Underground space and urban sustainability: an integrated approach to the city of the future

C. Paraskevopoulou[1,5*], A. Cornaro[2,5], H. Admiraal[3,5] and A. Paraskevopoulou[4,5]
[1]School of Earth and Environment, University of Leeds, UK
[2]Amberg Group, Switzerland
[3]Enprodes, The Netherlands
[4]The Barlett Development Planning Unit, UCL, London, UK
[5]ITACUS (International Tunnelling Association Committee on Underground Space)

*Corresponding author: E-mail: c.paraskevopoulou@leeds.ac.uk, Tel +44 (0) 113 343 1449

Abstract
The use of underground space is not a recent novelty. Its use was primarily defined in regards to survival reasons; protection from natural hazards. Currently, there is a notable increase of underground space applications especially in urban environments. The field of underground space uses is vast in response to various reasons: for commuting and transporting goods to shopping centers, housing and even farming facilities and storage facilities, mining and geothermal energy to nuclear waste disposals. This paper focuses on examining underground space use in today's urban environments, specifically in urban centers adopting an interdisciplinary and comprehensive approach. This research work introduces the eight global goals for sustainable development based on the United Nations sustainability goals. The methodology used takes into consideration the existing social and economic setting in the cases under investigation, which include both hypothetical models and practices, as well as applied examples of underground spaces in use internationally.
Based on two different models of economy, the circular economy and the doughnut economy this paper highlights the principles that should be embedded to achieve resilience and sustainability during the construction and operation of urban infrastructures emphasizing on the spatial contribution of underground developments, on an economic, environmental and furthermost social perspective. By looking into the infrastructural construction of underground spaces, we wish to articulate on their spatial production through the relationships that emerge with the urban environment, and thus examine the balanced evolution of the underground space and its uses. Focusing on determining the underground space's eco-system will allow for further understanding of its social dimensions and active processes of production, as a spatial node on an intertwined web of spatial networks formulating our urban environments.
Keywords: underground space development; spatial production; urban sustainability; smart cities

1. INTRODUCTION

Urbanization has radically increased in the last two decades as a result of the population increase that has led to the growth of megacities which account for the 9% of the urban population around the globe. [1] states that megacities have a big impact in the economy and politics of urban development at a global scale. The latter scales up the conventional urban problems which require an innovative and smart solutions approach, considering both sustainable and resilient solutions that on a second note can be adopted by all urban settings. This set of actions will further impact the social and economic aspect of the cities by improving their existence or creating resilient infrastructures, increasing the quality of life and establishing a sustainable development plan. It is prevailing to assume that urban sites face scarcity of space, thus establishing the need to their development spatially more pertinent. Underground space can contribute towards this future development by hosting activities and facilities enabling the surface area to be used for further and additional purposes targeting a more sustainable lifestyle. The presented research work analyses

how underground space can benefit urbanism to achieve sustainability by targeting specific goals using a holistic approach by taking into consideration various models of economy.

2. UNDERGROUND SPACE

[2] on their book about "Underground Spaces Unveiled: Planning and creating the cities of the future" argue towards considering the subsurface as the foundation of life for any living creature and entity. They further develop their argument by stating that the underground space is used to build the foundations of buildings, harvest the crops, extract ores and minerals which are all non-renewable resources with an expiration date. Underground space is considered to be related to construction infrastructure (i.e mining and tunnelling), specifically in urban settings, where its main daily application is transportation infrastructure. However, there is a redundant number of other underground applications such as: geothermal energy, groundwater resource, storage facilities, parking even underground farming and public recreational facilities (such as swimming halls and sport centres). There is consequently the need of changing the public perception of the underground space of that being a welcoming and friendly environment, that fosters social interaction and inclusion.

The processes of urbanization therefore ask of a comprehensive understanding, rethinking and reshaping of the underground spaces that become even more vital and crucial in the urban transformation of our cities, considering overpopulation and extended density figures that urban settings suffer from. The 'right to the city' defined from [3] as the "right to change ourselves by changing the city" in order to achieve urban and social transformation, transcends from the over ground spatiality of our cities to their adjacent underground spaces.

One successful example of utilization of such underground space, is the Stockholm metro station where the visitors can stroll around unsupported granite stations due to the artistic component and the welcoming environment that the painted unsupported surrounding rock has created. Figure 1 shows an example of an underground space model in an urban megacity environment.

Figure 1. Underground Space Model in Urban Environments (modified after: http://www.tduk.org).

3. SUSTAINABILITY

In this respect, there is historical evidence that ancient civilizations (Greeks, Egyptians, Romans) were dealing with environmental challenges such as deforestation, salinization, loss of soil fertility that currently are identified as sustainability problems. During that time the above had also been acknowledged as environmental degradation issues and there is evidence of suggested mitigation techniques to extend the earth's lifetime. However, the first time the concept of sustainability was discussed in the literature was by John Stuart Mill in 1843, where the idea of stationary state in terms of capital and population was introduced, through which prosperity was to be achieved. He argues that the society's ability to development can be managed by sustaining the natural resources so as the future generation can enjoy this natural environment as the present generation currently is. [4] also states that "the mankind has forgotten that the earth was given to him for usufruct alone, not for consumption, still less for profligate waste" and thus such an approach can stipulate the humankind extinction. The latter is aligned with today's approach for sustainable development [5]. With the oil industry boom in the 1920s-1950s the idea of the natural resources overexploitation (both raw materials and energy sources) emerged and was discussed [6].
It can be inferred from the afore-mentioned that the concept of sustainability was introduced since the ancient times with a dramatic increase in the last century when the overconsumption of natural sources at faster paces magnified their scarcity, embracing thus the idea of examining other natural sources or making the existing ones sustainable to elongate their lifetime and preserve them for the future generations.
The challenge of using the natural resources in such way to make them sustainable is considered crucial and it is directly connected with economic growth. After the World War II and the industrial and commercial growth which reflected both an economic and a population boom the mankind's footprint to the environment was increased radically. It was not until the 1970s where the concepts of 'growth', 'progress' and 'development' came under question, as economic growth failed to prove that hoped-for solution or always be related to a positive or optimistic evolution [5]. That period the idea of sustainability was adopted from the ecological sciences and was mainly referred to a state of condition.
The most common definition used to describe sustainability (or sustainable development) was given in the Our Common Future report during the World Commission on Environment and Development, chaired by Gro Harlem Brundtland in 1987 as: "the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [7].

3.1 Sustainability Development Goals (SDGs)

In 2015 all United Nations Member States adopted The 2020 Agenda for Sustainable Development based on which 17 Sustainable Development Goals (SDGs) were introduced and 169 targets were set that are integrated within the three-fold sustainable development of social, economic and environmental cycles and are mainly focusing on human rights realization, gender equality, women and girls empowerment. Figure 2 illustrates the 17 SDGs that must be achieved by 2030, focusing on people, planet, prosperity, peace and partnership. Their main vision is "a world free of poverty, hunger, disease and want, where all life can thrive; a world free of fear and violence. A world with universal literacy. A world with equitable and universal access to quality education at all levels, to health care and social protection, where physical, mental and social well-being are assured. A world where we reaffirm our commitments regarding the human right to safe drinking water and sanitation and where there is improved hygiene; and where food is sufficient, safe, affordable and nutritious. A world where human habitats are safe, resilient and sustainable and where there is universal access to affordable, reliable and sustainable energy"[8].

Figure 2. Sustainable Development Goals introduced in the 2030 Agenda for Sustainable Development proposed by the United Nations members in 2015 [8].

4. ECONOMY AND SUSTAINABILITY

Since the first Industrial Revolution the Linear Economy model based on the concept of take-make-use-dispose of consumption was adopted by the global economy (Andrews, 2015). The quantity and the speed of production was the primary concern which led to the automation and mechanisation as well to the development of new energy systems and sources of power. This boost was complimented by the industrial robots during the second half of the 20th century and the second Industrial Revolution. Another critical aspect of the Linear Economy model was the 'national production' which led to a radical increase of mass-productions of goods and indirectly to mass-consumption or else overconsumption and over-waste. Consequently, this model of the Linear Economy has been proven not sustainable based on social, economic and environmental factors and there is an urgent need for an alternative. In this section two different models of Economy that are considered to facilitate sustainability are discussed further. These are the model of Circular Economy [9] and the Doughnut Economy [10,11].

4.1 Circular Economy

The origins of the Circular Economy model lie in Biomimicry when this term was first used to describe "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies" [12]. Such example of innovation towards sustainability is considered to be the Circular Economy model that mirrors natural life cycles where dead organic material decomposes to become a nutrient for the next generation of living organisms [13]. Other examples of the Circular Economy include organic waste (compost) or non-organic polymers. However, it was not until 1970s when Walter Stahel a Swiss Architect when he argued that the materials can be processed in 'closed loops' and the main resource is the 'waste' and the product's life can be extended through remanufacturing [9]. The basis of the Circular Economy model includes 4 stages:

- Raw materials extractions,
- Processing,

- Manufacturing,
- Use and end of life.

One of the main benefits and added value of this model is the reduced risk related to depletion of supply and resources and to low consumption energy needs. According to this model there are also 3 main principles that must be followed, as shown in Figure 3.

- Principle 1: preserve and enhance natural capital by controlling finite resources and stabilizing the flow of renewable resources.
- Principle 2: optimize resource yields by circulating products, components, and materials at the highest utility both in the technical and biological cycles.
- Principle 3: foster system effectiveness by revealing and getting rid of negative side effects from designs and productions.

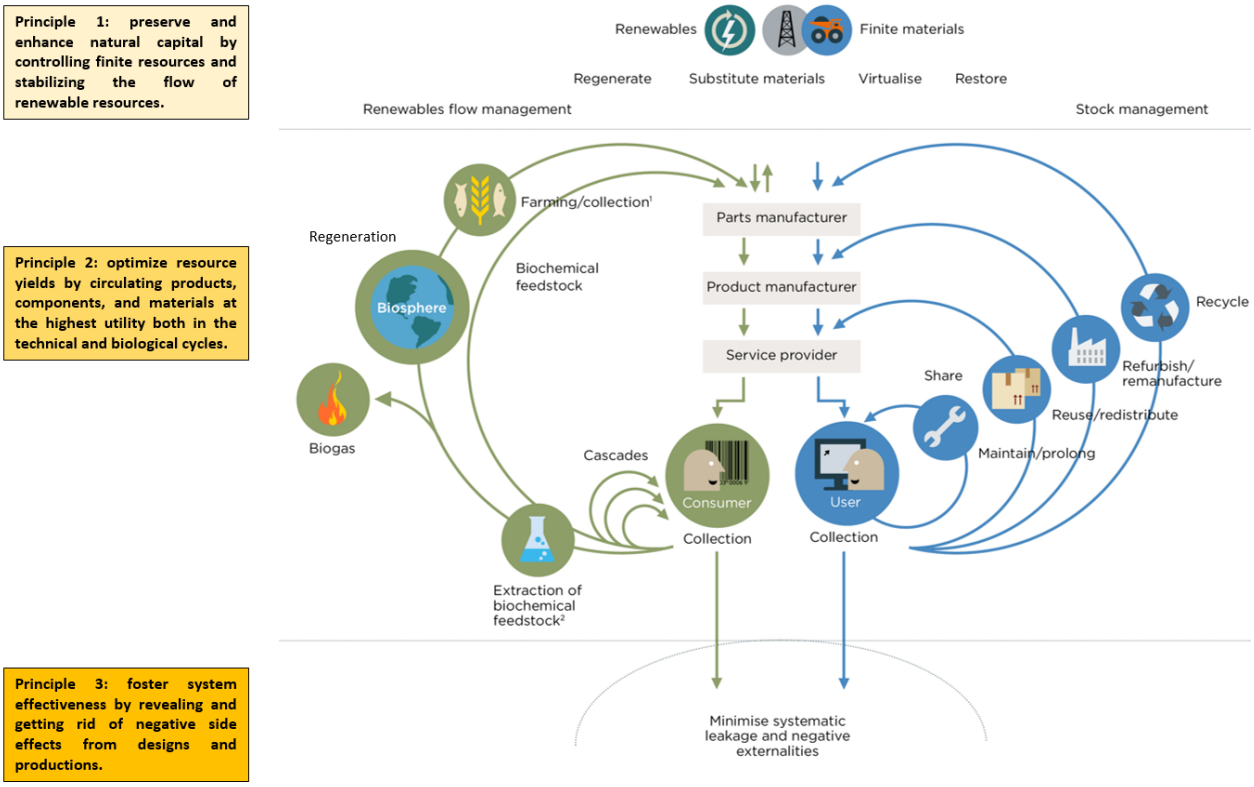

Figure 3. Circular Economy Model (modified after Ellen MacArthur Foundation, SUN, and McKinsey Centre for Business and Environment; 201. Drawing from Braungart & McDonough Cradle to Cradle C2C, 2015).

4.2 Doughnut Economy

Another model that embeds sustainability is the recently proposed model of Doughnut Economy and introduced by Kate Raworth in 2012 [10]. The name of this model as it can be inferred has come from the shape of the proposed diagram as shown in Figure 4 which brilliantly brings together developmental and environmental issues as [14] argues. The core question that the Doughnut model attempts to answer is 'How can we ensure that every human being has the resources they need to meet their human rights – but that collectively we do it within the means of this planet?'. In the Doughnut shape three rings exist which represent the three main components of the model: the ecological ceiling (outer dark-green ring), the social foundation (inner dark-green ring) and the empty ring in the centre of the doughnut captures all human-related activities. The closer a human

being is to the centre of this doughnut the more deprived is and his/her rights are ultimately removed. For this reason the 'safe space for humanity' ring (light green) exists between the ecological ceiling and the social foundation rings. Consequently, this model suggests that the human beings and their activities should lie within this safe zone in order to sustain balance in the environment and achieve ultimately sustainability. In addition, [11] argues that there 5 keys factor to work on to live in the safe and just space for humanity:

1. Population: to "guarantee a life without deprivation," above the social limits.
2. Distribution: a more equitable and efficient use of global resources is needed to fit within the confines of the donut.
3. Aspiration: the greater our aspiration towards material needs, the greater will be our pressure on planet Earth.
4. Urbanization: the choice of technologies in the construction, transport and energy sectors will play a decisive role in determining the amount of CO_2 emitted.
5. Governance: strong local, national and global governance is needed to tackle the most pressing challenges in a more systematic way and with a long-term vision.

In this respect, it becomes apparent that the focus on sustainability is drawn on the four domains of domains of sustainable development (social-ecology, economics, politics and culture), shifting the focus on good governance and its relation to social factors. Specifically, as defined by the UN "urban governance is the sum of the many ways individuals and institutions, public and manage the common affairs of the city. […] Good governance is achieved by the following: sustainability, subsidiarity, equity, efficiency, transparency and accountability, civic engagement and citizenship, and security."

This definition of good governance is further developed, considered and enhanced within the Doughnut Economy Model which proposes boundaries and the governing factors of an eco-system where sustainability can be achieved in the 21st century. More specifically, [11] introduces 'seven ways to think like a 21st economist whose main goal is to live within a sustainable model.

1. Change the Goal – from GDP (Gross Domestic Product) to the Doughnut
2. See the Big Picture – from self-contained market to embedded economy
3. Nurture Human Nature – from 'rational economic man' to social adaptable humans
4. Get Savvy with Systems – from mechanical equilibrium to dynamic complexity
5. Design to Distribute – from 'growth will even it up again' to distributive by design
6. Create to Regenerate – from 'growth will clean it up again' to regenerative by design
7. Be Agnostic about Growth – from growth addicted to growth agnostic

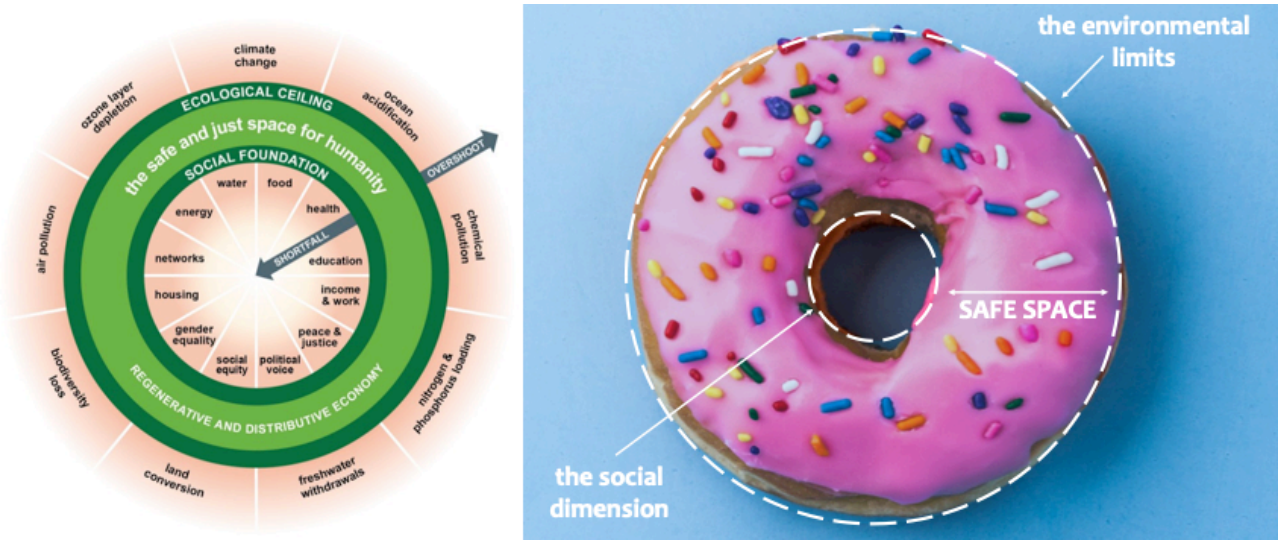

Figure 4. Doughnut Economy Model (modified after [11,12]).

Moreover, as a model it proposes to equally focus on social factors of sustainable development placing in the center of the discussion the rights of human beings to transform their urban

environments. As [15] asserts (2008:23) “the right to the city is far more than the individual liberty to access urban resources: it is a right to change ourselves in changing the city. It is moreover, a common rather than an individual right since this transformation inevitable depends upon the exercise of collective power to reshape the processes of urbanization.”. It therefore comes as no surprise that the Doughnut model is currently used as ‘a compass’ by several NGOs, government agencies and corporations for long-term planning.

5. UNDERGROUND SPACE URBAN SUSTAINABILITY: a holistic approach

Underground space applications can target various Sustainable Development Goals (SDGs). In this section case examples of various applications of underground space in urban environments are presented highlighting the specific SDGs that are being targeted.

5.1 SDG 2: Zero Hunger

Currently examples of underground farming are being developed, implemented and preferably used mainly in developed countries to produce greens and specific vegetables to achieve a more sustainable production in agriculture by using hydroponics or aquaponics. However, a primary reason for underground farming is to end hunger, achieve food security and improved nutrition. The underground space ensures sustainable food production systems by using hydroponics or aquaponics as well as is independent to climate change, extreme weather, earthquakes, flooding and other geohazards maintaining thus a suitable eco system. Examples of underground farming located in Europe are illustrated in Figure 5.

Figure 5. Examples of Underground Farming: a) SCAUT in Switzerland and b) Growing Underground in the UK.

5.2 SDG 6: Clean Water and Sanitation

Underground Space can contribute in achieving the SDG 6: Clean Water and Sanitation by securing access to safe and affordable drinking water for all, improve water quality by reducing pollution and increase water use efficiency overall. This can be done by water storage in underground aquifers through rainfall infiltration and by constructing an underground pipeline system to collect the surface and ground water, filter it in underground treatment plants and then transport it to provide access to high quality drinking water to all.

5.3 SDG 7: Affordable and Clean Energy

Underground Space is inherently an energy resource related to geothermal. Existing caverns or abandoned mines can be used as aquifers for heat recovery or storage (renewable sources of energy). The latter directly contributes in reducing the need of carbon- and based energy and achieving lower CO_2 emissions for heating and cooling.

5.4 SDG 8: Decent Work and Economic Growth

By hosting applications in the underground space there is the benefit of using the above-ground surface for other purposes, such as creating public spaces for recreational activities, commercial use or green spaces. A common example in urban environment is parking store buildings.

5.5 SDG 9: Industry, Innovation and Infrastructure

As it can be inferred the use of underground space is contributing directly to technological innovation and infrastructure as the industrial needs tend to push the limits even further to meet existing needs or create new ones. Building caverns and underground structures or maintaining existing ones lead engineers, designers and scientists to come up with new innovative solutions to these challenging problems.

5.6 SDG 11: Sustainable Cities and Communities

World Commission on Environment (1987) highlighted the importance of promoting harmony among human beings and nature. Subsurface is considered to be the foundation of life and a resource of non-renewables. However, if a policy framework is established for sustainable underground environment, subsurface in urban communities can create an ecological infrastructure system within the existing aboveground land.

5.8 SDG 12: Responsible Consumption and Production

Considering only the use of underground space towards sustainability implies the reasonable consumption of the aboveground space so reducing the overconsumption of land in urban areas.

5.9 SDG 13: Climate Action

Moving facilities and activities underground or using underground space for other energy resources directly impacts climate change and acts against its deterioration. Climate action is one of the biggest challenges which makes urban areas more susceptible to erratic weather patterns (i.e. heat, draught, flood, storms etc). Underground space can provide sheltered areas during such geohazards securing also the integrity of underground transportation systems.

5.10 Models for Underground Development

Sustainability is closely associated with models of economy as these are considred the mean of implementation. Without them sustainability can only be a concept or a utopic idea. This approach holistically considers how underground space as part of the ecosystem can contribute in achieving global sustainability. This holistic appraisal method for determining (planning and designing) was initially introduced by [2] and considers 4 factors investigating the geological, ecological, planning and the environmental aspects while considering the past, present and the future as shown in Figure 7.a. Another example of how the underground space can contribute in sustainability by using the Doughnut Model and targeting 8 out of the 17 SDGs is illustrated in Figure 7.b, the inner area (doughnut area), the safe area is where the eight goals are achieved by including the underground space and thus contributing holistically in the long-term development of the eco-system. More specifically, it is encouraged not to examine the subsurface independently from the aboveground system but as as an integral part of the overall system focusing also on its long-term impact in this eco-system.

It should be noted that through urban sustainability the capacity of individuals, communities and systems to survive, adapt, and grow in the face of stress and shocks, and transform when required, in other words urban resilience, is achieved. When the latter is attained people, communities, and systems are better prepared to withstand catastrophic events-both natural and manmade-and able to bounce back more quickly and emerge stronger from these shocks and stresses [16].

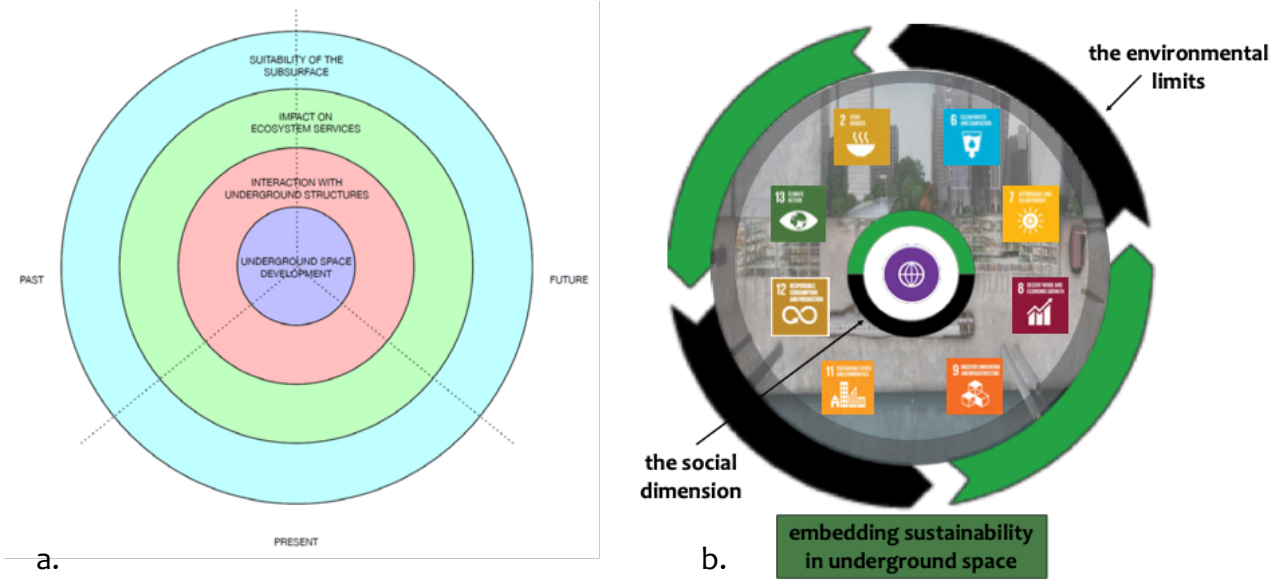

Figure 7. Examples of embedding sustainability in urban environments a) a holistic appraisal method [2] and b) a Doughnut Economy Model application in underground space

6. Concluding remarks

In the presented research work it was shown that underground space is a major strategic asset of cities worldwide, and when perceived and encountered holistically in the urban eco-system can contribute towards securing long-term sustainability and resilience of cities. Moreover, it was shown that in urban environments by using the underground space to host facilities and activities that were previously host in the surface 8 out of the 17 SDGs are targeted and achieved. However, for the latter to be attained, planning and organization of the underground development is required not only in terms of spatial organization or overcoming the engineering challenges but also in regards to the establishments of policies, regulations and social factors consideration. Consequently, developing a framework for holistically encountering underground space in existing urban eco-systems demands bringing together a multi-disciplinary group of people consisting of experts,

scientists, engineers, lawyers, planners, architects, ecologicts, economists etc. with fresh minds, ideas and intuition to make the world we live together a better sustainable and resilient environment for the next generations.

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