Tunnelling and Underground Space Technology 55 (2016) 40–51

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Underground space as an urban indicator: Measuring use of subsurface

Nikolai Bobylev *[,1]

Institute of Earth Sciences, Saint Petersburg State University, 7-9, Universitetskaya nab., Saint Petersburg 199034, Russia
Saint Petersburg Research Centre for Ecological Safety of the Russian Academy of Sciences, 18, Korpusnja ul., Saint Petersburg 197110, Russia
Peter the Great Saint-Petersburg Polytechnic University, Polytechnicheskaya, 29, St.Petersburg, 195251, Russia

ARTICLE INFO

Article history:
Received 25 July 2015
Received in revised form 22 September 2015
Accepted 9 October 2015
Available online 30 October 2015

Keywords:
Urban underground space
Urban indicators
Urbanisation
Sustainability
Resilience
Density

ABSTRACT

Use of Urban Underground Space (UUS) has been growing significantly in the world's biggest and wealthiest cities. UUS has been long acknowledged to be important to the urban development agenda: sustainability, resilience, livability, and creating a better urban environment in particular. These issues are traditionally monitored using urban indicators, however UUS has not been properly included and considered in urban indicator lists (sets or systems) yet – the gap this paper is aiming to bridge. The paper reviews existing approaches to the composition of urban indicator lists, highlighting indicator types, challenges related to data collection, and agencies that are concerned with the issue. Further the paper has identified the importance of UUS inclusion in the lists that give integrated assessment and monitor urban sustainability, resilience, climate change adaptation and mitigation, as well as progress towards smart, livable, and compact cities. Existing global quantitative data on UUS have been examined in 8 cities; and three key indicators (descriptors) were suggested to monitor UUS use: Developed UUS volume (m^3); UUS use density (m^3/m^2); and Developed UUS volume per person (m^3/person). Current average UUS use densities in cities are identified as up to about 0.05 (m^3/m^2) (which can be interpreted as a virtual depth of UUS use of 5 cm), and the developed UUS volume per person is up to about 10 m^3/person; while city central areas (central business districts) can have a virtual depth of developed UUS of several metres (m^3/m^2). Compatibility, comparability, uniformity, and sustained monitoring of urban indicators data (including UUS indicators) found to be posing significant challenges to the research across geographies, and industry/economic sectors.

1. Introduction

Urban Underground Space (UUS) use has been growing significantly in the world's biggest and wealthiest cities. Arguably, the main driving factors of this growth were lack of surface space and a need for a better environment, including abatement of motor traffic and pollution problems. Generalising, we can suggest that awareness of *the urban sustainability agenda* and a need to make cities more liveable have been growing concurrently with intensification of UUS development.

Indeed, UUS development can contribute a lot to urban sustainability, ranging from local renewable energy provisioning to urban space cohesiveness and aesthetics. Sustainability issues related to UUS use were raised by Carmody and Sterling (1993), Sterling (1997), Bobylev (2006, 2011), Rogers (2009), ITACUS (2010), and systematised by Sterling et al. (2012).

Measuring sustainability is an important subject, both in scholarly terms and as a policy informing tool. Lists of urban indicators or urban sustainability indicators have been adopted by many cities, countries, and international organizations to monitor progress in sustainable urban development. Sustainability is just one of the concepts that require to be informed by urban indicators; most recently the concepts of *ecosystem services*, *resilience*, *smart cities* have been developed and require input of urban data. Thus urban indicators become a more general notion, pertaining to developing, collecting, and analysing data from different aspects of urban life and then applying this knowledge to develop a better urban environment.

Usually urban indicators are presented in a form of lists where individual indicators are grouped according to a subject or knowledge area. Data behind these lists have different degrees of comprehensiveness and accuracy in terms of indicator monitoring. Specific indicators can have a variety of methodologies of data collection, ranging from field monitoring and comprehensive numerical data to expert estimations and rankings.

In spite of acknowledgement of UUS importance to the concepts and urban issues highlighted by use of urban indicators (e.g. sustainability, resilience), this subject has not made it yet into routine

---

* Address: Institute of Earth Sciences, Saint Petersburg State University, 7-9, Universitetskaya nab., Saint Petersburg 199034, Russia.

E-mail addresses: n.bobylev@spbu.ru, nikolaibobylev@gmail.com

[1] Postal address: P.O. Box 45, 195267, St. Petersburg, Russia.

http://dx.doi.org/10.1016/j.tust.2015.10.024
0886-7798/

urban indicator lists. The importance of UUS as an urban activity sector is on a par with long established urban sectors as transport (widely used indicator: motorisation rate), land use and planning (widely used indicator: built stock density), environment (widely used indicators: air pollution, water quality).

The undeservingly marginal role of UUS in urban sustainability and resilience discourse is reflected by the fact that the UUS topic has not made it yet into executive summaries of the most known *policy documents related to urban development*, i.e. United Nations Human Settlements Programme State of Cities Reports (UN Habitat, 2006, 2013a); United Nations Environment Programme Geo Outlook (UNEP, 2012); The World Bank Annual Reports and Urbanization Reviews (World Bank, 2012); Organisation for Economic Co-operation and Development Infrastructure Outlooks (OECD, 2006, 2008). However, the progress regarding mainstreaming UUS into urban agendas has been made. The United Nations Secretary General's formal address to the International Tunnelling Association conference in Bangkok in 2006 highlighted UUS relevance to global development and urban sustainability agendas (UN, 2012b). Famous architect Norman Foster highlighted the strategic importance of UUS as well: "One of the greatest challenges facing mankind is to achieve higher density while at the same time improving urban existence. The underground has enormous potential for realising spatial benefits" (Foster, 2011).

This paper argues that considering UUS in urban indicators lists will help to better understand the role that UUS plays in urban sustainability, resilience, and creating a better urban environment and life in general. Considering underground space as an urban indicator will help both: (1) better urban policy informing, and (2) better understanding of UUS sector industries needs and directions for development.

One challenge is arguing and promoting UUS inclusion into urban indicators; another one is to suggest how to do it. The paper will review existing approaches to composition of urban indicator lists, highlighting indicators types, problems related to data collection, and agencies that are concerned with the issue. Further the paper will examine existing data on UUS globally, trying to make sense of what actually can be measured in UUS and how this could help to better inform sustainability and resilience agendas. Finally, some possible UUS related indicators and their descriptors will be suggested, along with available data cross-sector analysis and comparisons.

2. Urban indicators

2.1. Emergence, systems, agencies

The emergence of *the urban indicator theme* stems from *the Sustainable Development Concept* (Brundtland Commission, 1987), and one of the first widely accepted set of indicators was part of the Local Agenda 21 (United Nations, 1995). Attempts for a singular comprehensive indicator set were made by United Nations Sustainable Development office (1998), comprising the list of 134 sustainability indicators. During about two decades of urban indicator research numerous lists, sets or systems of indicators have emerged. These lists were adopted by a variety of agencies and at a variety of levels (from national to local), which suggests the importance of diversity and fine turning of indicator lists. The need for development and structuring of urban indicators in a specific context was reflected in recent scholarly publications dealing with regionalization (e.g. Gonzalo et al., 2015; Michael et al., 2014; Shen et al., 2011), and the development of different indicator tools that aim to analyse urban sustainability (e.g. Castanheira and Bragança, 2014). Some questions regarding UUS and indicators include whether UUS should be featured in any specific lists (i.e. pertaining to a certain level or developed for any specific purpose), and/or if it is appropriate to have UUS in any lists dealing with topics of UUS concern: e.g. sustainability.

Urban indicator lists, sets, or systems have been developed by different *agencies*. The most famous of them aim on comprehensiveness and global applicability United Nations (2007), Organisation for Economic Co-operation and Development (OECD, 2004), the World Bank (World Bank, 2015), European Union (Eurostat, 2009), World Health Organisation (WHO, 1999), United Nations Human Settlements Programme (UN-Habitat, 2013b).

There is a number of specific *assessment tools*, that are in fact using urban indicators, as summarised and classified by Gonzalo et al. (2015), who considered 13 systems. Amongst them are certification systems developed for urban related industries: construction, planning, transportation. Major international systems are Leadership in Energy and Environmental Design (LEED) (US GBC, 2009), Building Research Establishment Environmental Assessment Method (BREEAM) (BRE Global, 2011), Sustainable Community Rating (SCR, 2015), Key Indicators for Territorial Cohesion and Spatial Planning (Daly and González, 2013).

A number of a *large scale research projects* were aimed at creating a comprehensive online databases of urban indicators: European Common Indicators (European Commission, 2003), Urban Audit (Urban Audit, 2004), European Thematic Network on Construction and City Related Sustainability Indicators (CRISP Project, 1999), Cities Environment Reports on the Internet (CEROI Project, 2010). Unfortunately, in majority of cases, the data update has been discontinued after the projects have ended, nonetheless, these projects remain an important methodological reference.

2.2. Types and classifications

The most traditional approach to create an indicator list would be to group indicators according *to three pillars of sustainability* (environment, economy, society). However nowadays a purpose-driven approach prevails in most urban indicator lists, i.e. broad indicator categories reflect agenda or concerns of the list proponent. Table 1 exemplifies aggregated indicator categories of the highest hierarchical level presented by several agencies.

As Table 1 reflects, indicator lists tend to be as comprehensive as possible, prioritising main concerns of the developer (e.g. note category "poverty" in the UN Habitat list). Urban indicator lists presented in Table 1 represent *different scales* – from global to national and a city one. Indicator assessment is done at an urban (city) level in any system, but the UN Habitat list is concerned with global relevance, while the Thessaloniki list is concerned just with the issues relevant to this particular city. Urban indicators bring *different meaning to different levels* (Lynch et al., 2011). At a local level the indicators are mainly used to monitor and inform urban development by city authorities; at the regional and national levels indicators inform development programmes and policies; at the global level the indicators are used to inform policies of international development agencies, including setting cross sector priorities (e.g. financing, climate change) that go beyond urban agendas.

Indicators differ in actual *approaches to measure them*. Significant division is between *quantitative and qualitative indicators*. This division can be referred to as different measurement methods, or different descriptors. An indicator formulation usually reflects what we want to know according to our (e.g. sustainability) goals e.g. "outdoor air quality"; the descriptor would reflect on available data we can monitor, e.g. "proportion of population exposed to SO_x above x mg/m^3", or "$PM_{2.5}$ mean annual exposure, % of population exceeding World Health Organisation guidelines level" (World Bank, 2015). Similar quantitative indicators in different indicator lists can have different descriptors.

Descriptors can differ in data collection methods, which could make comparisons amongst different indicator systems difficult

Table 1
Examples of major aggregated categories of urban indicators as suggested by different proponents.

Name and purpose of indicator system/list	Urban indicators reflecting United Nations agenda and the progress towards millennium development goals	Indicator system to assess urban sustainability for the Spanish context	A system of indicators for the city of Thessaloniki, Greece
Major aggregated categories	• Shelter • Social development and eradication of poverty • Environmental management • Economic development • Governance	• Site and soil • Urban morphology • Mobility and transport • Nature and biodiversity • Building and housing • Energy • Water • Materials • Waste • Pollution • Social aspect • Economic aspect • Management and institution • Innovation	• Economy and population • Land and urban planning • Energy • Transportation • Agriculture, livestock, fishery • Industry • Tourism • Air pollution and climate change • Water resources and sea environment • Solid waste • Biodiversity • Health • Education, research, and technology
Reference	United Nations Human Settlements Programme (2013b)	Gonzalo et al. (2015)	Moussiopoulos et al. (2010)

Table 2
Summary of major contemporary issues regarding urban indicators.

An issue or a challenge	State-of-the-art	Urban Underground Space (UUS) perspective
Purpose	Policy driven; urban sustainability, resilience agenda; can be fine-turned for specific agency or industry needs; can be relevant to global environment/development agenda	(1) To provide more comprehensive perspective on urban issues (2) To help UUS being developed in a more sustainable way
Level/scale	Urban data is used for urban, regional, national, or global information	All scales are relevant to UUS, for details see Table 9
Geographies	Cities in different regional groups may have specific to them urban indicator needs	Ground conditions (hard rock or weak soils) would be the main diversifying factor for UUS
Agency/industry	Indicators may reflect specific industry needs (e.g. transport focused), or contributing specific industry data to holistic urban policies	(1) UUS is relevant to holistic urban policies (e.g. energy, environment) (2) UUS agenda can be combined with agendas of close (sister) industries (e.g. water management, transport, waste) (3) UUS has its own distinct sustainability, resilience, climate change agendas
Types	Qualitative, quantitative, proxy	For suggested types of UUS indicators see Table 5
Continuity	Some indicator systems have been feeding data in for some time, but have major gaps or monitoring have been discontinued	Not relevant yet, UUS is just emerging as an indicator
Compatibility and comparability	Variety of methodologies for data collection make challenging analysis across indicator systems	UUS data is collected in different units (e.g. floor area or volume), accuracy can suffer while to making data compatible
Data quality	Variety quality and accuracy of data requires making tolerances in analysis and conclusions	As UUS is an emerging indicator, data is scarce yet, comparisons allow for big tolerances

(Bobylev, 2009b, 2010a; World Bank, 2011). Data on qualitative indicators is presented in a form of expert judgements, an example of this indicator type is “effectiveness of environmental planning guidelines”.

Proxy indicators, or proxy descriptors are used when we assume a correlation between different processes, e.g. daytime population density can be measured as density of mobile phones registration in a network cell. Proxy descriptors are important in public transport, land use, energy, and many other indicators.

2.3. Challenges

Persisting challenges of urban indicators research and practice are in *comprehensive data collection and handling*. As it was reflected in the previous sections: (1) actual indicator data would be collected by different agencies (industries); (2) a variety of methodologies for data collection are used; (3) data have different degrees of reliability. *Monitoring* urban environment and sustainability is a holistic task, however urban indicators data required for this task are mostly specific to the relevant industry. Data on urban indicators are usually compiled by local authorities' office, but data on specific indicators are collected in the form of statistics which are provided by industries (e.g. water related data would be provided by a water management company). Usually industries would have their own statistics and other types of monitoring indicators (e.g. key performance indicators) that are focused on their needs. This means that there is often *a mismatch between data available from industry and data required for urban indicators*. For instance, one of the urban sustainability indicators is “proportion of rainwater reused”, but a water management company would usually know just volumes of water treated by the sewerage system. If over the years the latter decline (when adjusted for

Table 3
Global development and urbanisation related concepts and Urban Underground Space (UUS).

A concept and reference to the Urban Underground Space (UUS) research	Summary of major Urban Underground Space (UUS) relevant issues
Sustainability (Sterling et al., 2012)	Rational use of UUS resources Rational land use Combating urban sprawl and compact city Geothermal energy (deep) and shallow subsurface heat exchange) Urban infrastructure efficiency (transport, water, others)
Resilience (Sterling and Nelson, 2013; Bobylev et al., 2013; Makana et al., 2016)	Urban natural and artificial disasters preparedness Emergency response and civil defence facilities Mitigation of city scale adverse environmental impacts (e.g. urban heat island effect) Critical infrastructure reliability
Climate change adaptation and mitigation (Bobylev, 2009b, 2013)	Urban networks energy efficiency (mitigation) Stable temperature mode benefits while locating urban functions underground (mitigation) Enabling urban compactness (mitigation) Underground infrastructure facilities for urban climate change adaptation Adaptation of urban underground infrastructure to climate change (reflecting changes in water balance, extreme temperatures)
Smart city (Bobylev, 2014)	Greater use of information and communication technologies to enable more efficient use of existing urban underground infrastructure facilities (e.g. water sewers)
Liveable city (Hunt et al., 2016)	Compact and high quality public spaces; Enhancing urban green and recreational areas by putting infrastructure underground
Compact city (Bobylev, 2009a; Wende et al., 2010)	Densification Quality of life and the environment Proximity
"0-land use" (Vahaaho, 2013)	A concept of "0-land use" is an idealistic approach to urban growth and development using just underground space. The concept originates from the city of Helsinki, Finland, where significant advancements in UUS planning has been made

population and other factors) one can assume that more rainwater is reused. This example illustrates a challenge of actually feeding and interpreting data in urban indicator lists.

Compatibility and comparability of urban indicator data are important issues as well. Making comparisons between cities using indicators is an essential base for policy advice and judging on progress towards sustainability. The significance of analysis across geographies and indicator systems has been acknowledged by many, including the World Bank. The World Bank, which has been doing comprehensive research on the subject, admits that even its own urban indicator data "should be used with care, and because of different data collection methods and definitions may have been used, comparisons can be misleading" (World Bank, 2015). This can be illustrated on such a trivial example as "urban area", which can refer to (1) administrative district, (2) build up area of a certain density, (3) it can include or exclude large water bodies and green parks.

Table 2 presents a summary of discussed issues in urban indicators research, giving a UUS perspective on the subject.

3. Urban underground space as an urban indicator

3.1. Background and relevance

Urban Underground Space (UUS) can be defined as a geo space beneath urban areas, including wider areas of UUS that provide direct services to a city, like groundwater supply or geothermal energy. UUS encompasses geologically formed rocks and soils, and artificial spaces, as well as caverns of various origins.

Manmade UUS includes *Urban Underground Infrastructure*, which can be defined as a set of artificial structures, located entirely or partially below ground level, interconnected physically or functionally (Bobylev, 2007). UUI is represented by a variety of utilities, rail and motor tunnels, buildings' basements used as storages, garages, public pedestrian and shopping zones, etc.

UUS services, or functions in the city, can be summarised as storage (e.g. food, water, oil, industrial goods, waste); industry (e.g. manufacturing); energy production (e.g. geothermal energy sourcing); transport (e.g. railways, roads, pedestrian tunnels); utility supply (e.g. water, gas, electricity and communications) and waste disposal (e.g. waste water); and provision of public space (e.g. shopping centres, hospitals, parking, civil defence structures) and private space (e.g. cellars, household garages and dwellings) (amended after Bobylev, 2009a; Sterling et al., 2012).

As it was mentioned in the introduction, urban indicators help to monitor cities' performance and progress towards sustainability, resilience, climate protection, liveability, etc. UUS is very relevant to all this issues, as it was shown during the last decade of UUS research. Table 3 names urbanisation related scholarly concepts, and explains UUS relevance to them, giving key references to a research on the subject.

As Table 3 shows, inclusion of UUS into urban indicators is quite justified by the number and significance of the issues related to underground space.

3.2. Urban underground space in urban indicator lists

Urban indicator systems have been unfair to UUS and urban underground infrastructure so far in comparison to other sectors and infrastructures, e.g. transport, water, telecom. Table 4 illustrates this by showing the number of indicators of the lowest level in respective groups (e.g. transport) in different indicator lists. Table 4 suggests where UUS indicators might be appropriate in the indicator lists. Table 4 is build upon three indicator lists, which were earlier discussed in Table 1. The aim is to show needs and opportunities for UUS indicators to be included in the indicators list of *variety of purposes, levels/scales, and originating agencies*. Readers can see full lists (several pages each) in the respective publications. As it was cited in the previous chapters, there is not and should not be just one universal, fit for all purposes, urban indicator list. Similarly, *there should not be only one way or an indicator*

Table 4
Suggestions for Urban Underground Space (UUS) indicators inclusion into urban indicator lists.

Major aggregated category	Indicator system – level/scale (i.e. "Global" indicates Global relevance)	Existing indicators at the lowest level (only relevant are shown)	Proposed Urban Underground Space (UUS) indicators at the lowest level
Environmental management	Global	Planned settlements	UUS integrated into master plan
Environmental management	Global	Disaster prevention and mitigation instruments	Adequate consideration and use of UUS in disasters preparedness
Site and soil	Regional	Planning according to climatic zones	Planning according to UUS conditions (soils, groundwater)
Urban morphology	Regional	Design and quality of public space	Design and quality of public space, including underground public spaces
Building and housing	Regional	Proportion of abandoned or unused buildings	Underground structures that are abandoned or inefficiently used
Building and housing	Regional	Consideration of solar orientation in building design	Consideration of UUS use (also adjacent) in building design
Energy	Regional	Proportion of buildings whose energy rating is higher than average	Proportion of energy efficient UUS premises
Energy	Regional	Proportion of self-sufficiency with renewable energy	Proportion of buildings using UUS for energy sourcing or storage
Innovation	Regional	Innovation practices based on BRE Global (BRE, 2011)	Innovations in infrastructure and UUS use
Economy and population	City	Population density	UUS use density
Land and urban planning	City	Share of land use by activity (function)	UUS use by function
Energy	City	Renewable energy	Share of renewable energy by source, including underground
Transportation	City	Public transportation vehicles average speed	Average speed of passenger travel on underground public transport
Industry	City	Share of industries with environmental management systems	Share of urban functions that are underground and not consuming urban land
Land use	*Additional suggestion (indicator was not mentioned in the reviewed systems)	Share of land cover by cover type (asphalt, soil, building, etc.)	Stratification of UUS use by depth

Notes:
Short names:
Global – Urban indicators reflecting United Nations agenda and the progress towards millennium development goals (United Nations Human Settlements Programme, 2013b).
Regional – Indicator system to assess urban sustainability for the Spanish context (Gonzalo et al., 2015).
City – A system of indicators for the city of Thessaloniki, Greece (Moussiopoulos et al., 2010).

reflecting UUS related issues, but rather UUS indicators should not be forgotten in the lists.

Table 5 was developed on the basis of the "*proposed UUS indicators at lowest level*" section in Table 4, and further suggests specifics of UUS indicators. These UUS indicators were developed on the basis of analysis of urban indicator lists and UUS relevance to the goals of these lists. Arguably, UUS can be included into urban indicator lists as a separate category (such as transport), however (1) since UUS is relevant to many categories (see Table 4), and (2) UUS development is not a goal in itself, it is deemed more beneficial to have indicators reflecting UUS use included into traditional categories (as for example shown in Table 4).

3.3. Data for urban underground space indicators

How can UUS indicators be measured? What can be the units? Is data available? Who collects and handles the data on UUS?

To discuss the above questions it is appropriate to give a brief historical overview of the subject. A number of scholarly articles mention *early use of underground spaces* giving location and date (e.g. Kaliampakos, 2015), but publications giving quantitative characteristics are comparatively rare.

An early publication introducing "volume of tunnelling" and "total [developed] subsurface volume of a city" appeared in 1976 in Underground Space journal (Jansson, 1976). Duffaut (1980) pioneered quantification of UUS use in relation to other city characteristics. In his article "Past and future use of underground space in France and Europe" Pierre Duffaut presented the total volume of developed UUS in Paris, and divided it by city area resulting in "average height of [developed] underground space under the entire Paris area" as 90 centimetres. Duffaut presented data on stratification of UUI by depth as well, breaking it into three categories (0–4 m depth; 4–10; and 10–50).

Anttikoski et al. (1989) presented detailed calculations of volumes of spaces comprising a subsurface public assembly hall in Helsinki, resulting in a total volume of 62,000 cubic metres.

Bobylev (2010b) made *a comprehensive underground assets inventory* of Alexanderplatz area in the centre of Berlin, Germany, using "volume of developed underground space" as the basic descriptor. In this study, share of urban functions "on land" and "underground" (respectively) were presented, as well as "UUI distribution by depth" and "volume of developed underground space per land area" were calculated.

He et al. (2012) attempted establishing *correlations* between "UUS density" and several urban indicators when analysing use of UUS in Shanghai, China. The strongest positive correlations were found between "UUS density" and "population density", "UUS density" and "real estate price"; weak correlation was found between "UUS density" and "Gross Domestic Product per capita". In this study, the indicator "real estate price" was represented by a proxy descriptor "annual turnover" of real estate market in respective districts of Shanghai adjusted to area size.

There are some *statistical studies* on UUS use as well. ITA (2012) indicates that there are 48 underground public rail transport systems in the world to date, while Broch (2016) estimates this figure as more than 100. Cui et al. (2013) presents analysis of 19 underground pedestrian systems in cities, citing the total number of those in the world as 51. Unfortunately this type of data hardly can be used in urban indicators research, since there is no basis for comparative analysis between cities or connection to any other

Table 5
Urban Underground Space (UUS) indicators for urban indicator lists.

Urban Underground Space (UUS) indicator proposal (lowest level of hierarchy)	Possible types of indicator and explanations. Suggestions for units	
	Qualitative	Quantitative
UUS integration into master plan	Yes/no; Quality and detail rating	
Adequate consideration and use of UUS in disasters preparedness	Yes/no; Quality and detail rating	
Planning according to UUS conditions (soils, groundwater)	Yes/no	
Design and quality of public space, including underground public spaces	Expert rating [important is to have a holistic approach to public/open spaces, including large underground developments]	
Underground structures that are abandoned or inefficiently used		Ratio of inefficiently used underground space to the total developed space
Consideration of UUS use (also adjacent) in building design	Expert rating	Share of buildings that were designed taking into account current or perspective UUS use
Proportion of energy efficient UUS premises		Ratio of total floor (non residential) area in the city to energy efficient floor area, share of underground of those
Proportion of buildings using UUS for energy sourcing or storage		Share of buildings using geothermal or shallow subsurface energy exchange to the total building stock
Innovations in infrastructure and UUS use	Expert rating	
UUS use density		Volume of all physical infrastructure assets located beneath city area, divided by respective area
UUS use by function		Share of different urban functions in UUS by occupied volume
Share of renewable energy by source, including underground		Share of geothermal energy in the total energy mix (may be limited to housing sector)
Average speed of passenger travel on underground public transport		Average speed as provided by e.g. public rail operator; can be compared to above ground speeds
Share of urban functions that are underground and not consuming urban land	Expert rating	Share of different urban functions in UUS as compared to above ground functions. Descriptor can be taken as annual turnover
Stratification of UUI by depth		Share of developed UUS according to depth occupied. Categories can be taken by e.g. 1 m

Table 6
Enabling data for Urban Underground Space (UUS) urban indicators.

Urban Underground Space (UUS) indicator/descriptor	Units	Units symbol
Developed UUS volume	Cubic metres	m^3
UUS use density	Cubic metres per land area	m^3/m^2
Developed UUS volume per person	Cubic metres per person (respective [urban] area population)	m^3/person
Underground premises floor area	Square metres	m^2

urban characteristics which can be uniformly established. This highlights the challenges described in the previous sections regarding industry specific data use in urban indicators research.

A new initiative on the *Underground Atlas Project* (Kaliampakos et al., 2016) attempts to use crowdsourcing to create an online database of underground structures world-wide, which would help to expand knowledge *on geography of the structures* and eventually have some input of urban indicators cross-city analysis.

Table 6 summarises available quantitative data on UUS use, presenting a basis for UUS statistical analysis and UUS use monitoring as an urban indicator. Each of the UUS descriptors presented in Table 6 has particularities regarding its meaning and data availability options, which are summarised below:

> *Developed UUS volume* can be sourced from construction companies, civil defence offices, or owners of the structures. Data on linear infrastructure and utilities can be calculated by sourcing data on its length and type (diameter) from utility companies. Bobylev (2010b) sourced data from 12 companies to calculate the volume under a half square kilometre area. Data on *cultural heritage (archaeological objects)* usually relies on expert judgement based on historical documents. There is a difference between inner and outer volume of the structures, which preferably should be taken into account. Most volume calculations would have a degree of *approximation* related to the above complexities. *City authorities* do not possess information on volumes of underground structures, no is there any other agency where this information can be found in one place (at least there were no reports worldwide suggesting the opposite to date). *The shallow subsurface* can be screened for *buried objects*, which is a contemporary scholarly and technologically challenging task (Metje et al., 2007) and is usually done during site investigation for new construction.
>
> *UUS use density* descriptor obviously has the above described particularities pertaining to “volume of underground structures”. Data on the other component of this descriptor, land area, is usually well documented and easily available from local authorities of respective city and its districts. Attention should be given to the situations where there are significant areas distinct from a considered urban area, e.g. unused sites, water bodies, which have no developed UUS and population. Inclusion of green areas is a difficult question, since large urban forests obviously can significantly alter results of densities for urban indicators.
>
> *Developed UUS volume per person* descriptor is perhaps less vulnerable to distortion than “density of UUS use”. Numbers of urban population are well documented and available. All urban population is using UUI (at least utilities), no matter of its exact *location*, hence the above described problems with spatially distributed indicators are avoided.

Table 7
City and Urban Underground Space (UUS) use indicators in selected cities.

City	Area, km^2	Population ('000)	Population density, persons/km^2	Developed UUS volume, m^3 ('000 000)	UUS use density (m^3/m^2), shown in cm	Developed UUS volume per person m^3/person
Beijing, China 2006	3497	11,455	3275	90.0	2.6	7.9
Beijing, China 2020	3497	14,296	4088	270.0	7.7	18.9
Berlin (AlexB), Germany 2010	0.57			0.736	128.0	
Berlin (AlexS), Germany 2010	0.14			0.377	275.0	
Helsinki, Finland 1998	492	1117	2270	6.0	1.2	5.4
Helsinki, Finland 2013	215	600	2790	10.0	4.6	16.6
Paris (centre), France 1980	90	2211	24,566	82.0	91.1	37.1
Paris, France 2007	2845	10,485	3685	94.0	3.3	9.0
Quebec, Canada 1990	550	456	829	1.6	0.3	3.5
Shanghai, China 2012	6340	16,575	2614	120.0	1.9	7.2
Stockholm, Sweden 2005	382	1285	3363	11.3	2.9	8.8
Uddevalla, Sweden 1975	17	31	1823	0.35	2.1	11.3

Data sources:
City area: (Demographia, 2013), except for Uddevalla (www. uddevalla.se); Paris 1980 (Duffaut, 1980), Quebec (Boivin, 1990), Berlin (Bobylev, 2010b).
City population: (United Nations, 2012a).
Population density: (Demographia, 2013) or calculated using this table data.
Developed UUS volume: Uddevalla 1975 – (Jansson, 1976); Quebec 1990 – (Boivin, 1990); Helsinki 1998 – (Ronka et al., 1998); Helsinki 2013 – (Vahaaho, 2013); Shanghai (He et al., 2012); Beijing 2006, 2020 – (Shi, 2006); Paris 1980 – (Duffaut, 1980); Paris 2007 – (Duffaut, 2007); Stockholm 2005 – (Bobylev, 2008), Berlin (Bobylev, 2010b).
Notes:
The year in the first column refers to when the data on UUS volume was estimated.
"UUS use density" and "Developed UUS volume per person" has been calculated using this table data.

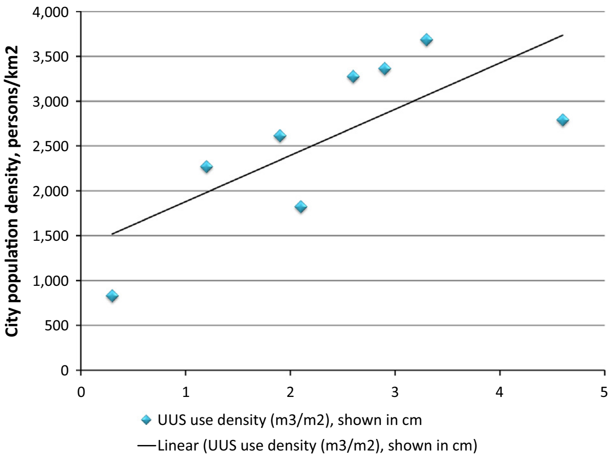

Fig. 1. Urban population and developed underground space densities.

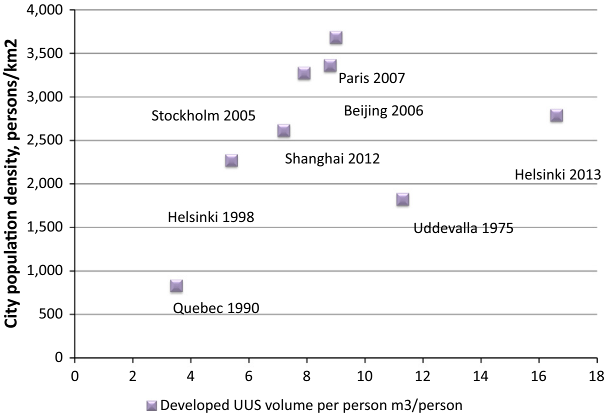

Fig. 2. Urban population density and developed underground space volume per person.

Underground premises floor area is easily available descriptor for any *commercial* premises, and constitutes the core of the real estate knowledge sector. The problem for UUS indicators research is that "floor area" is in most cases not sufficient to describe underground structures. This descriptor also is not applicable to utilities.

4. Urban underground space indicators in urban sustainability research

This section attempts to put the above described ideas on UUS urban indicators into practice. There was no special data sourcing commissioned for this study, the information presented have been sourced from scholarly publications.

Table 7 summarises the information that has been found for this study. Data on "Developed UUS volume" was available for 8 cities, and for 3 of them the data was available in two different years. Indicators "UUS use density" and "Developed UUS volume per person" were calculated using data in the table. By UUS use density we mean estimation of the volume of all physical infrastructure assets located beneath city area. UUS assets include building basements, utility infrastructure, possible abandoned structures and cultural artefacts. UUS density, as population density, is shown as average for a city.

Table 7 data was used to plot 6 diagrams, which are presented in Figs. 1–5 and 8.

Fig. 1 presents the correlation between urban population and developed underground space densities. This graph represents *the best fit amongst the others plotted* using Table 7 data. Cites (areas) shown here are Beijing, Helsinki, Paris, Quebec, Shanghai, and Stockholm. Central areas of Berlin and Paris are excluded, as well as projections for Beijing and Uddevalla. Hence, UUS use densities are limited here to below 0.05 m^3/m^2. Usually *city centres would have much more significant volumes of UUS*. Duffaut (2007) found that central area of Paris has on average about 91.1 cubic metre of underground structures' volume per square metre of land area (m^3/m^2), or an UUS virtual layer of just less than 1 m. Bobylev, 2010b, estimated this figure as *2.75* m^3/m^2 for the Alexanderplatz area in Berlin during a comprehensive case study. Average UUS densities for cities are much lower and are currently in the range of about *0.01–0.05* m^3/m^2.

Fig. 1 shows positive correlation between urban population and developed underground space densities for selected cities, which are developed cities that have significant financial resources. It can be interpreted that high population densities in developed

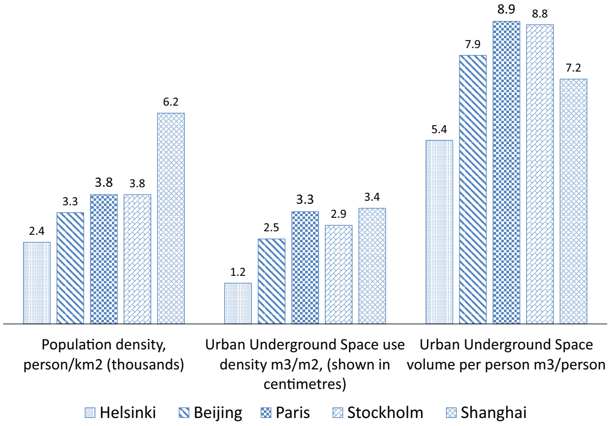

Fig. 3. Urban population density and two urban underground space use indicators in five cities.

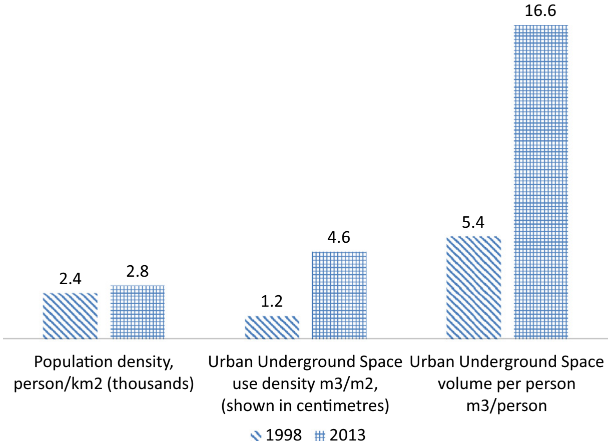

Fig. 4. Changes in population density and urban underground space use indicators in Helsinki.

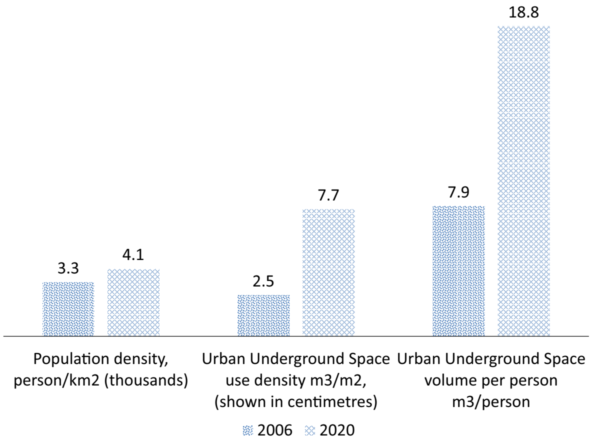

Fig. 5. Changes in population density and urban underground space use indicators in Beijing.

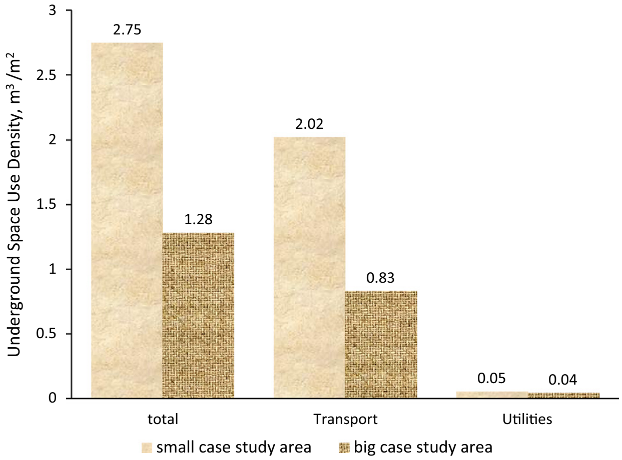

Fig. 6. Densities of the developed underground space in two case study areas. Underground infrastructure associated with Transport and Utility functions is presented as a part of all developed space. Case study of Alexanderplatz area, Berlin. *Source:* Bobylev (2010b), edited.

cities are drivers for UUS use. Further explanations regarding this correlation can be found in the discussion section.

Fig. 2 presents correlation between urban population density and developed underground space volume per person, which *is less straightforward than the correlation shown in Fig. 1*. Still we can assume meaningful correlation, since the cities of Helsinki and Uddevalla stand out by famously well developed underground space. Favourable ground conditions (bed rock) is a significant enabler for this development in both cities. Indicator UUS volume per person reflects UUS in a city not taking into account size of the urban area. This "population based" UUS indicator is a convenient way of reflecting on underground infrastructure which is used by all city dwellers, and might be located even outside the urban area (for example, sewerage treatment plants usually have sizable underground parts and often located outside city area).

Fig. 3 summarises urban population density and two UUS use indicators in five cities. This diagram presents no correlation, its purpose is to show the range of indicators values, and to show that they are in about one range for these diverse, but commonly large and important cities.

Figs. 4 and 5 make the best use of the available data and *compare UUS use in two cities*, Beijing and Helsinki. In both cities, data is available for two different years making a similar step of 15 years in Helsinki and 14 Beijing (the latter is projection to 2020 year). Interestingly, both cities show *rise in population densities*, which is not typical since wealthy developing cities are currently *sprawling* (assertion on the basis of the World Bank data (Angel et al., 2005)). One reading of this indicators comparison for Beijing and Helsinki is that both cities were able to maintain population densities growth by active use of UUS which had allowed further *densification* of the cities. Having in mind both cities and their respective country's development stage and context, we can further speculate that a need to accommodate growing population and provide public transportation is the driving force behind the Beijing UUS use growth; and *favourable ground conditions* for underground construction (bed rock) and available *wealth* facilitated UUS development in Helsinki. In these two cities we can see significant growth in UUS use, both in terms of land use density and its volume per person.

Figs. 6 and 7 give a more *local perspective on UUS use in a city centre*. The figures are sourced from *a comprehensive case study of UUS* use in two areas in the centre of Berlin around Alexanderplatz (Bobylev, 2010b). Berlin is, of course, a developed city with a rich history, the oldest documented underground structure in the case study areas was a sewer which dated back to 1880. Case study areas included the immediate vicinity of Alexanderplatz (small case study area 136 thousand square metres), and a larger area that covered several blocks of the city centre (big case study area 574

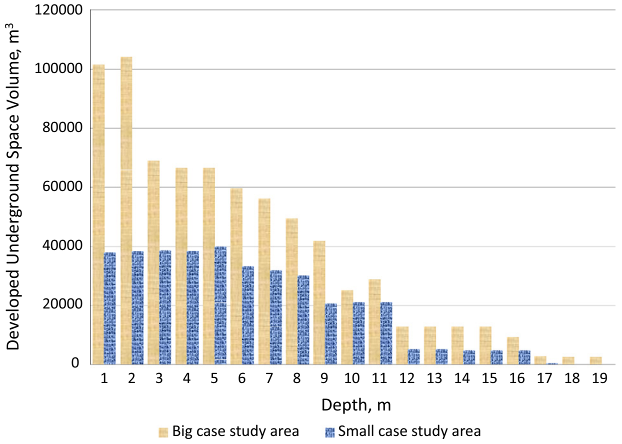

Fig. 7. Distribution of the developed underground space by depth. Case study of Alexanderplatz area, Berlin. *Source:* Bobylev (2010b), edited.

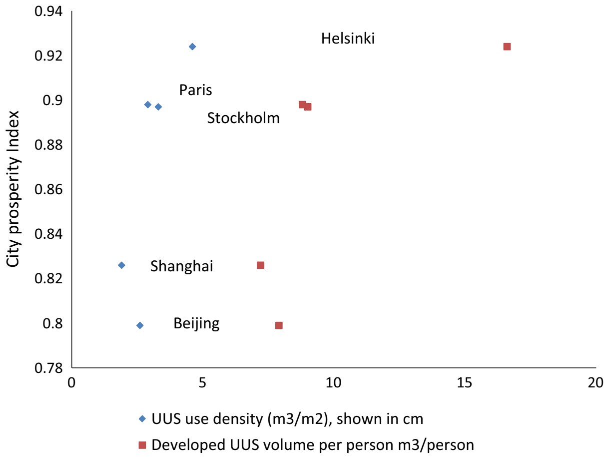

Fig. 8. City prosperity index and underground space use.

thousand square metres). As Fig. 6 shows, density of UUS use constitutes about 1–3 m^3/m^2, which can be considered as a typical representation of the current developed UUS densities in city centres of *developed or "mature" and wealthy cities*. Fig. 7 specifies distribution of underground infrastructure volume by depth, and highlights very intensive use of the first and the second metres depth of the shallow subsurface.

Fig. 8 is based on Table 8 and compares a city's prosperity index and two indicators of UUS use. *A City Prosperity Index* (UN Habitat, 2013a) is one of the similar integrated indexes which aim to capture all aspects of cites' life (e.g. by UNDP, UNECE, OECD, EUROSTAT, national governments). Urban prosperity is defined as a social construct that materialises in the realm of human actions (UN Habitat, 2013a), and a prosperous city is considered according to five main categories (productivity, infrastructure, quality of life, equity and social inclusion, environmental sustainability). According to the available statistics, there is weak correlation between city prosperity and UUS use, however we would argue that active UUS use is a sign of prosperity (which corresponds with UN Habitat "infrastructure" category), and, on the other hand, a city would need to achieve some level of prosperity to be financially able to significantly develop its UUS.

Presented data on urban UUS indicators is based on the scarce available statistics and is *indicative*, it might have a significant degree of inaccuracy. However it is important data that arguably estimates the direction and a scale of the urbanisation and UUS development processes accurately. It is worth mentioning the potential sources of inaccuracies in this research: (1) data on UUS represent credible estimations made by experts, there is no available comprehensive "*audit*" *of UUS assets*; (2) data on city areas and population can vary significantly, depending on *methodologies* of their estimation, here the challenges are whether city borders should be considered as those for administrative districts, and should empty lots, brownfields, parks, large water bodies be included. Reflecting further on data accuracy we can point out challenges to consider day and night population densities, and whether these should be based on census or surveys of actual residence. A discussion on challenges for urban indicators data collecting can be found in e.g. World Bank, 2011. None the less, this data is *credible at the level of precision required* to analyse global trends and gasp the essence of the UUS indicators importance to urban development.

5. Discussion

Urban indicators research is an important way to encourage and *monitor progress* towards sustainability. The data presented on UUS indicators, although still limited in numbers and geographically, is important *to mainstream UUS into urban sustainability research* and shows potential for *cross-disciplinary indicator analysis*. Table 9

Table 8
Urban Underground Space (UUS) use indicators and prosperity index in selected cities.

City	Area, km^2	Population ('000)	Population density, persons/km^2	Prosperity index	Developed UUS volume, m^3 ('000 000)	UUS use density (m^3/m^2), shown in cm	Developed UUS volume per person m^3/person
Beijing, China 2006	3497	11,455	3275	0.799	90.0	2.6	7.9
Helsinki, Finland 2013	215	600	2790	0.924	10.0	4.6	16.6
Paris, France 2007	2845	10,485	3685	0.897	94.0	3.3	9.0
Shanghai, China 2012	6340	16,575	2614	0.826	120.0	1.9	7.2
Stockholm, Sweden 2005	382	1285	3363	0.898	11.3	2.9	8.8

Data sources:
City area: (Demographia, 2013).
City population: (United Nations, 2012a).
Population density: (Demographia, 2013) or calculated using this table data.
Prosperity Index (with 5 dimensions): (UN-Habitat, 2013a).
Developed UUS volume: Helsinki 2013 – (Vahaaho, 2013); Shanghai (He et al., 2012); Beijing 2006 – (Shi, 2006); Paris 2007 – (Duffaut, 2007); Stockholm 2005 – (Bobylev, 2008).
Notes:
The year in the first column refers to when the data on UUS volume was estimated.
"UUS use density" and "Developed UUS volume per person" has been calculated using this table data.

Table 9
Levels/scale of urban indicators use and Urban Underground Space (UUS) relevance.

Indicator use scale	Urban Underground Space (UUS) relevance (arranged from top to bottom broadly corresponding to the Indicator categories from Global to Distinct Building)
Global	Urban sprawl
National	Land cover change
Regional	Urban energy efficiency (transport of people and goods)
Agglomeration	Rational land and underground planning
City	Rational use of urban space
City district	Efficiency of urban infrastructure
Municipality	Public open space
Block, street, square	Energy efficiency
Distinct building	

suggests how UUS indicators are relevant to different levels or scales of their use.

The analysed data show that global UUS use is a complex, *multi-dimensional* subject, which perhaps would not show any correlation or dependency upon other cities indicators that would be applicable to any city. This is true for the vast majority of urban indicators stemming from other disciplines as well, which is explained by the diverse nature of urban settlements.

Indeed, the *highest population densities* are observed in *poorly developed megacities*, often incorporating slum areas (e.g. Dhaka, Bangladesh has the highest density of 44,500 people per square kilometre (UN Habitat, 2013a)). These urban areas have hardly any underground infrastructure at all. However, in the developed cities, densification is required to make UUS use to be *economically feasible* (population densities in city centres, people per square kilometre: Helsinki – 16,500 (Vahaaho, 2013); Paris – 21,196 (INSEE, 2009)).

There is no direct correlation between city size in terms of area or population, city *wealth or prosperity*, and UUS indicators, although intensive UUS use is inherent to developed, wealthy countries and cities, or cities which are capitals and wealthy in comparison to others in the country (e.g. Moscow, Russia has elaborated metro and other UUS facilities).

An important factor that influences UUS development is, of course, *ground conditions*, upon which the price of underground excavations and construction risks largely depend. However unfavourable ground conditions (e.g. highly water saturated weak soils) cannot be nowadays seen as an obstacle for UUS development, since many e.g. European cities are built on weak soils and use UUS actively (e.g. Amsterdam).

UUS use in a city is a complex phenomenon and depends upon a large number of factors, including but not limited to ground conditions; climate; geographical location; urban area size in terms of area and population; variety of urban densities, including build stock, population, economic activity; policy and politics for using resources, including renewable energy and contemporary climate change agenda. Most notably, UUS use depends upon city development stage, i.e. transformation village–town–city, which is a complex notion in itself. City "maturity" is a necessary, but not sufficient condition for intensive UUS use.

6. Conclusion

6.1. Results

The paper has reviewed *urban indicator lists (systems)* and has identified the importance of UUS inclusion in the lists that give integrated assessment and monitor *urban sustainability, resilience, climate change adaptation and mitigation, as well as progress towards smart, liveable, and compact city*.

Urban indicators and the UUS themes are relevant to each other in two ways: (1) helping enhance *comprehensiveness and validity* of traditional urban indicator lists focused on sustainability, resilience, etc. (see Table 3 for details), and (2) helping better development of UUS, bringing *wider perspective on its resources use*.

Compatibility, comparability, uniformity, and sustained monitoring of urban indicators data (including UUS indicators) were found to be posing significant challenges to the research across geographies, and industry/economic sectors.

The best way to consider UUS in urban agendas is to include UUS relevant indicators at the *lowest hierarchy level* under the *established categories* in the lists. UUS can feature in several categories (see Table 4 for details).

Three key indicators (descriptors) are suggested to monitor UUS use:

- Developed UUS volume (m^3).
- UUS use density (m^3/m^2).
- Developed UUS volume per person (m^3/person).

Additionally data on *share of urban functions* in underground space and in above ground space can be collected, as well as stratification of UUS use by depth.

Current average UUS use densities in cities are up to about 0.05 (m^3/m^2) (which can be interpreted as a virtual depth of UUS use of 5 centimetres), and the developed UUS volume per person is up to about 10 m^3/person; while city central areas (central business districts) can have a virtual depth of the developed UUS of several metres (m^3/m^2).

Theoretically, the indicator "Developed UUS volume per person" should more accurately reflect on urban UUS use sine it avoids *conceptual problems* with defining the correct area for analysing *density;* however, the best fit correlation was found with the "UUS use density" indicator (Fig. 1).

6.2. Recommendations

- Enable co-ordination in developing methodological assistance, data collection, and monitoring of the *UUS urban indicators at an international level* (this role can be assumed by one of the *United Nations* agencies concerned with urban indicators). Similar co-ordination can be arranged at national levels as well.
- Create *inventory of UUS assets*, to make informed decisions on further development of UUS at the regional and city level. In fact this has been first highlighted by Sterling (1996) as a public policy recommendation stemming from a Colloquium on underground space utilisation in the US: "mandate the investigation and recording of an inventory of existing underground structures for future reference". This recommendation can be expanded to UUS resource use, including inventory of groundwater use and energy extraction/storage.
- Consider including UUS indicators in international "*green*" *building certification systems* like LEED and BREAM.

UUS is extremely relevant to the urban agendas, but without its *explicit inclusion into urban indicator lists*, UUS issues remain invisible to *policy makers*.

Acknowledgement

The reported research has been funded by the European Community 7th Research Framework programme under People Marie Curie actions, Grant PIIF-GA-2010-273861.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tust.2015.10.024.

References

Angel, S., Sheppard, S.C., Civco, D.L., 2005. The Dynamics of Global Urban Expansion. World Bank, Washington, DC.

Anttikoski, U., Grön, V., Halme, A., Juhola, M., Palmu, M., i Parkkamäki, O., Tuisku, T., Äyräväinen, O., 1989. Subsurface public assembly spaces in Finland. Tunn. Undergr. Space Technol. 4 (1), 17–22, ISSN 0886-7798.

Bobylev, N., 2006. Strategic environmental assessment of urban underground infrastructure development policies. Tunn. Undergr. Space Technol. 21 (3–4), 469–479. http://dx.doi.org/10.1016/j.tust.2005.12.106 (Elsevier) ISSN: 0886-7798.

Bobylev, N., 2007. Sustainability and vulnerability analysis of critical underground infrastructure. In: Linkov, I., Wenning, R., Kiker, G. (Eds.), Managing Critical Infrastructure Risks, NATO Security through Science Series. Springer, Netherlands, pp. 445–469. http://dx.doi.org/10.1007/978-1-4020-6385-5_26, ISBN: 978-1-4020-6385-5.

Bobylev, N., 2008. Urbanization and environmental security: infrastructure development, environmental indicators, and sustainability. In: Liotta, P.H. et al. (Eds.), Environmental Change and Human Security, NATO Science Series: IV: Earth and Environmental Sciences. Springer Science + Business Media B.V., pp. 203–216, ISBN 978-1-4020-8550-5.

Bobylev, N., 2009a. Mainstreaming sustainable development into a city's master plan: a case of urban underground space use. Land Use Policy 26 (4), 1128–1137. http://dx.doi.org/10.1016/j.landusepol.2009.02.003 (Elsevier).

Bobylev, N., 2009b. Urban underground infrastructure and climate change: opportunities and threats. In: 5th Urban Research Symposium, Marseille, France, June 28–30, 2009, 17p <http://go.worldbank.org/P74DFSRCD0>.

Bobylev, N., 2010a. Ecosystem services in the context of human development. In: Liotta, P.H. et al. (Eds.), Achieving Environmental Security: Ecosystem Services and Human Welfare. IOS Press, Amsterdam, pp. 183–205, ISBN 978-1-60750-578-5.

Bobylev, N., 2010b. Underground space use in the Alexanderplatz area, Berlin: research into the quantification of urban underground space use. Tunn. Undergr. Space Technol. 25 (5), 495–507. http://dx.doi.org/10.1016/j.tust.2010.02.013.

Bobylev, N., 2011. Comparative analysis of environmental impacts of selected underground construction technologies using analytic network process. Automat. Constr. 20 (8), 1030–1040. http://dx.doi.org/10.1016/j.autcon.2011.04.004 (Elsevier).

Bobylev, N., 2013. Urban physical infrastructure adaptation to climate change. In: Saulnier, J.B., Varella, M.D. (Eds.), Global Change Energy Issues and Regulation Policies, Integrated Science & Technology Program 2. Springer Science+Business Media, Dordrecht, pp. 77–102. http://dx.doi.org/10.1007/978-94-007-6661-7_4.

Bobylev, N., 2014. Addressing urban disaster risks via a combination of responsible land use and critical infrastructure management. In: Presentation at the Geospatial World Forum. Land Information Systems for Smart Cities 8–9 May 2014, Geneva, Switzerland <www.unece.org/index.php?id=34473>, <http://www.geospatialworldforum.org/proceedings.htm>.

Bobylev, N., Hunt, D.V.L., Jefferson, I., Rogers, C.D.F., 2013. Sustainable infrastructure for resilient urban environments. In: Zhou, Cai, Sterling (Eds.), Advances in Underground Space Development, Copyright 2013 by The Society for Rock Mechanics & Engineering Geology (Singapore). Published by Research Publishing, pp. 906–917. ISBN: 978-981-07-3757-3, http://dx.doi.org/10.3850/978-981-07-3757-3 (RP-107-P219).

Boivin, D.J., 1990. Underground space use and planning in the Québec City area. Tunn. Undergr. Space Technol. 5 (1–2), 69–83. http://dx.doi.org/10.1016/0886-7798(90)90062-O, ISSN 0886-7798.

BRE Global, 2011. SD5065 Technical Guidance Manual: Version 1. BREEAM for Communities Assessor Manual: Development Planning Application Stage.

Broch, E., 2016. Planning and utilisation of rock caverns and tunnels in Norway. Tunn. Undergr. Space Technol., Special Issue on Urban Underground Space: A Growing Imperative. 55, 329–338.

Brundtland Commission, 1987. Our Common Future, Report of the World Commission on Environment and Development, World Commission on Environment and Development, 1987. Published as Annex to General Assembly Document A/42/427, Development and International Co-operation: Environment August 2, 1987.

Carmody, J., Sterling, R., 1993. Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces. Van Nostrand Reinhold, New York, January 1993.

Castanheira, G., Bragança, L., 2014. The evolution of the sustainability assessment tool SBToolPT: from buildings to the built environment. Sci. World J. 62 (4), 1 (2356–6140).

CEROI Project, 2010. Cities Environment Reports on the Internet (CEROI) Official Webpage <http://www.ceroi.net> (last visited: 22.3.2010).

CRISP Project, 1999. A European Thematic Network on Construction and City Related Sustainability Indicators. Final Report.

Cui, J., Allan, A., Taylor, M., Lin, D., 2013. Underground pedestrian systems development in cities: influencing factors and implications. Tunn. Undergr. Space Technol. 35, 152–160. http://dx.doi.org/10.1016/j.tust.2012.12.009, ISSN 0886-7798.

Daly, G., González, A., 2013. Key indicators for territorial cohesion and spatial planning: the reform of the EU cohesion policy and the new role of spatial indicators. Borderl. J. Spat. Plan. Irel. 3, 77–89.

Demographia, 2013. World Urban Areas: 9th Annual Edition (2013.03) <http://www.demographia.com/>.

Duffaut, P., 1980. Past and future use of underground space in France and Europe. Undergr. Space 5 (2), 86–91.

Duffaut, P., 2007. Urbanisme souterrain. Pano-rama historique et géographique. Techniques de l'Ingénieur C3061-2, Paris.

European Commission, 2003. European Common Indicators: Towards a Local Sustainability Profile. European Common Indicators Project, Final Project Report, Milano, Italy, May.

Eurostat, 2009. Sustainable Development in the European Union: 2009 Monitoring Report of the EU Sustainable Development Strategy. Eurostat Statistical Books.

Foster, N., 2011. Lord Foster Inaugural Lecture as Humanities Visiting Professor of Architecture at the University of Oxford <http://podcasts.ox.ac.uk/norman-foster-lecture-audio>.

Gonzalo, M.B., Bovea, M.D., Ruá, M.J., 2015. Sustainability on the urban scale: proposal of a structure of indicators for the Spanish context. Environ. Impact Assess. Rev. 53 (2015), 16–30.

He, L., Song, Y., Dai, S., Durbak, K., 2012. Quantitative research on the capacity of urban underground space – the case of Shanghai, China. Tunn. Undergr. Space Technol. 32 (2012), 168–179.

Hunt, D.V.L., Makana, L.O., Jefferson, I., Rogers, C.D.F., 2016. Liveable cities and urban underground space. Tunn. Undergr. Space Technol., Special Issue on Urban Underground Space: A Growing Imperative. 55, 8–20.

INSEE, 2009. Institute National de la Statistique et des Études Économiques: INSEE (France's National Institute of Statistics and Economic Studies) online database <http://www.insee.fr>.

ITA, 2012. Report on Underground Solutions for Urban Problems. International Tunnelling and Underground Space Association. ISBN 978-2-9700776-5-7.

ITACUS, 2010. ITA Committee on Underground Space White Paper #2 "Planning the Use of Underground Space".

Jansson, B., 1976. Terraspace – a world to explore. Undergr. Space 1 (1), 9–18.

Kaliampakos, D., 2015. New challenges in the use of underground space. SEE Tunnel: promoting tunneling in SEE Region. In: Proceedings of the ITA WTC 2015 Congress and 41st General Assembly, Dubrovnik, Croatia, May 22–28, 2015.

Kaliampakos, D., Benardos, A., Mavrikos, A., Panagiotopoulos, G., 2016. The Underground Atlas Project. Tunn. Undergr. Space Technol., Special Issue on Urban Underground Space: A Growing Imperative. 55, 229–235.

Lynch, A.J., Andreason, S., Eisenmen, T., Robinson, J., Stelf, K., Birch, E.L., 2011. Sustainable urban Development Indicators for the United States. Reports in Penn Penn Institute for Urban Research. White Paper Series on Sustainable Urban Development <http://penniur.upenn.edu/>.

Makana, L.O., Jefferson, I., Hunt, D.V.L., Rogers, C.D.F., 2016. Assessment of the future resilience of urban sub-surface environments. Tunnel. Undergr. Space Technol., Special Issue on Urban Underground Space: A Growing Imperative. 55, 21–31.

Metje, N., Atkins, P.R., Brennan, M.J., et al., 2007. Mapping the underworld: state of the art review. Tunn. Undergr. Space Technol. 22 (5–6), 568–586.

Michael, F.L., Noor, Z.Z., Figueroa, M.J., 2014. Review of urban sustainability indicators assessment – case study between Asian countries. Habitat Int. 44 (2014), 491–500.

Moussiopoulos, N., Achillas, C., Vlachokostas, C., Spyridi, D., Nikolaou, K., 2010. Environmental, social and economic information management for the evaluation of sustainability in urban areas: a system of indicators for Thessaloniki, Greece. Cities 27 (2010), 377–384.

OECD, 2004. Organization for Economic Co-operation and Development Key Environmental Indicators. OECD Environment Directorate, Paris, France.

OECD, 2006. Organization for Economic Co-operation and Development. Infrastructure to 2030: Telecom, Land Transport, Water and Electricity. ISBN 92-64-02398-4.

OECD, 2008. Organization for Economic Co-operation and Development. "Urbanisation", in OECD Environmental Outlook to 2030, OECD Publishing ISBN 978-92-64-04048-9.

Rogers, C.D.F., 2009. Substructures, underground space and sustainable urban environments. Engineering Geology for Tomorrow's Cities. In: Culshaw, M.G., Reeves, H.J., Jefferson, I., Spink, T.W. (Eds.), Geological Society, London, Engineering Geology Special Publications, No. 22, pp. 177–188.

Ronka, K., Ritola, J., Rauhala, K., 1998. Underground space in land-use planning. Tunn. Undergr. Space Technol. 13 (1), 39–49.

SCR, 2015. Sustainable Community Rating <www.places.vic.gov> (Last access June 2015).

Shen, L.Y., Ochoa, J.J., Shah, M.N., Zhang, X., 2011. The application of urban sustainability indicators – a comparison between various practices. Habitat Int. 35 (2011), 17–29.

Shi, X.D., 2006. Review and Vista of Beijing Underground Space Utilization. Planning and Construction of Beijing. Beijing Planning Review, Beijing, pp. 32–40.

Sterling, R., Nelson, P., 2013. City resiliency an underground space use. In: Zhou, Cai, Sterling (Eds.), Advances in Underground Space Development, Copyright 2013 by The Society for Rock Mechanics & Engineering Geology (Singapore). Published by Research Publishing. pp. 56–14. ISBN: 978-981-07-3756-6.

Sterling, R., 1996. Going under to stay on top, revisited: results of a colloquium on underground space utilization. Tunn. Undergr. Space Technol. 11 (3), 263–270.

Sterling, R., 1997. Underground technologies for liveable cities. Tunn. Undergr. Space Technol. 12 (4), 7–8.

Sterling, R., Admiraal, H., Bobylev, N., Parker, H., Godard, J.P., Vähäaho, I., Rogers, C. D.F., Shi, X., Hanamura, T., 2012. Sustainability issues for underground space in urban areas. Proc. ICE – Urban. Des. Plan. 165 (4), 241–254. http://dx.doi.org/10.1680/udap.10.00020 (14).

UN Habitat, 2006. The United Nations Human Settlements Programme. State of the World's Cities 2006/7, UN-HABITAT, Nairobi.

UN Habitat, 2013a. United Nations Human Settlements Programme. State of Cities Report. Routledge for and on Behalf of the United Nations Human Settlements Programme (UN-Habitat). ISBN13: 978-0-415-83888-7.

UN Habitat, 2013b. United Nations Human Settlements Programme. Urban indicators Guidelines: Monitoring the Habitat Agenda and the Millennium Development Goals <http://ww2.unhabitat.org/programmes/guo/documents/urban_indicators_guidelines.pdf>.

UNEP, 2012. United Nations Environment Programme. GEO5 Global Environment Outlook: Environment for the Future We Want. United Nations Environment Programme, Valletta, Malta.

United Nations, 1995. Agenda 21 <http://web.archive.org/web/20090420073232/> (last access, June 2015).

United Nations, 2007. Indicators of Sustainable Development: Guidelines and Methodologies, third ed. Department of Economic and Social Affairs, Commission on Sustainable Development, New York.

United Nations, 2012a. World Population Prospects. Population Division of the United Nations Department of Economic and Social Affairs of the United Nations Secretariat <http://www.un.org/esa/desa>.

United Nations, 2012b. Secretary-General's Video Message to the World Tunnel Congress. Bangkok, Thailand, 21 May 2012 <http://www.un.org/sg/statements/?nid=6064> (Accessed on May 27).

United Nations Sustainable Development Office, 1998. Indicators of Sustainable Development: Guidelines and Methodologies.

Urban Audit, 2004. Urban Audit Methodological Handbook. Office for Official Publications of the European Communities.

US GBC, 2009. LEED for Neighborhood Development. The U.S. Green Building Council.

Vahaaho, I, 2013. 0-Land use: underground resources and master plan in Helsinki. In: Zhou, Cai, Sterling (Eds.), Advances in Underground Space Development, Copyright 2013 by The Society for Rock Mechanics & Engineering Geology (Singapore). Published by Research Publishing. pp. 56–14. ISBN: 978-981-07-3756-6.

Wende, W., Huelsmann, W., Marty, M., Penn-Bressel, G., Bobylev, N., 2010. Climate protection and compact urban structures in spatial planning and local construction plans in Germany. Land Use Policy 27 (3), 864–868. http://dx.doi.org/10.1016/j.landusepol.2009.11.005.

WHO, 1999. World Health Organization. Environmental Health Indicators: Framework and Methodologies. Protection of the Human Environment Occupational and Environmental Health Series, Geneva.

World Bank, 2011. The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium. World Bank, Washington, D.C..

World Bank, 2012. The World Bank Annual Report 2012: Volume 2. Responding with Knowledge and Experience. Washington, DC <https://openknowledge.worldbank.org/handle/10986/11845>.

World Bank, 2015. World Development Indicators 2015. World Bank, Washington, DC