vice Versa. *World Tunnel Congress 2004.* Singapore, ITA Open Session. Available at: file:///C:/Users/Asus/Downloads/HParker.pdf, (Accessed: 03-02-2025)
14. Mohirta, A 2012. Natural Lighting and Psychological Barriers in Underground Space. *Ph.D. thesis, Oxford Brookes University, Oxford. [online]*. Available at: https://www.academia.edu/8753610/Natural_Lighting_and_Psychological_Barriers_in_Underground_Space (Accessed: 19-01-2025)
15. Oliynyk, O 2021. Prostorovyi syntaksys yak instrument doslidzhennia struktury ta konfihuratsii hromadskoho prostoru [Spatial syntax as an instrument of structure improvement and configurations of mass space]. *Mistobuduvannia ta terytorialne planuvannia* **76**, 195–204
16. Hillier, B 1996. Space is the machine: A configurational theory of architecture *Space Syntax*, London.
17. Cox, W 2015. Demographia World Urban Areas *E-book library [online]*. Available at: http://www.demographia.com/db-worldua.pdf, (Accessed: 12-01-2025)
18. Ma, X, Cheng, B, Peng, G, and Liu, W 2009. A numerical simulation of transient heat flow in double layer wall sticking lining envelope of shallow earth sheltered buildings. *In Proceedings of the International Joint Conference on Computational Sciences and Optimization, CSO 2009*, **1** (Sanya: IEEE Computer Society), 195–198. Available at: doi: 10.1109/CSO.2009.230
19. Agenda 2030: Sustainable development 2015 UN General Assembly resolution A/RES/70/1 *[online]*. Available at: https://www.unic.un.org.pl/files/164/Agenda%202030_pl_2016_ostateczna.pdf, (Accessed: 12-01-2025)
20. Hajer, M and Dassen, T 2014. Slimme steden: de opgave voor de 21e eeuwse stedenbouw in beeld. Rotterdam.
21. Oliynyk, O 2017. Gendernì oznaki v arhìtekturì ta mìs′komu prostorì [Gender markings in the architectural structure of the space]. *Problemi rozvitku mìs'kogo seredoviŝa* **2**, 105-115. Available at: http://nbuv.gov.ua/UJRN/Prms_2017_2_14

22. Oliynyk,O and Troshkina, O, 2023. Analysis of architectural urban spaces based on Space Syntax and scenario methods. *Spatium* **50**, 24–32. Available at: DOI: https://doi.org/10.2298/SPAT230407010O (Accessed: 02-02-2025)
23. Admiraal, H 20006. A bottom-up approach to the planning of underground space Tunnelling and Underground Space Technology **21(3),** 464-465**,** Available at: DOI: 10.1016/j.tust.2005.12.102
24. Antonenko, I 2021. Systemic development of Kyiv underground space. Priority tasks and elimination of possible risks. *In Sworld Journal,* **1(10-01),** 108–114. https://doi.org/10.30888/2663-5712.2021-10-01-032
25. Lee, EH, Christopoulos, GI, Lu, M, Heo, MQ and Soh, C-K 2016. Social aspects of working in underground spaces. *Tunn. Undergr. Space Technol* **55**, 135–145. Available at: https://doi.org/10.1016/j.tust.2015.12.012, (Accessed: 12-01-2025)
26. Admiraal & Cornaro, 2016. Urban Underground Space: Planning and creating the cities of the future. ICE Publishing, 232.
27. Reynolds, E, 2019. Underground Urbanism, New York, Routledge. Available at: DOI https://doi.org/10.4324/9781315523330