

Supplementary Materials (SM)

Assessing Resource Efficiency of City Neighbourhoods: A Methodological Framework for Structuring and Practical Application of Indicators in Urban Planning

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SM to Chapter 2.2: Literature Review on the application of Indicators in Urban Planning

For a survey on the application of indicators for sustainability assessment in urban planning, a review of literature was carried out. The databases Web of Science and Google Scholar were searched using the following keywords or combinations: “Indicators in urban planning”, “urban planning indicators”, “material indicators in urban planning”, “environmental indicators in urban planning”, “resource indicator in urban planning”, “sustainability indicators in urban planning”. From the researched papers the following were excluded: exclusively theoretical publications; publications on the topic of building sustainability assessment. Finally, 45 peer reviewed full journal published between 1998 and 2022 were selected for evaluation (Table S1).

Table S1. Listing of the literature reviewed on the application of Indicators in Urban Planning

No.	Author	Title	Doi	Year
1	Huang, S.-L.; Wong, J.-H. & Chen, T.-C.	A framework of indicator system for measuring Taipei's urban sustainability	10.1016/S0169-2046(98)00054-1	1998
2	Whitford, V.; Ennos, A.R. & Handley, J.F.	“City form and natural process” - Indicators for the ecological performance of urban areas and their application to Merseyside, UK	10.1016/S0169-2046(01)00192-X	2001
3	Black, J. A.; Paez, A. & Suthanaya, P. A.	Sustainable Urban Transportation: Performance Indicators and Some Analytical Approaches	10.1061/(ASCE)0733-9488(2002)128:4(184)	2002
4	Huang, S. L. & Hsu, W. L.	Materials flow analysis and emergy evaluation of Taipei's urban construction	10.1016/S0169-2046(02)00152-4	2003
5	Holden, M.	Revisiting the local impact of community indicators projects: Sustainable Seattle as prophet in its own land	10.1007/s11482-007-9020-8	2006
6	Holden, M.	Urban indicators and the integrative ideals of cities	10.1016/j.cities.2006.03.001	2006
7	Repetti, A. & Desthieux, G.	A Relational Indicatorset Model for urban land-use planning and management: Methodological approach and application in two case studies	10.1016/j.landurbplan.2005.02.006	2006
8	Hunt, D. V., Lombardi, D. R., Rogers, C. D. & Jefferson, I.	Application of sustainability indicators in decision-making processes for urban regeneration projects	10.1680/ensu.2008.161.1.77	2008

9	Li, Feng; Liu, Xusheng; Hu, Dan; Wang, Rusong; Yang, Wenrui; Li, Dong & Zhao, Dan	Measurement indicators and an evaluation approach for assessing urban sustainable development: A case study for China's Jining City	10.1016/j.landurbplan.2008.10.022	2009
10	Fernández-Sánchez, G. & Rodríguez-López, F.	A methodology to identify sustainability indicators in construction project management—Application to infrastructure projects in Spain	10.1016/j.ecolind.2010.04.009	2010
11	González, A; Donnelly, A; Jones, M; Klostermann, J.; Groot, A. & Breil, M.	Community of practice approach to developing urban sustainability indicators	10.1142/S1464333211004024	2011
12	Rosales, N.	Towards the modeling of sustainability into urban planning: Using indicators to build sustainable cities	10.1016/j.pro-eng.2011.11.2060	2011
13	Zhao, C.; Fu, G.; Liu, X. & Fu, F.	Urban planning indicators, morphology and climate indicators: A case study for a north-south transect of Beijing, China	10.1016/j.build-env.2010.12.009	2011
14	Gómez-Baggethun, E. & Barton, D. N.	Classifying and valuing ecosystem services for urban planning	10.1016/j.ecolecon.2012.08.019	2013
15	González, A.; Donnelly, A.; Jones, M.; Chrysoulakis, N. & Lopes, M.	A decision-support system for sustainable urban metabolism in Europe	10.1016/j.eiar.2012.06.007	2013
16	Petralli, M.; Massetti, L.; Brandani, G. & Orlandini, S.	Urban planning indicators: useful tools to measure the effect of urbanization and vegetation on summer air temperatures	10.1002/joc.3760	2013
17	Chrysoulakis, N.; Feigenwinter, C.; Triantakou, D.; Penyevskiy, I.; Tal, A.; Parlow, E.; Fleishman, G.; Düzgün, S.; Esch, T. & Marconcini, M	A Conceptual List of Indicators for Urban Planning and Management Based on Earth Observation	10.3390/ijgi3030980	2014
18	Inostroza, L.	Measuring urban ecosystem functions through 'Technomass'—A novel indicator to assess urban metabolism	10.1016/j.ecolind.2014.02.035	2014
19	La Rosa, D.	Accessibility to greenspaces: GIS based indicators for sustainable planning in a dense urban context	10.1016/j.ecolind.2013.11.011	2014
20	Massetti, L.; Petralli, M.; Brandani, G. & Orlandini, S.	An approach to evaluate the intra-urban thermal variability in summer using an urban indicator	10.1016/j.envpol.2014.04.026	2014
21	Michael, F. L.; Noor, Z. Z., & Figueroa, M. J	Review of urban sustainability indicators assessment—Case study between Asian countries	10.1016/j.habitatint.2014.09.006	2014
22	Piña, W. H. A. & Martínez, C. I. P.	Urban material flow analysis: An approach for Bogotá	10.1016/j.ecolind.2013.10.035	2014
23	Behling, R.; Bochow, M.; Foerster, S.; Roessner, S. & Kaufmann, H.	Automated GIS-based derivation of urban ecological indicators using hyperspectral remote sensing and height information.	10.1016/j.ecolind.2014.08.003	2015
24	Kitchin, R.; Lauriault, T. P. & McArdle, G.	Knowing and governing cities through urban indicators, city benchmarking and real-time dashboards.	10.1080/21681376.2014.983149	2015
25	Pissourios, I. A.	Critical analysis of the official Greek urban planning indicators of private uses.	10.1016/j.landusepol.2014.07.007	2015

26	Rodríguez, M. I.; Cuevas, M. M.; Huertas, F.; Martínez, G. & Moreno, B.	Indicators to evaluate water sensitive urban design in urban planning	10.2495/SD150321	2015
27	Triantakostas, Dimitrios; Chrysoulakis, Nektarios; Sazonova, Anna; Esch, Thomas; Feigenwinter, Christian; Düzgün, Sebnem; Parlow, Ebwerhard; Marconcini, Mattia & Tal, Abraham	On-line Evaluation of Earth Observation Derived Indicators for Urban Planning and Management	10.14355/updr.2015.03.003	2015
28	King, L. O.	Functional sustainability indicators	10.1016/j.ecolind.2016.01.027	2016
29	Medved, P.	A contribution to the structural model of autonomous sustainable neighbourhoods: new socio-economical basis for sustainable urban planning	10.1016/j.jclepro.2016.01.091	2016
30	Saarela, S. R. & Rinne, J.	Knowledge brokering and boundary work for ecosystem service indicators. An urban case study in Finland	10.1016/j.ecolind.2015.07.016	2016
31	Lina, P.; Siu Yu Lau, S.; Qin, H. & Gou Z.	Effects of urban planning indicators on urban heat island: a case study of pocket parks in high-rise high-density environment	10.1016/j.landurbplan.2017.09.024	2017
32	Liu, Meng; Zhong, Yiqun; Tan, Jingyue	Impact of Urban Planning Indicator on Spatial Distribution of Residential Heating and Cooling Energy Demand	10.1016/j.proeng.2017.10.150	2017
33	Mohamed, R. S., Bakr, A. F., & Anany, Y. M	New Urban Indicators for Evaluating Urban Polices in Egypt: City Capacity and Capability (Capa2)	10.1016/j.proenv.2017.03.017	2017
34	Pupphachai, U., & Zuidema, C.	Sustainability indicators: A tool to generate learning and adaptation in sustainable urban development.	10.1016/j.ecolind.2016.09.016	2017
35	Chudiniva, O. & Afonina, M.	Formation of "Urban planning" indicators for "Smart City" concept (on the example of SKOLKOVO, Moscow)	10.1051/mateconf/201817002021	2018
36	Garau, C. & Pavan, V.	Evaluating Urban Quality: Indicators and Assessment Tools for Smart Sustainable Cities	10.3390/su10030575	2018
37	Badach, J. & Raszeja, E.	Developing a Framework for the Implementation of Landscape and Greenspace Indicators in Sustainable Urban Planning. Waterfront Landscape Management: Case Studies in Gdańsk, Poznań and Bristol	10.3390/su11082291	2019
38	Musa, H. D.; Yacob, M. R. & Abdullah, A. M.	Delphi exploration of subjective well-being indicators for strategic urban planning towards sustainable development in Malaysia	10.1016/j.jum.2018.08.001	2019
39	Rajaonson, J. & Tanguay, G. A.	Urban Sustainability Indicators from a Regional Perspective: Lessons from the Montreal Metropolitan Area	10.1007/s11205-017-1823-x	2019
40	DiNapoli, B. & Jull, M.	Urban planning sustainability metrics for Arctic cities	10.1088/1748-9326/abc37b	2020

41	Kramer, C. & Wagner, M.	Enhancing Urban Sustainable Indicators in a German City—Towards Human-Centered Measurements for Sustainable Urban Planning	10.3390/world1020009	2020
42	Luo, Y. & He, J.	Evaluating the heat island effect in a planned residential area using planning indicators.	10.1016/j.jobe.2021.102473	2021
43	Patias, N.; Rowe, F.; Cavazzi, S. & Arribas-Bel, D.	Sustainable urban development indicators in Great Britain from 2001 to 2016.	10.1016/j.landurbplan.2021.104148	2021
44	Reicher, O.; Delgado, V. & Arumi, J.-L.	Use of Indicators in Strategic Environmental Assessments of Urban-Planning Instruments: A Case Study	10.3390/su132212639	2021
45	Schinkel, U.; Becker, N.; Trapp, M. & Speck, M.	Assessing the Contribution of Innovative Technologies to Sustainable Development for Planning and Decision-Making Processes: A Set of Indicators to Describe the Performance of Sustainable Urban Infrastructures (ISI)	10.3390/su14041966	2022

For the 45 journal articles the application areas for indicators were evaluated by a structured list of topics related to sustainability assessment presented in (Table S2) The topics addressed include issues directly related to natural resources (e.g. water, land, material flows), but also go beyond (e.g. sociocultural aspects). The term resource efficiency is not used explicitly, but was found as a subtopic, notably in the topics material flows and sustainability assessment.

Table S2: Topics of application areas for indicators in urban planning (total: 46 publications, multiple entries possible)

Issues	Number of entries	Topics
Water	4	water cycle and waste water management
Material Flows	4	material flows analysis based on the concept of urban metabolism. Single authors use the term natural resources
Mobility	3	Urban transportation
Climate	10	Inner city climate (e.g. surface temperature), heat islands
Land use, Biodiversity and Ecosystem services	23	Urban land use planning, landscape and green space, Green infrastructure
Sociocultural aspects	6	Social factors of neighbourhoods; sociocultural aspects are often connected to other topics (e.g. as aspects of quality of urban life, How do citizens perceive and react
Sustainability assessment (general)	16	Comprehensive assessment of ecological, social, economic dimensions, (possibly further dimensions, e.g. political, cultural). Auch Zertifizierungsschemata für nachhaltige Gebäude. Covers i.a. also resource efficiency
Other	9	Environmental quality, Strategic Environmental Assessment (SEA), Smart City, subjective well-being, governance, infrastructures/technologies

Table S3: Interpretation of the DPSIR Model for the neighbourhood level

Element of Causal network		Examples	Interpretation for neighborhoods	Application in urban development
D	Driving Force	Population development (changes in the number and structure of the population), development of industry, trade and commerce	<p>Profile indicators used as background information describing the character of the neighbourhood (residential, industrial, mixed), the status and trend of population development, the status and trend of economic development, and the status and trend of the local climate. As a rule, background aspects cannot be directly influenced in the neighbourhood; they can be interpreted as framework conditions.</p> <p>If in the focus of investigation, alternatively, number and structure of population can also be interpreted as state and the trend of change as state change.</p>	<p>The description of the "driving forces" can be used, among other things, for the characterisation of the object of assessment ("neighbourhood"). This provides a basis for addressing questions of the (non-)comparability of neighbourhoods. The "driving forces" can thus become part of the "profile indicators as background information. These include the character of the neighbourhood (residential, industrial, mixed), the status and trend of population development, the status and trend of economic development, and the status and trend of the local climate. As a rule, such aspects cannot be directly influenced in the neighbourhood; they can be interpreted as framework conditions.</p>
P	Pressure	energy and material flows resulting from the driving forces	<p>energy and material flows triggered by activities in the neighbourhood. Such pressures can be assessed both directly (measurements) and indirectly (calculations), dependent also from the question whether and with what effort the required data can be determined or which data is already available.</p>	<p>As to pressures", the energy and material flows triggered by activities in the neighbourhood can be recorded. They can be determined both directly (measurements) and indirectly (calculations). The type and scope of the recording is strongly influenced by whether and with what effort the required data can be determined or which data is already available. "Pressures" usually describe events or activities that can affect states or lead to changes in states.</p>

S	State	Conditions with regard to soil, water, outdoor air	<p>Conditions in the district or neighborhood are of interest to be recorded and assessed as initial and final conditions and as changes in condition. By tracking trends, state changes can be identified in terms of magnitude and direction. There is an interest in continuous recording and evaluation of states, preferably via measurements. The results can be summarised i.a. as the "local state of the environment in the neighbourhood". This can be interpreted as the initial state. An evaluation is possible through a comparison with relative or absolute values. Target states can be defined and the pace and degree of target achievement can be analysed as a result of activities and measures.</p>	<p>The "State" always is related to a certain point in time. By tracking trends, state changes can be identified in terms of magnitude and direction. There is an interest in continuous recording and evaluation of states, preferably via measurements. The results can be summarised, among other things, as the "local state of the environment in the neighbourhood". This can be interpreted as the initial state. An evaluation is possible through a comparison with relative or absolute values. Target states can be defined and the pace and degree of target achievement can be analysed as a result of activities and measures.</p>
I	Impacts	Effects on the environment, economy and society, in the broader sense as part of a sustainability assessment	<p>"effects on the local but also regional and global environment of districts and neighbourhoods. Environmental impacts can be recorded as midpoints and/or endpoints. Target values can also be formulated for impact categories. In a broader sense in view of sustainability assessment, impacts on the economy and society can be included.</p>	<p>"Impacts" describe the effects on the local and global environment and assess them using evaluation criteria. In a broader sense, impacts on the economy and society can be included. Such impacts can be recorded as midpoints and/or endpoints. Target values can also be formulated for impact categories.</p>
R	Responses	Reactions or measures	<p>Organisational, technical or structural measures of urban development (also as part of projects), but sometimes also campaigns, support programmes, legislative initiatives.</p>	<p>"Responses" describe reactions. These are organisational, technical or structural measures, but sometimes also campaigns, support programmes, legislative initiatives.</p>

Table S4: Scheme for classification of indicators into the typology

It is shown how the DPSIR model can be transferred to the area of urban development at neighbourhood level

Drivers	State indicators in a broader sense		Performance indicators	Impact indicators
	Pressures	State		
Socio-economic activities (e.g. mobility)	Air pollution	Quality of outdoor air	Serviceability	Global warming potential
	Water pollution	Quality of surface water	Technical efficiency ¹	Resource depletion
	Soil pollution	Quality of ground water	Technical service life	Impact on biodiversity
		Quality of soil	Environmental performance	Impact on community
			Social performance	Impact on society
			Economic performance	External cost

¹In the meaning of technical efficiency of measures like filter performance, cleaning performance, evaporation performance

Table S5: Selected examples of indicators

The examples comply to the requirement stated in Schebek et al. 2022 that a complete definition of an indicator shall include at least the following information:

- (1) The textual description of the conceptual idea of the indicator,
- (2) the procedure for its derivation, including the unit for quantification
- (3) the specification of a measurement rule for an indicator

For a Performance Indicator, also the measure to which it refers must be specified.

Example State Indicator

Denomination	Degree of sealing
Description	Percentage of a sealed area in relation to a total area.
Background	Sealing of surfaces/soil prevents precipitation from seeping into the ground. This has consequences for groundwater recharge, flood risk, and the local wastewater network, which can become overloaded. At the same time, a high degree of sealing in urban neighborhoods leads to the formation of heat islands.
Recording/measurement	The actual coverage of the soil is recorded via evaluated aerial photographs or on the basis of reports from property owners.
Unit	%
Reference unit(s)	-

Example Performance Indicator

Denomination	Rainwater retention
Measure	Installation of Green Roofs
Description	Indicated is the amount of rainwater that can be stored by 1 m ² of green roof.
Background	The retention of rainwater relieves the local sewer system and reduces the risk of flooding. At the same time, green roofs contribute to the improvement of the local microclimate through their evaporation performance.
Recording/measurement	As a rule, this is a manufacturer's specification or a calculation/measurement result.
Unit	Liter per 1 m ²
Reference unit(s)	m ² green roof

Example Impact Indicator

Denomination	Biological diversity (Biodiversität)
Description	Development of populations of selected animal species typical for settlement areas (e.g. species of birds), which serve as bioindicators.
Background	Biodiversity forms a natural basis for life. A green roof provides species with additional habitat.
Recording/measurement	Recording the number of selected species (census)
Unit	For each selectes species: number of individuals in the species population per area of observation
Reference unit(s)	Area of observation

References:

Schebek, L.; Lützkendorf, T.; Uhl, M. *Handreichung zur Typologie von Indikatoren sowie ihrer Anwendung in Planungsprozessen und Projekten zur nachhaltigen Quartiersentwicklung*, Darmstadt / Karlsruhe / Münster, 2022. Available online: https://ressourceneffiziente-stadtquartiere.de/wp-content/uploads/2022/03/Handreichung_Indikatoren_2022_01_18_TUprints.pdf (accessed on 22 April 2022).