# Supplementary Materials (SM)

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

**Liselotte Schebek [1], Thomas Lützkendorf [2]**

[1] Material Flow Management and Resource Economy, Institute IWAR, Technical University of Darmstadt, Franziska-Braun-Straße 7, 64287 Darmstadt, Germany.
[2] Chair for Sustainable Management of Housing and Real Estate, Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany.

**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 |

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| 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.proeng.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.buildenv.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.; Triantakonstantis, 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 |

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| 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 | Triantakonstantis, 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/matecconf/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 Gda´nsk, Pozna ´n 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 |

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| 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 explicitely, 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 | 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.<br>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. | 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 | Pressure | energy and material flows resuling from the driving forces | 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. | 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. |

| | | | | |
|---|---|---|---|---|
| S | State | Conditions with regard to soil, water, outdoor air | 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. | 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. |
| I | Impacts | Effects on the environment, economy and society, in the broader sense as part of a sustainability assessment | “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. | “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. |
| R | Responses | Reactions or measures | Organisational, technical or structural measures of urban development (also as part of projects), but sometimes also campaigns, support programmes, legislative initiatives. | “Responses” describe reactions. These are organisational, technical or structural measures, but sometimes also campaigns, support programmes, legislative initiatives. |

**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*

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

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

**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 m² 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 m2 |
| Reference unit(s) | m² 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).