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Review

Indicators for urban sustainability: Key lessons from a systematic analysis of 67 measurement initiatives

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ABSTRACT

Today, the centrality of cities in the global sustainability challenge is widely acknowledged, and numerous initiatives have been developed worldwide for monitoring and comparing the sustainability performance of urban areas. However, the escalating abundance of indicators makes it difficult to understand what really counts in urban sustainability and how to properly select the most suitable indicators. By methodically collecting and mapping the diversity of available indicators, our work aims to elucidate the emphases, as well as the gaps, that exist in the way urban sustainability is currently translated into metrics, and to draw instructive lessons to support the development of future indicator sets. Representing the most comprehensive study ever performed in the field, this analysis relies on both an innovative research approach entailing multi- and cross-typological systematic analysis of indicators and an extensive data sample comprising 67 indicator sets (for a total of 2847 indicators) from academia and practice. The findings highlight the most frequent indicators in urban sustainability measurement initiatives, and demonstrate the prominence of social issues (e.g., quality of life, access to services, consumer behaviour, employment) and to a lesser extent, of environmental stakes. In contrast, urban sustainability indicator sets generally pay marginal attention to political questions (e.g., participation, policies, institutional settings), gender issues and distributional concerns. From a systemic point of view, the analysis reveals the strong emphasis placed on the status of actual and potential resources as well as the satisfaction of current needs. The study further highlights seven key lessons on how to deal with three typical tensions faced during indicator selection processes: (i) parsimony vs. comprehensiveness; (ii) context-specificity vs. general comparability; and (iii) complexity vs. simplicity. The directly implementable recommendations proposed herein will support both scholars and practitioners in the design of future urban sustainability measurement initiatives.

1. Introduction

During the last decades, the concept of sustainability has increasingly captured public attention by highlighting the difficult reconciliation between global population needs and the burden that those needs place on the environment. The concept has also been firmly positioned at centre stage in international policy at least since the United Nations' (UN) adoption of Agenda 21 in 1992. Given advancing urbanization worldwide, the sustainability of cities and their surroundings constitutes a major component of the general global sustainability challenge. Urban areas hosted 55% of the world's population in 2018, and according to the projections of the United Nations (UN, 2019), this figure will reach 68% by 2050. Meanwhile, studies estimate urban areas to be responsible for approximately 80% of the global gross domestic product (GDP) and 75% of energy-related CO_2 emissions (IPCC, 2014; GEA, 2012).

By now, the centrality of cities in the global sustainability challenge is widely acknowledged in the political sphere. For example, one of the UN's Sustainable Development Goals (SDG 11 - Make cities and human settlements inclusive, safe, resilient and sustainable) is specifically dedicated to cities and communities, and the 167 countries participating in the UN's Habitat III conference in 2016 elaborated the New Urban Agenda (UN, 2017b) as a global guideline for urban development. Beyond national governments, cities are also emerging as significant actors in their own right, and city networks such as the C40 Cities Climate Leadership Group and ICLEI (Local Governments for Sustainability) are providing a platform for international policy diffusion for urban sustainability.

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Concomitant with the advent of the urban sustainability concept in policy and academic circles, a broad range of measurement initiatives have been developed for monitoring and comparing the sustainability performance of cities worldwide (e.g., ISO, 2018a; Global Platform for Sustainable Cities, 2018). In particular, the development and use of sustainability indicators has proliferated so rapidly that some authors describe the field as an 'indicator industry' (King et al., 2000) or 'zoo' (Pintér et al., 2005). Such an 'explosion of indicators' stems from several factors, including the blurriness of the sustainability concept, increased data availability, and the plurality of purposes for which sustainability assessments are used (Tanguay et al., 2010).

Given the above-described background, critical reviews and comparative analyses on existing measurement initiatives are needed to provide an overview of the diversity of available metrics and draw lessons to inform future indicator-based assessments. Accordingly, we inscribe our work in this incipient line of research by addressing the following research questions (RQ):

RQ.1: How do current indicator sets translate urban sustainability into metrics?
RQ.2: What lessons can be drawn from current practices to support the development of future indicator sets for urban sustainability?

Our work contributes to research in related fields in several ways. In particular, it is arguably the most thorough review to date focusing exclusively on indicators for urban sustainability. The 67 indicator sets (totalling 2847 indicators) analyzed in the study include initiatives promoted by both international and local actors, thereby offering an unprecedently comprehensive view on the status of indicator-based urban sustainability initiatives. The comprehensiveness of the analysis is further enhanced by the use of several complementary analytical frameworks or typologies (see Section 3.4), namely, SDGs, STEEP (Social, Technological, Economical, Environmental, and Political) analysis and MONET (Monitoring Sustainable Development) through which all collected indicators are methodically characterized.

The remainder of this paper is organized as follows. **Section 2** provides the theoretical background of the study. **Section 3** presents the methodological approach followed to collect and characterize the 2847 indicators finally included in the analysis. **Section 4** elucidates the study's results, and Section 5 discusses those findings in light of current knowledge in the field. Finally, Section 6 summarizes the conclusions.

2. Indicators for urban sustainability

2.1. Looking at indicators sets as de facto conceptualizations of urban sustainability

The use of indicators has emerged in recent years as a popular means for the practical operationalization of the concept of urban sustainability. For this purpose, a variety of indicator sets have been developed and applied by international as well as local actors (Tanguay et al., 2010; Boyko et al., 2012; Verma & Raghubanshi, 2018). There are two distinct ways of understanding the nature and purpose of sustainability indicators. On the one hand, indicators are often conceived as *neutral* and purely technical instruments that assist decision-making processes towards sustainable development at the national and urban scales (Astleithner & Hamedinger, 2003; Gudmundsson, 2003; Elgert, 2018). From this standpoint, indicators are primarily 'data carriers'—i.e., measuring entities whose identity exclusively relies on the variables and parameters with which they are associated, independently from the context, purpose and logics behind their use. According to this understanding, indicators must be supported by available, reliable and easily updatable data, and they are expected to provide direct input to policy-making (Hezri, 2004; Sébastien et al., 2014).

On the other hand, sustainability indicators can be seen as 'message carriers' (Lehtonen et al., 2016)—i.e., arguments, ideas and expectations that particular actors mobilize regarding sustainability issues. In that sense, developing an indicator set is not just about measuring a concept which is fully defined *ex ante*, but rather constitutes a process through which the concept (urban sustainability) acquires content and is defined *in medias res*[1] (O'Connor & Spangenberg, 2008; Mickwitz & Melanen, 2009). Such a process is not merely technical, but also political and normative (Bossel, 1996; Valentin & Spangenberg, 2000; Kates et al., 2005).

In this paper, we focus on the conceptual role that indicators play in (re)shaping the urban sustainability concept and making it tangible and operational in practice. From this perspective, the systematic analysis and comparison of the composition of urban sustainability indicator sets aims at enhancing our understanding of the meaning of urban sustainability, as if each indicator set was a distinct definition of the concept. As shown in Table 1, several such comparative studies exist to date. These studies vary in their specific thematic scopes, methodological approaches and respective samples.

Our work contributes to this existing body of literature in several ways. In contrast to most previous reviews that have combined the concept of sustainability with other adjacent concepts (e.g., greenness, well-being) or mixed the urban scale with other scales (e.g., regional), our focus is exclusively on *urban sustainability*. Our work encompasses the most comprehensive sample of indicator sets—particularly those related to local initiatives (22 out of 67 sets)—compiled to date. Indeed, earlier studies have clearly paid more attention to international standards (e.g., the International Organization for Standardization (ISO), Leadership in Energy and Environmental Design (LEED)) and/or indicator sets fostered by global organizations (e.g., the UN). Furthermore, the size of our sample (67 indicator sets; 2847 indicators) is significantly larger than those used in previous studies, and the multi-typological prism that we apply to analyze it provides particularly detailed and representative results about the ways the indicator sets depict and delimit the concept of urban sustainability (see Section 3.4).

2.2. Identifying the constituent elements of an indicator

In order to analyze and categorize indicators, it is necessary to understand and define their constituent elements. Indeed, the definition of an *indicator* varies considerably in both scientific and grey literatures (Gallopín, 1997; Boesch et al., 2014; Waas et al., 2014). In this paper, we understand indicators as *allegorical* representations through which an issue of larger and usually complex significance is broken down into specific and comprehensible features. Indicators are multifaceted constructs that are ideally composed of the following interrelated elements (Fig. 1): (i) a **label** or title that is immediately understandable and makes the indicator easily distinguishable; (ii) a specific **unit of measurement** (either qualitative or quantitative); (iii) a **definition** that succinctly explains the way the label must be understood (either narratively or mathematically, or both); (iv) accessible **data** that is consistent with the relevant label and definition; (v) a more or less precise **reference point** (e.g., a target, a benchmark, a threshold, a range or simply an orientation) through which the data might be properly considered (this element is particularly important in sustainability assessments but might be especially challenging due to scientific uncertainties and societal controversies (e.g., Lancker & Nijkamp, 2000; Spangenberg et al., 2002)); and (vi) the specific **anchoring** in the conceptual framework in which the indicator is deployed (e.g., the internal category(ies) with which it is associated). Regarding the anchoring, it is important to note that conceptual frameworks express the way the topic under study is understood (e.g., urban sustainability)

[1] In or into the middle of events or a narrative (https://www.collinsdictionary.com).

Table 1
Previous comparative analyses of urban sustainability indicator sets. The “n° of sets” refers to the number of initiatives considered in previous analyses (the share of local initiatives is specified in brackets). The columns titles “Academic initiatives?” and “Non-academic initiatives” highlight whether initiatives developed by academics and non-academics were considered in previous studies.

References	Clear focus on urban systems?	Clear focus on Sustainability?	Analytical Level 1: indicator sets	Analytical Level 2: Indicators	n° of sets and % of local initiatives	n° of (gross) indicators	Academic initiatives?	Non-academic initiatives?	Criteria applied to compare the INDICATOR SETS (when applicable)	Criteria applied to compare the INDICATORS (when applicable)		
Tanguay et al., 2010	YES	YES	NO	YES	17 (29%)	616	YES	YES	n/a	Sustainability dimensions (ENV/ECO/SOC)	List of 20 themes	
Shen et al. 2011	YES	NO	YES	YES	9 (100%)	?	NO	YES	Purposes; goals; boundaries; milestones.	Compliance with a list of indicators	List of 37 themes based on previous int. Initiatives	Sustainability dimensions (ENV/ECO/SOC/GOV)
Lynch et al. 2011	NO	NO	YES	YES	22 (32%)	377	YES	YES	Interpretations of sustainability; list of goals developed by the research team.	Sustainability dimensions (SOC/ECO/ENV)	List of 17 themes	SMART criteria + PSR typology (Pressure / State / Response)
Mori & Christodoulou 2012	NO	NO	YES	NO	14 (0%)	?	YES	YES	Consideration of external impacts (leakage effects); coverage of triple bottom line			
Sharifi & Murayama 2013	NO	YES	YES	YES	7 (0%)	?	NO	YES	Developer(s); country; rating systems; themes; date; scoring and weighting systems; part. methods; results reporting; applicability.	List of 5 themes and 13 sub-themes		
Moreno Pires et al. 2014	YES	NO	YES	NO	16 (0%)	?	YES	YES	Goals; main conclusions.	n/a	n/a	n/a
Huang et al. 2015	NO	NO	YES	NO	10* (0%)	?	YES	YES	Developer(s); normalization technique; weighting method; aggregation rule; scale.	n/a	n/a	n/a
Braulio-Gonzalo et al. 2015	YES	YES	YES	YES	13 (15%)	786	YES	YES	Developer(s); assessor(s); country/region; scope; year of publication, year of last revision; n° categories; n° and type of ind.; weighting method.	List of 14 topics and 69 sub-topics and goals		
Komeily & Srinivasan 2015	NO	YES	YES	NO	5 (0%)	?	YES	NO	Developer; rating method; certification process; internal categories	n/a	n/a	n/a
Ahvenniemi et al. 2017	YES	NO	YES	YES	16 (12%)	959	YES	YES	n° categories; n° indicators.	Sustainability dimensions (ENV/ECO/SOC)	List of 10 domains adapted from a previous study	
Dizdaroglu 2017	NO	NO	YES	NO	52 (38%)	?	YES	YES	Only through their internal categories.	n/a	n/a	n/a
Verma & Raghubanshi 2018	YES	YES	n/a	n/a	?	?	YES	NO	n/a	n/a	n/a	n/a
Feleki et al. 2018	NO	NO	YES	YES	25 (0%)	284 (net?)	YES	YES	Scales; sustainability pillars reflected.	Sustainability dimensions (ENV/ECO/SOC)	List of 24 thematic categories and 103 sub-categories	
Zinkernagel et al. 2018	NO	NO	YES	YES	7 (14%)	?	NO	YES		Frequency of use		

(continued on next page)

Table 1 (*continued*)

References	Clear focus on urban systems?	Clear focus on Sustainability?	Analytical Level 1: indicator sets	Analytical Level 2: Indicators	n° of sets and % of local initiatives	n° of (gross) indicators	Academic initiatives?	Non-academic initiatives?	Criteria applied to compare the INDICATOR SETS (when applicable)	Criteria applied to compare the INDICATORS (when applicable)		
									N° applications; focus on urban aspects.		relatedness to SDGs	
Science Communication Unit 2018	YES	NO	YES	NO	27 (7%)	?	NO	YES	Frameworks are presented in a qualitative unstructured manner.	n/a	n/a	n/a
Kaur & Garg 2019	YES	NO	YES	YES	6	251	NO	YES	N° of items, rating scale, weightings, country	Sustainability dimensions (ENV/ECO/SOC/CULT/INST)	List of 23 themes	
Present paper	**YES**	**YES**	**YES**	**YES**	**67 (33%)**	**2847**	**YES**	**YES**	**Year; promoter(s); assessor(s); country; implementation scale; size; internal categories.**	**SDGs**	**STEEP**	**MONET**

and/or how the system is characterized (e.g., urban area). Therefore, how an individual indicator is anchored in a particular conceptual framework reveals how it specifically contributes to the 'entire story' as well as how it articulates with the remaining indicators within the same set.

All of the above-mentioned core elements are influenced by the kind of assessment in which the indicators are embedded. Such influence might operate at: (i) the normative level—e.g., how is the sustainability concept apprehended?; (ii) at the systemic level—e.g., how are the functions and processes of a system concretely translated into a logical structure of interrelated indicators?; or (iii) at the procedural level—e.g., what are the stages of the assessment? who participates? how are data aggregated? (Wiek & Binder, 2005; Binder et al., 2010).

Finally, several contextual factors might have an effect on both indicators and assessments, such as the purpose motivating the set (Guy & Kibert, 1998), the temporal and spatial circumstances in which the set is developed (Mitchell, 1996; Briassoulis, 2001), the type of institution leading the process, or participants' roles and rights (Rametsteiner et al., 2011; Lyytimäki et al., 2013).

2.3. Tensions in the development of indicator sets for sustainability

The process of developing an indicator set for sustainability faces a number of tensions between competing goals and methodological principles. Some of these tensions relate to conflicting quality criteria of individual indicators, whereas others emerge when considering the indicator set in its entirety. In this article, we focus on three tensions: (i) parsimony vs. comprehensiveness; (ii) context-specificity vs. general comparability; and (iii) complexity vs. simplicity. These tensions are among the most frequently commented in the literature, and relevant insights about them can be derived from a quantitative analysis of the data available to us. However, it is important to note that other tensions exist and this is not an exhaustive list (Mccool & Stankey, 2004; Fraser et al., 2006; Reed et al., 2006; Lehtonen et al., 2016; etc.).

The tension between parsimony and comprehensiveness emerges at the indicator set level; it focuses on the number of indicators that are required to perform the key functions of the assessment. A parsimonious indicator set represents the system under study with as much simplicity as possible (Binder et al., 2010) and only as many indicators as needed (Spangenberg et al., 2002), which makes it advantageous in terms of resource requirements and ease of use. At the same time, there is a need to cover all the key aspects of the system under consideration both in terms of its sub-systems (Dale & Beyeler, 2001) and different dimensions of sustainability (UN, 2007). This requirement for comprehensiveness usually translates into a pressure to increase the number of indicators in a set, which imposes a direct conflict with the need for parsimony.

Whether to select indicators that are in use across cities or indicators that are tailored for local needs embodies the tension between context-specificity and general comparability (Gasso et al., 2015; de Olde et al., 2017). This tension operates at both the indicator and the set levels. The advantage of standard indicator sets such as those promoted by prominent international organizations (e.g., UN, EU, World Bank) is in the comparability, accountability and reproducibility that they enable (Pintér et al., 2005; Donnelly et al., 2007; Uhlmann et al., 2014). However, standardized indicators and indicator sets also impose certain value-based choices that do not take local specificities into account. In contrast, context-specific indicators can be designed to explicitly integrate critical issues and values that are inherent to the area under consideration (Astleithner et al., 2004; Rydin, 2007), thereby increasing both their effectiveness and the potential outcomes of the measurement initiative (Binder et al., 2010).

Finally, the tension between complexity and simplicity arises from the need to represent the system at hand with a sufficient amount of detail and scientific credibility while also retaining a suitable level of understandability for all involved stakeholders (Falck & Spangenberg,

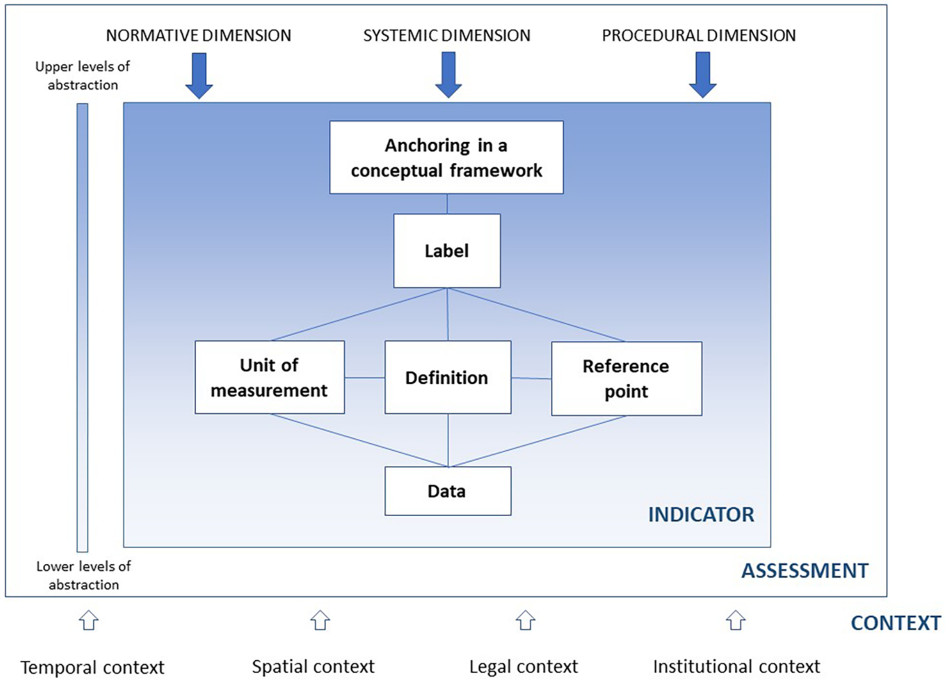

Fig. 1. Core elements of an ideal indicator and potential influencing factors.

2014). In that sense, whereas the tension between parsimony and comprehensiveness is largely a matter of quantity (of indicators or pertinent information), that between complexity and simplicity is first and foremost about quality. The latter is a tension that concerns both individual indicators and the conceptual framework upon which the set of indicators is constructed. Indeed, sophisticated indicators (based on intricate algorithms and/or theoretical abstractions) and elaborated conceptual frameworks (such as those that allow plural vantage points) may be attractive for their scientific acknowledgement. However, this may come at the expense of accessibility to non-experts, thereby resulting in reduced resonance with local decision-making and discourses (Guy & Kibert, 1998; Reed et al., 2006; Cook et al., 2017). This tension is well expressed in the dichotomy of 'cold' indicators (i.e., indicators that are scientifically robust but complex) and 'warm' indicators (i.e., indicators that are understandable but lacking scientific rigour) (Macnaghten & Jacobs, 1997; Abbot & Guijt, 1998; Cartwright, 2000).

Given this theoretical background, this paper aims at deriving lessons learned from the current use of urban sustainability indicators to support practitioners and scholars in their effort to cope with the above-mentioned tensions.

3. Methods and data

The approach applied in this study followed six successive steps (Fig. 2). The process lasted over 11 months and involved five researchers working in the field of sustainability science.

3.1. Sampling indicator sets

When collecting indicator sets, the retrieval of measurement initiatives from both academia and practice (i.e., scientific and grey literature) was considered necessary in order to significantly contribute to the existing literature. For both types of literature, only documents published from 2010 onwards and written in either English, French, German, Italian or Spanish were considered. Academic measurement initiatives were identified through a systematic literature review, for which the Scopus search engine was selected due to its wide coverage of sustainability journals. The search was conducted using 'indicator*' AND 'sustain*' AND 'urban' as keywords[2]. The search yielded 522 results as of May 26, 2020.

Because the nature of grey literature does not allow such a systematic procedure, the approach for identifying initiatives in this case was more explorative and combined several complementary strategies. The Google search engine enabled the identification of a significant number of indicator sets using the same keywords described above in all the selected languages. Other initiatives were uncovered using a snowball sampling method, through references in scientific articles or institutional reports. Finally, several sets were identified through the authors' professional networks. The search yielded 369 results as of May 26, 2020.

All identified initiatives (i.e., 891 = 522 + 369) were then filtered and included in the final sample according to the following criteria: (i) empirical orientation; (ii) recent activity; (iii) clear and comprehensive focus on sustainability; (iv) urban scale; and (v) access to indicators (see Supplementary material for further details).

The application of the above-mentioned filters yielded a final sample of 67 indicator sets, including 30 from academia[3] and 37 from public, private or non-profit entities operating at the local, regional, national or international levels (Table 2). Although not exhaustive, the sample is certainly extensive.

3.2. Profiling the selected indicator sets

In order to enable the detection of differences across sets, metadata including publication dates, promoters/assessors, implementation

[2] The exact search query used in Scopus was: KEY (indicator*) AND KEY (sustain*) AND KEY (urban) AND PUBYEAR > 2009 AND PUBYEAR < 2020 AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English") OR LIMIT-TO (LANGUAGE, "Spanish") OR LIMIT-TO (LANGUAGE, "French") OR LIMIT-TO (LANGUAGE, "Italian") OR LIMIT-TO (LANGUAGE, "German")).

[3] Five indicator sets contained in scientific articles were included in the final sample even if they were not identified through our Scopus search (they are all explicitly referred to in at least one of the reports coming from the grey literature).

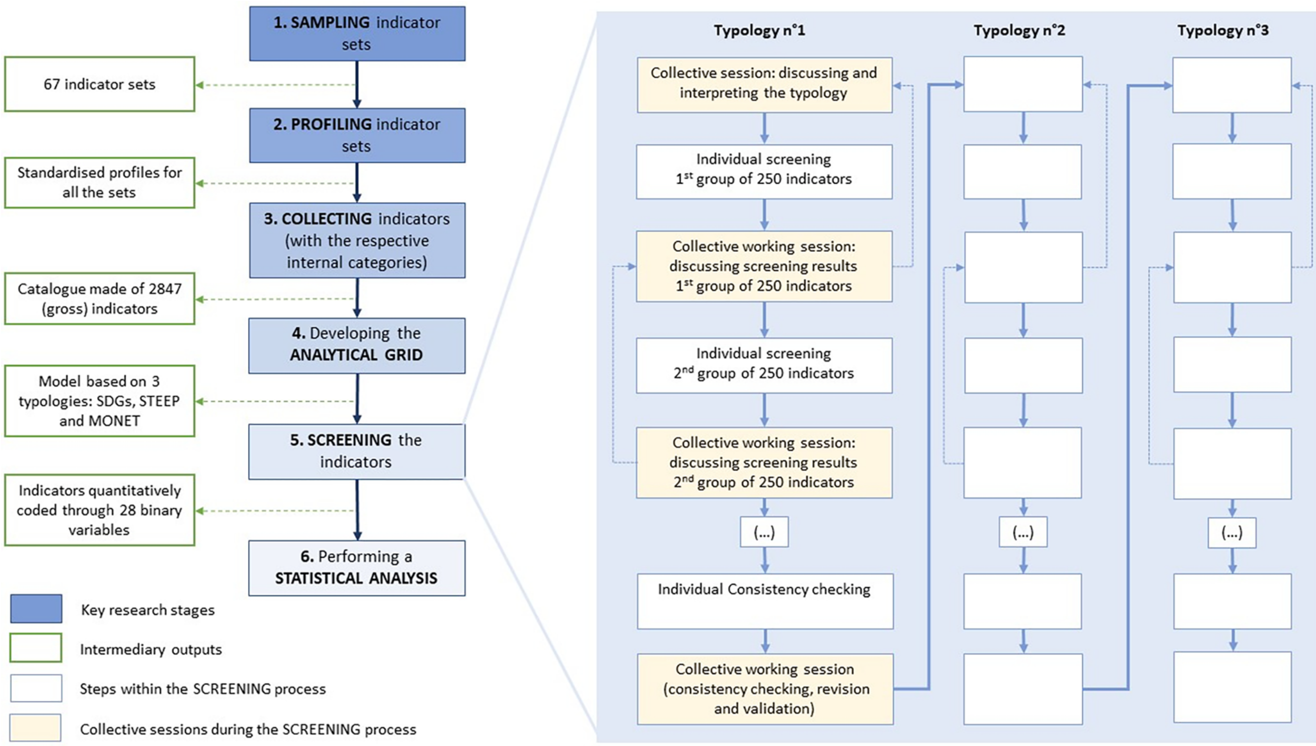

Fig. 2. Key steps followed in the present study.

scales and sizes (n° of indicators) were retrieved and stored for all 67 indicator sets.

3.3. Collecting indicators

Indicators were directly extracted from the reports, websites and/or articles associated with the respective measurement initiative. We understood each indicator as being a multifaceted construct (see Section 2.2) made of a label, a unit of measurement, its definition (when applicable) and all the categories to which the indicator was associated within the related framework (i.e., its anchoring). Although our ideal definition of an indicator includes a reference point, the available documentation related to the majority of the cases did not include such information. In total, 2847 indicators (including doubles) were collected, thus constituting the largest such catalogue ever developed.

3.4. Choosing appropriate typologies to screen the indicators

In order to determine how urban sustainability is translated into metrics (RQ1), a systematic analysis of the 2847 collected indicators was performed by assigning each indicator to one or several categories of particular typologies applied in the field of sustainability. Three typologies were selected to this end (SDGs, STEEP, and MONET), which are presented more in depth below. The use of typologies as analytical frameworks responds to several challenges, namely complexity, interpretative ambiguity and inconsistent granularity. Indeed, typologies might be seen first as conceptual models enabling the 'compression' of the complexity that is inherent to large samples of indicators coming from heterogeneous sources. Additionally, typologies bring a standard language through which all indicators are evenly formulated, independently from the way the indicator concept was expressed in the initiative at hand. Finally, the use of typologies enables coherent articulation of the dissimilar levels of granularity (or 'abstraction levels' in terms of Turnhout et al. (2007)), to which indicators might refer. In contrast to most previous studies, in order to reduce subjectivity and increase replicability, we used well-known pre-existing conceptual frameworks as typologies rather than classifications drawn inductively from the sample.

The research team initially considered several potential typologies derived from both academia and practice. The final selection relied on four criteria: (i) simplicity of use (typologies must be simple without being simplistic); (ii) operationality (excessively theoretical classifications were not considered); (iii) resonance (typologies must be legitimate and immediately understandable in both academia and practice); and (iv) complementarity (in order to maximize the amount of information provided, each typology has to be clearly different from the others). To implement the last criterion, we considered the classification suggested by Maclaren (1996), who distinguished six types of conceptual frameworks for sustainability indicators: *domain-based*; *goal-oriented*; *sectoral*; *issue-based*; *causal*; and *combination*.

3.4.1. Sustainable development goals (SDGs)

The SDGs constitute a combined goal- and issue-oriented framework that forms the core of the United Nations' 2030 Agenda for Sustainable Development (UN, 2015). Each of the 17 SDGs covers a thematic area and is sub-defined in several targets (169 in total). To monitor progress across goals and targets, the framework was complemented in 2017 by a set of 244 indicators (UN, 2017a). Agenda 2030 aims to surpass UN's earlier related policy frameworks (e.g., Agenda 21, Millennium Development Goals) in scope and ambition by putting greater emphasis on the integration and balancing of the different dimensions of sustainable development.

3.4.2. STEEP classification

The STEEP framework (also called PESTE) is a domain-based categorization of contextual factors that has mainly been used in strategic management and scenario analysis to understand which driving forces might affect an organization, an issue or an area (Bradfield et al., 2005; van Notten, 2006; Chermack, 2011). The acronym refers to five principal domains: (i) Social (consumer behaviour, demographics, religion, lifestyles, values); (ii) Technological (innovation, infrastructure, R&D, transport, energy); (iii) Economic (employment, production, interest

Table 2
Indicator sets included in the sample (N = 67). The 'N' and 'C' for the assessment scale denote whether the indicator set was applied at the city (C) or neighbourhood (N) level. The size refers to the number of indicators listed in each set. This number can differ from the official number of indicators reported in the original reference due to the aggregation or disaggregation of single indicators (as explained in Section 3.3). The information on the implementation scale specifies the number of cases (cities/neighbourhoods) in which each set has been applied.

Reference	N/C	Organization type	Size	Country of application	Implementation scale
BCN Ecología & City of Victoria-Gasteiz 2010	N	Multiple	50	Spain	Single
Alpopi et al. 2011	C	Academia	18	Romania	Multiple (4)
Dubiela 2011	N	Academia	31	Brazil	Single
Keough et al. 2011	C	NGO	36	Canada	Single
Ministry of env. & BCN Ecología 2011	C	Multiple	41	Spain	Multiple (4)
Zhao 2011	C	Academia	12	China	Multiple (35)
City of Minneapolis 2012	C	City	45	USA	Single
King 2012	C	Academia	25	USA	Single
Marín Cots et al. 2012	C	City	23	Multiple (North-mediterranean)	Multiple (11)
City of Sapporo 2013	C	City	53	Japan	Single
Corporate Knights 2013	C	Private	27	Canada & USA	Multiple (20)
Dublin City Council 2013	C	City	37	Ireland	Single
Emerging and Sustainable Cities Initiative 2013	C	Int.Org.	117	Latin America + Caribbean	Multiple (50)
Shamsuddin & Rashid 2013	C	National	36	Malaysia	Multiple (6)
Wang et al. 2013	N	Academia	33	China	Single
Baca 2014	C	City	49	Ecuador	Single
Li et al. 2014	C	Multiple	21	China	Multiple (185)
RFSC 2014	N/C	Int.Org.	28	Multiple (Europe)	Multiple (66)
San Francisco Department of Public Health 2014	N	City	106	USA	Single
Shen & Guo 2014	N	Academia	17	Canada	Single
Shen & Yang 2014	C	Academia	59	China	Multiple (24)
Statistical Office Berlin-Brandenburg, 2014	C	City	25	Germany	Single
Sustainable Society Foundation 2014	C	NGO	18	Netherlands	Multiple (408)
Istat 2015	C	National	65	Italy	Multiple (29)
MEWR et al. 2015	C	City	26	Singapore	Single
Yigitcanlar et al. 2015	N/C	Academia	38	Australia	Single
Zoeteman et al. 2015	C	Academia	80	Europe	Multiple (58)
Basque government & Udalsarea21 2016	C	Multiple	19	Spain	Multiple [39–108]
City of Issaquah, Office of sustainability 2016	C	City	26	USA	Single
City of Sidney 2016	C	City	163	Australia	Single
City of Surrey 2016	C	City	58	Canada	Single
UN Habitat 2016	C	Int.Org.	62	Multiple (worldwide)	Multiple (> 400)
Xu et al. 2016	C	Academia	25	China	Multiple (20)
Cercle Indicateurs 2017	C	City National	37	Switzerland	Multiple (25)
LSDC, 2017	C	NGO	31	UK	Single
Phillis et al. 2017	C	Academia	46	Multiple (worldwide)	Multiple (106)
Rajaonson & Tanguay 2017	C	Academia	20	Canada	Multiple (25)
Smiciklas et al. 2017	C	Int.Org.	91	Multiple (worldwide)	Multiple (> 50)
STAR Communities 2017	C	NGO	27	USA	Multiple (40)
Association suisse pour des quartiers durables 2018	N	NGO	60	Switzerland	Multiple (3)
Arcadis 2018	C	Private	48	Multiple (worldwide)	Multiple (100)
Bahadure & Kotharkar 2018	N	Academia	20	India	Single
City of Orlando 2018	C	City	55	USA	Single
Garau & Pavan 2018	N	Academia	38	Italy	Single
Gonzalez-Garcia et al. 2018	C	Academia	17	Spain	Multiple (26)
Haider et al. 2018	N	Academia	103	Canada	Single
ISO 2018a	C	Int.Org.	128	NA	Multiple
Municipality of Málaga, 2018	N	City	83	Spain	Single
Musa et al. 2018	C	Academia	37	Malaysia	Single
Peg 2018	C	NGO	19	Canada	Single
Resort Municipality of Whistler 2018	C	City	73	Canada	Single
Wu et al. 2018	C	Academia	27	China	Multiple (3)
Akande et al. 2019	C	Academia	32	Multiple (Europe)	Multiple (28)
Balaras et al. 2019	N	Academia	29	Multiple (North-mediterranean)	Multiple (9)
Dizdaroglu 2019	N	Academia	20	Turkey & Australia	Multiple (2)
Fouda & Elkhazendar 2019	C	Academia	30	Multiple (worldwide)	Multiple (3)
González-García et al. 2019	C	Academia	33	Spain	Multiple (64)
Hély & Antoni 2019	C	Academia	9	France	Single
Rajashree et al., 2019	C	Academia	28	India	Single
LEED 2019	N/C	NGO	15	Multiple (worldwide)	Multiple
Lynch et al. 2019	C	NGO	57	USA	Multiple (106)
Pozo et al. 2019	N	Academia	8	United Kingdom	Multiple (32)
Rajaonson & Tanguay 2019	C	Academia	12	Canada	Multiple (81)
Reddy & Tiwari 2019	C	Academia	57	India	Multiple (25)
SDSN & Telos 2019	C	Multiple	56	Multiple (Europe)	Multiple (45)
Shmelev & Shmeleva (2018)	C	Academia	16	Multiple (worldwide)	Multiple (57)
Valcárcel-Aguiar et al. 2019	C	Academia	16	Spain	Multiple (58)

Table 3
Categories included in the MONET Typology (adapted from Willi et al., 2012).

MONET categories	Refers to
Level (L)	Meeting of the current generation's individual and social needs. It typically entails indicators about the quality of life of the population
Capital (C)	The status and potential of environmental, economic, human and social resources
Input/Output (I/O)	The flows to (or from) the stocks of capital, such as energy consumption or infrastructural investments. So-called 'negative inputs' such as greenhouse gas emissions or waste generation are also part of this category
Efficiency (E)	Economic and environmental efficiency measures such as decoupling of natural resource consumption from economic growth
Disparities (D)	Distributional issues about needs and stocks of capitals among population groups or among regions
Response (R)	Social and political measures taken to counter undesired developments

rates, international trade, taxes, savings, inflation, subsidies); (iv) Environmental (preservation of the environment, GHG emissions, water and land management); and (v) and Political (political category comprises political stability, regulation of monopolies, tax policies).

3.4.3. MONET typology

The MONET typology is a causal framework that constitutes one of the defining elements of the Swiss sustainable development indicator system (Altwegg et al., 2004). It relies on a stock-flow model of the processes that influence sustainable development while also encompassing 'structural' criteria (i.e., efficiency and distributional factors) (de Montmollin & Scheller, 2007). Thus, it is similar to the Driving force – Pressure– State – Impact – Response (DPSIR) model developed by the European Environment Agency (Smeets & Weterings, 1999), but also extends beyond the environmental dimension. As shown in Table 3, the typology comprises six key categories.

3.5. Screening the indicators

The screening phase entailed linking each indicator (including all of its embedded constituent elements) to the most pertinent categories within each typology (Fig. 3 for an illustration), which bestowed the indicators with a cross-typological characterization (hereafter called 'tag combination'). The purpose of the tag combination was to create an identity for each indicator in a standard language, which was necessary for the comparison and statistical analysis of the indicator sets in our sample. More specifically, as Section 4 will show, the tag combinations allowed us to analyze the relative weights given by the indicator sets to different categories of sustainability (e.g., what is the percentage of indicators referring to SDG 11?). By covering three distinct typologies, the tag combinations also enabled a deeper cross-typological analysis of the indicator sets (e.g., what is the distribution of the indicators referring to SDG 11 across the STEEP categories?). Additionally, the tag combinations were used to evaluate the uniqueness of the indicators, as having a singular or rare tag combination means that an indicator is measuring an aspect of sustainability that is not addressed by other indicators.

The screening process was conducted on one typology at a time and systematically followed the same procedure for each typology (Fig. 2). Manual screening was preferred to automatic screening via computer software as a means to integrate non-explicit context-specificities and other latent information (such as the internal categories to which the indicators are related). The screening was an iterative process; in some cases, the discussion led us to reconsider previous results in order to harmonize previously determined decisions (see the vertical discontinuous arrows in Fig. 2). Finally, each screener individually looked for potential contradictions, and all eventual inconsistencies were discussed and addressed during a collective session (see the Supplementary material for further details).

The outcome of the screening process was a catalogue of 2847 indicators, each of which carries a particular message identified through both (i) an articulated sequence of constituent elements and (ii) a cross-typological characterization, i.e., a tag combination (Fig. 3). Overall, 542 unique tag combinations were found among the 2847 indicators.

4. Results

The first part of our results refers to the overall research question of how urban sustainability is translated into metrics and focuses on which features and dimensions of the concept are most prominently

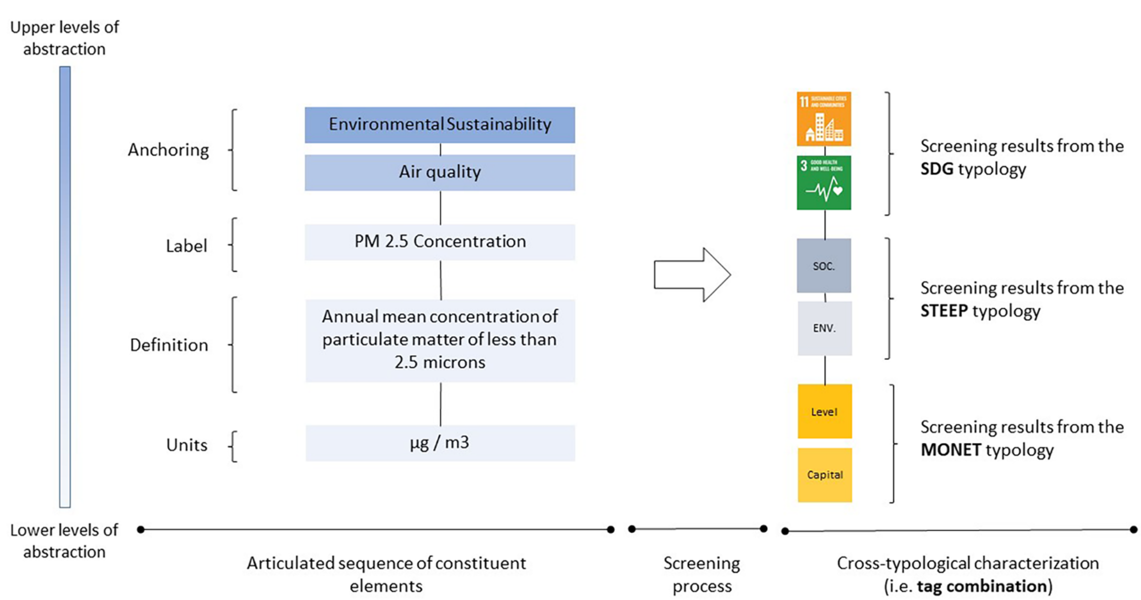

Fig. 3. Illustration of the screening process; example of the *PM2.5 Concentration* indicator.

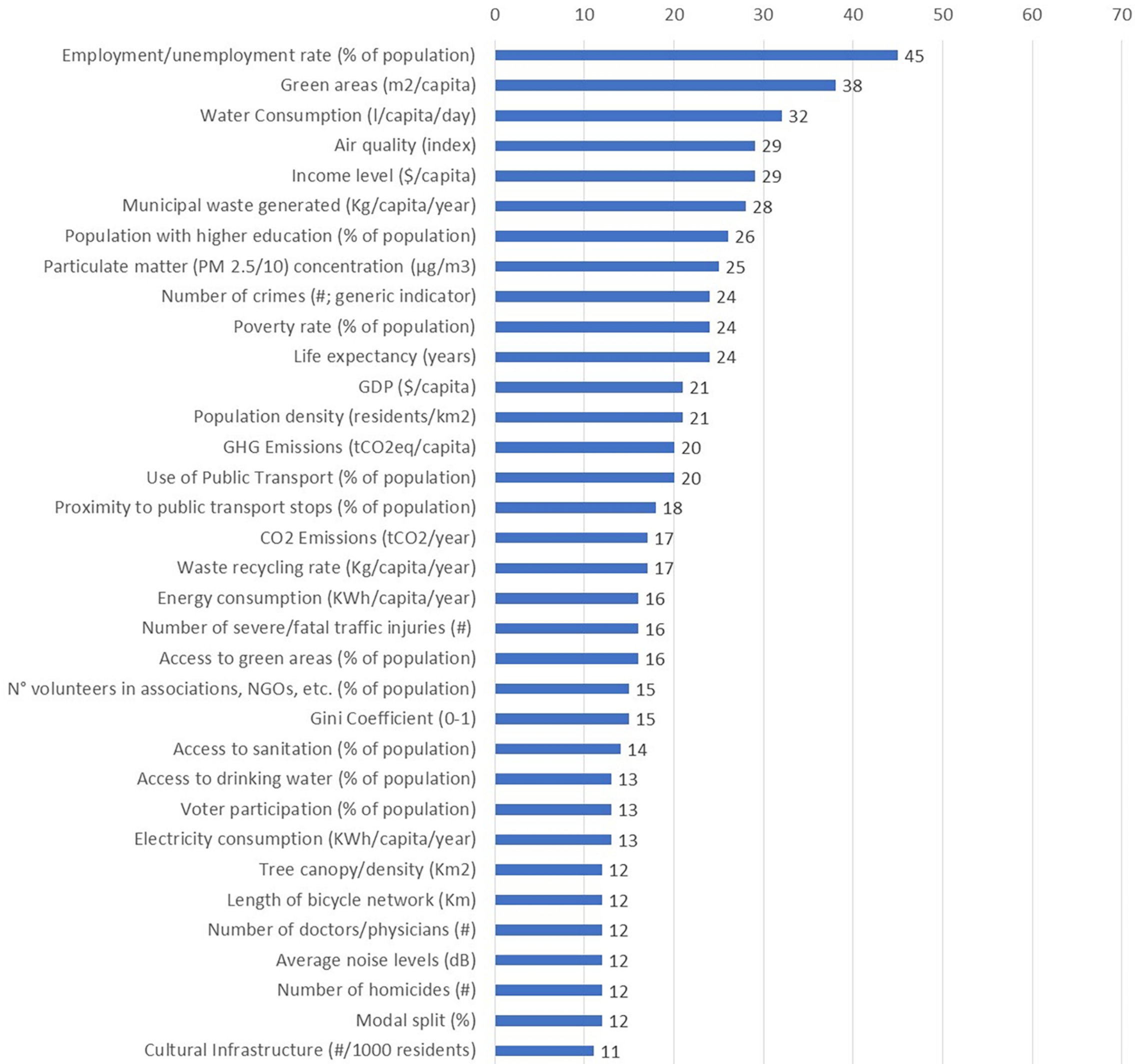

Fig. 4. Most frequent (net) indicators ranked by the number of indicator sets in which they appear. Brackets enclose exemplified measurement units for each indicator based on the most frequent unit used in the indicator sets.

represented in our sample versus which receive less attention. The analysis is based on two distinct angles: (i) the most commonly used indicators (Section 4.1.1); and (ii) the SDGs, STEEP and MONET categories referred to by the analyzed indicators (Section 4.1.2). Sections 4.2–4.4. answer our second research question by elucidating a number of lessons for the future development of indicator sets of urban sustainability. These lessons relate to the three tensions described in Section 2.3.

4.1. Urban sustainability in metrics

4.1.1. Most frequent indicators

Our large sample enabled the identification of the indicators that are most commonly found in urban sustainability indicator sets. For illustration, Fig. 4 presents those appearing in more than 10 sets (i.e., 15% of the sample). The results reveal that only two indicators were found in more than half of the sets (*employment/unemployment rate* and *Green areas*) and only 11 indicators were in more than a third of the sets, thus demonstrating the ambiguity surrounding the concept of urban sustainability.

The topics encompassed by the indicator list are diverse, including issues linked to the economy (e.g., *GDP*, *income level*), the environment (*energy consumption*, *GHG emissions*), health (*number of doctors/physicians*) and safety (*number of crimes*), among others. Although the majority of the 34 indicators that appear in at least 15% of the sets refer to issues that are pertinent to sustainability at any level, some (e.g., *particulate matter concentration, proximity to public transport stops, length of bicycle network,* etc.) represent challenges that are particularly relevant in urban contexts.

4.1.2. Dimensions of urban sustainability

The results illustrated in Fig. 5 reveal which of the 17 SDGs represent the core focus of urban sustainability. The box-plots depict the 67 indicator sets in quartiles (with triangles marking mean values) as a function of the normalized attention[4] that they devote to each SDG. The normalization takes into account both: (i) the number of indicators each set contains and (ii) the number of SDGs to which each indicator refers (see Merino-Saum et al., 2018)[5]. As expected, SDG11 (Sustainable cities

[4] Calculated as the percentage of indicators referring to each category. In our discussion we use the terms *attention* and *importance* to express this idea.

[5] To give an example, imagine a set of 50 indicators where a given SDG is referred to by two indicators, one of which only refers to the given SDG, whereas the other also refers to two additional SDGs. The normalized weight of the SDG in this set is then calculated by 1/(50*1) + 1/(50*3) = 2.6667%. The calculation of the normalized weights for the other typologies (STEEP and

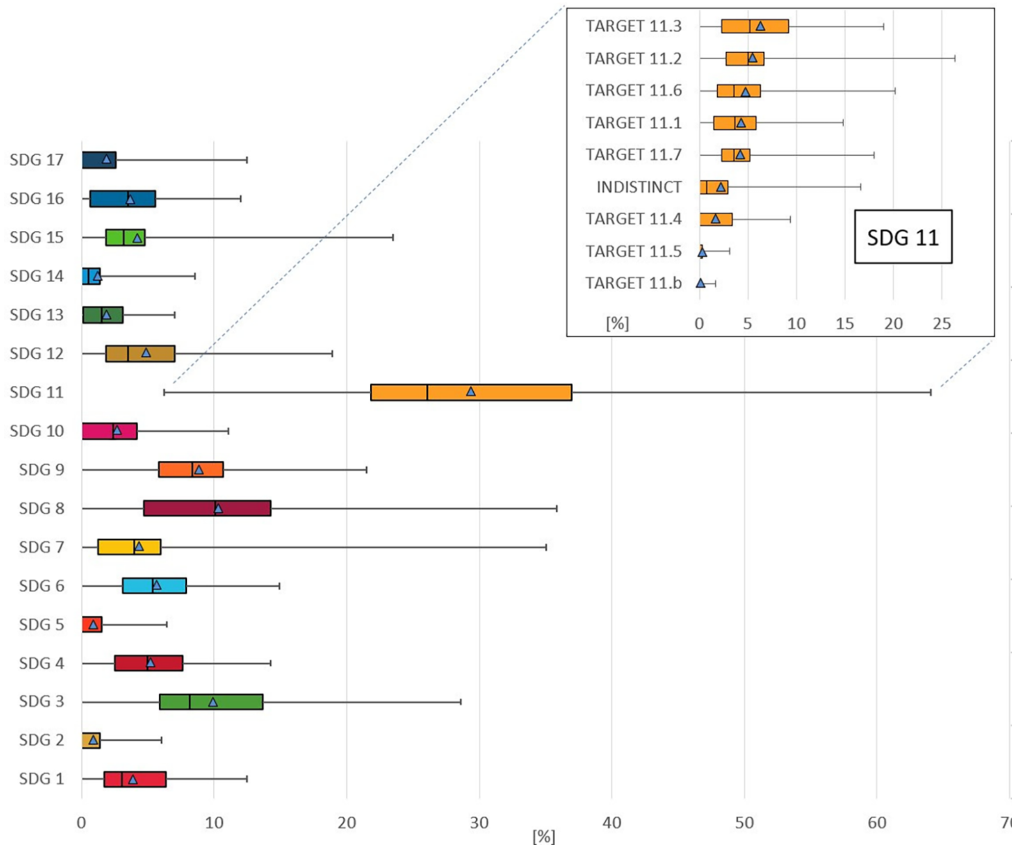

Fig. 5. Relative importance given to each SDG by the analyzed indicator sets.

and communities) is by far the most prominent of the SDGs, with an average attention of 29% across the indicator sets. Furthermore, its relative importance reaches over 60% in some cases, and it is the only SDG to be present in every set. After SDG11, the SDGs accorded the most importance are SDG3 (Good health and well-being), SDG8 (Good jobs and economic growth) and SDG9 (Innovation and infrastructure), each of which averages approximately 10%. In contrast, several other SDGs are typically only marginally covered. This is particularly the case for SDGs 2 (Zero hunger), 5 (Gender equality), 13 (Climate action), 14 (Life below water) and 17 (Partnerships for the goals). Of course, it is crucial to also look beyond the average values, as significant variability exists across sets. For example, the attention paid to SDG11 ranges from a maximum of 64% to less than 10%.

Given the prominence of SDG11, we analyzed the related indicators more in depth by checking which of the sub-targets of SDG11 are most often referred to. As illustrated in the inset of Fig. 5, this additional layer of analysis demonstrates the central importance attributed to targets 11.3 (Sustainable urbanization and human settlement planning), 11.2 (Provide access to transport systems), 11.6 (Reduce the environmental impact of cities); 11.1 (Ensure access to housing and basic services), and 11.7 (Provide access to green and public spaces).

The results for the SDG-related analysis might be compared with those from Zinkernagel et al. (2018), who analyzed seven indicator sets used by cities to monitor urban sustainability. These authors also found SDGs 3, 8 and 11 to be among those receiving the most attention; however, in contrast to our findings, their results also highlighted SDGs 6 and 16 as *hotspots* of urban sustainability.

Fig. 6 reveals the core focus of urban sustainability in terms of the STEEP categories. The attention paid to the social dimension is on average 46%, making it by far the most represented sustainability domain in the sample. The high attention paid to the social domain is in line with previous studies (see Shen et al., 2011; Ahvenniemi et al., 2017). The environmental dimension is the second most referred to, with 24% of the indicators. Economic and technological aspects of urban sustainability are given almost equal importance; each representing around 13% of the indicators. Finally, the political sphere receives the least attention, covering on average only 4% of the indicators. Unfortunately, our findings with regard to the technological and political domains cannot be contrasted with earlier findings in the literature, as no other studies of urban sustainability indicators have applied the STEEP categorization in their analysis. Again, as with the SDGs, it is important to take into account the huge variability between the indicator sets. For example, although the social dimension represents the strongest focus on average, several cases only give it a weight of around 20%.

Finally, concerning the MONET typology, the *capital* and *level* categories are the most represented aspects of urban sustainability, and they are the only categories covered by at least one indicator in all 67 indicator sets (Fig. 7). At the extreme opposite, the *disparities* component is most often overlooked, thus highlighting a low focus on distributional issues and equity concerns. On average, *disparities*, *efficiency* and *response* categories are covered by less than one in ten indicators. In terms of variability, considerable differences exist between sets. For example, the attention paid to the *level* category ranges from less than 10% to 95%, and whereas one set does not refer to the *efficiency* category at all, another attributes it an importance of 35%.

These results are not directly contrastable with previous findings, as the MONET typology has never been applied to analyzing indicator sets for urban sustainability.

(*footnote continued*)
MONET) follows the same logic.

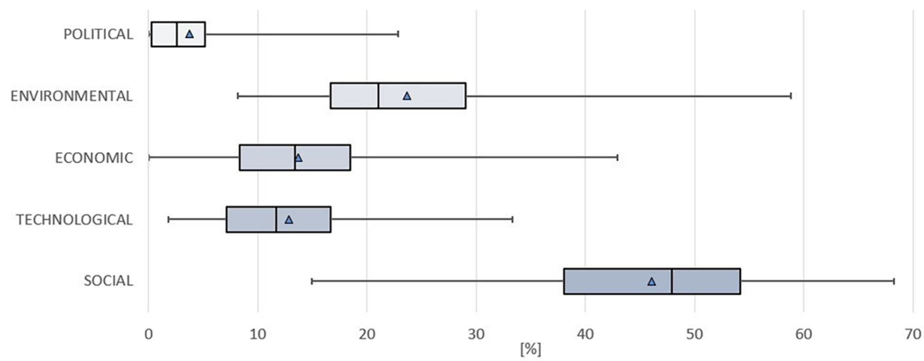

Fig. 6. Relative importance given to the STEEP categories by the analyzed indicator sets.

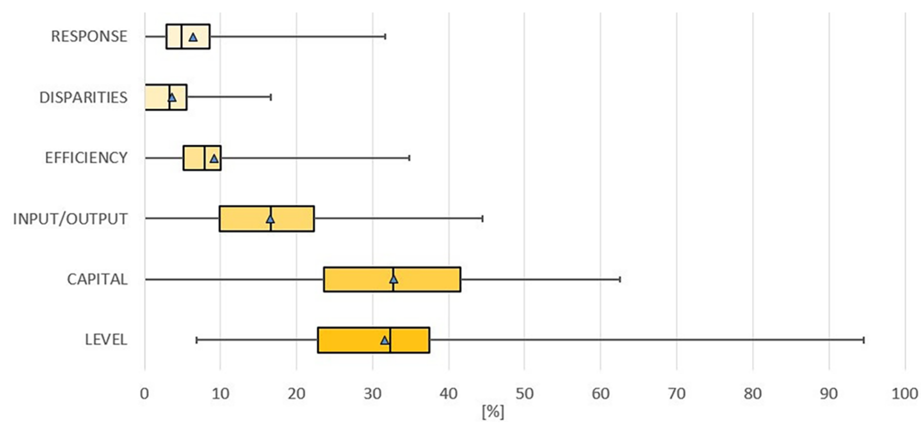

Fig. 7. Relative importance accorded to the MONET categories by the analyzed indicator sets.

4.2. Lessons related to the parsimony vs. comprehensiveness tension

Observation #1: Generally speaking, the larger the set, the fewer aspects of urban sustainability it neglects.

A first observation regarding the tension between parsimony and comprehensiveness is rather intuitive: the number of thematic gaps in a set tends to decrease when the number of indicators is enlarged ($R^2 = 0.5295$; p-value < 0.01; Fig. 8). None of the 40 smallest sets in our sample addresses all 17 SDGs, and the sets that neglect the highest number of SDGs are also among those that include the fewest indicators.

- **Lesson #1**: In order to cover all pertinent aspects of sustainability, caution is needed when considering smaller sets.

Observation #2: Smaller indicator sets are not always less comprehensive than larger sets.

Increasing the number of indicators in a set is one option to increase its comprehensiveness; however, it is not the only one. This idea is illustrated by Fig. 8, in which the positive relationship between size and SDG coverage is significant, but from which we can also observe that: (i) sets with similar sizes might have very different levels of comprehensiveness; and (ii) sets with similar levels of comprehensiveness might have very different sizes. In other words, gaps in coverage of SDG categories can be filled either by simply increasing the sheer number of indicators or by ensuring that those in use cover all the necessary categories of urban sustainability as carefully as possible. In fact, the proportion of potentially redundant indicators increases when a set gets larger ($R^2 = 0.3917$; p-value < 0.01; see Fig. 9)[6], meaning that the added value (in terms of coverage of additional areas of sustainability) of each additional indicator tends to decline as the set's size increases.

- **Lesson #2:** Comprehensiveness might be increased without necessarily having to increase the number of indicators, notably by ensuring that indicators covering all areas of sustainability are included.

Observation #3: Not all aspects of urban sustainability are automatically covered with larger indicator sets.

Exploring the relationship between size and coverage of sustainability issues (such as the SDGs) leads to our third observation: when the number of indicators increases, the observed number of gaps does not uniformly evolve for all aspects of sustainability. As illustrated in Fig. 10, four cases can be roughly distinguished:

(i) A first group of SDGs is either systematically present in all sets (SDG11) or only sporadically absent in relatively small sets ($n_i \leq 40$) (SDGs 3, 6, 8 and 9). This is also the case, albeit to a lesser degree, for SDGs 12 and 15. In other words, all of these issues are generally present regardless of the number of indicators. Unsurprisingly, these SDGs are also those receiving the highest relative importance (see Section 4.1.2).

(ii) A second group of SDGs (1, 10, and 13) is more frequently neglected, notably in small sets ($n_i \leq 40$), but is steadily present in sets comprising 60 indicators or more. These SDGs are those whose likelihood of being covered in a set is the most influenced by the number of indicators.

(iii) A third group of SDGs (2, 5, 14 and 17) is massively overlooked in the smallest sets (i.e. $n_i \leq 20$). Although these SDGs tend to be less frequently ignored in medium-size sets, they are still neglected in some of the largest ones (i.e. $n_i \leq 80$). Hence, although larger size generally reduces the marginality of such issues, it may not always

[6] For the sake of simplicity, we consider two indicators as being potentially redundant if both have identical tag combinations. Such a measure of redundancy must be understood only as an approximation.

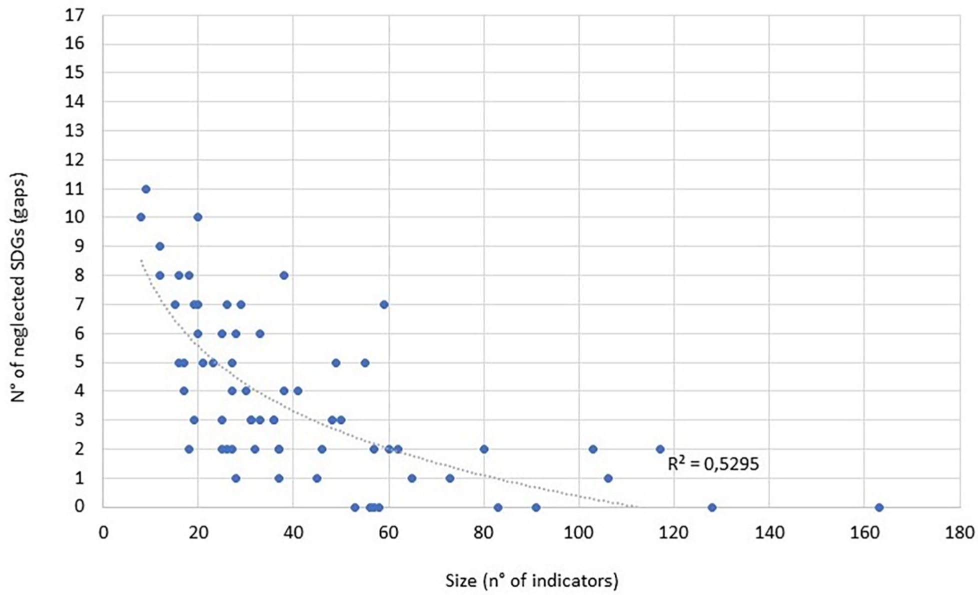

Fig. 8. Number of neglected SDGs and total number of indicators per indicator set. Each point in the figure represents a set.

be sufficient to render them visible.

(iv) Finally, for SDGs 4 and 16, the relationship between indicator set size and coverage is particularly unclear.

It is important to point out that although the size of the set may be related to the coverage of different aspects of urban sustainability when the latter is measured in binary terms (presence/absence), no such correlation can be found if we observe the relation between set size and attention paid to the different aspects. In other words, whereas the presence (or absence) of a topic is related to the size, the intensity of such presence is not.

- **Lesson #3**: For some specific issues, merely increasing the size of the indicator set might not be sufficient to guarantee their presence; a clear intention to cover them is needed.

4.3. Lessons related to the comparability vs. context-specificity tension

Observation #4: The comparability of indicator sets varies according to their size and the number of cities in which they have been implemented.

To express comparability levels, we calculated a *comparability index* for each set. The index is calculated as the average frequency with which the tag combinations identified for the respective sets appear in the entire catalogue of 2847 indicators. In other words, the higher the index, the more tag combinations the set shares with other indicator sets, which can be taken as a proxy for comparability.

The calculation of a comparability index for the entire sample led to two important observations. First, larger sets generally score lower on the comparability index (Fig. 11). This means that smaller sets typically consist of commonly used indicators, whereas larger sets include on average a relatively higher number of unique or at least peripheral indicators (i.e., those used in only a few sets).

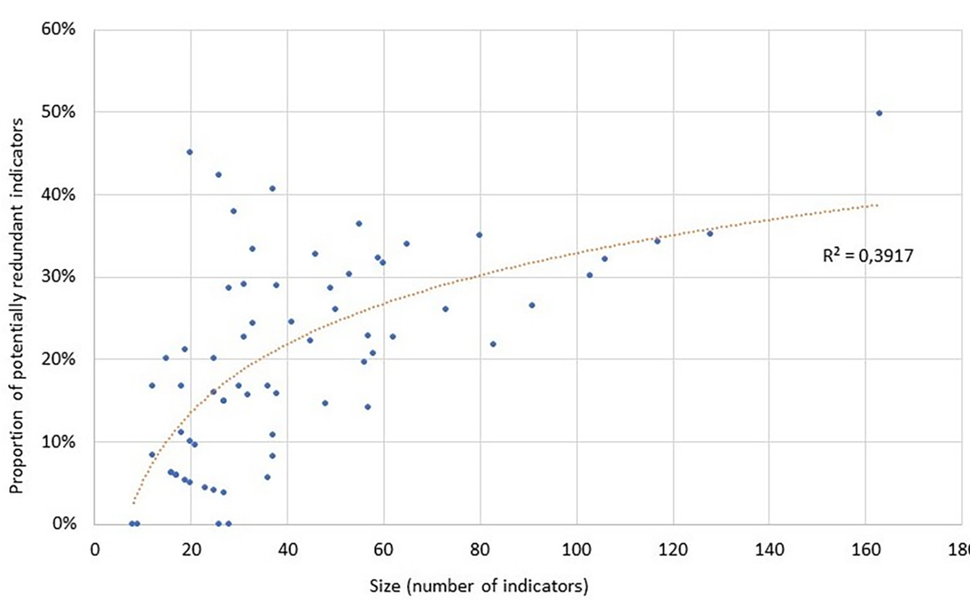

Fig. 9. Proportion of potentially redundant indicators and number of indicators per set.

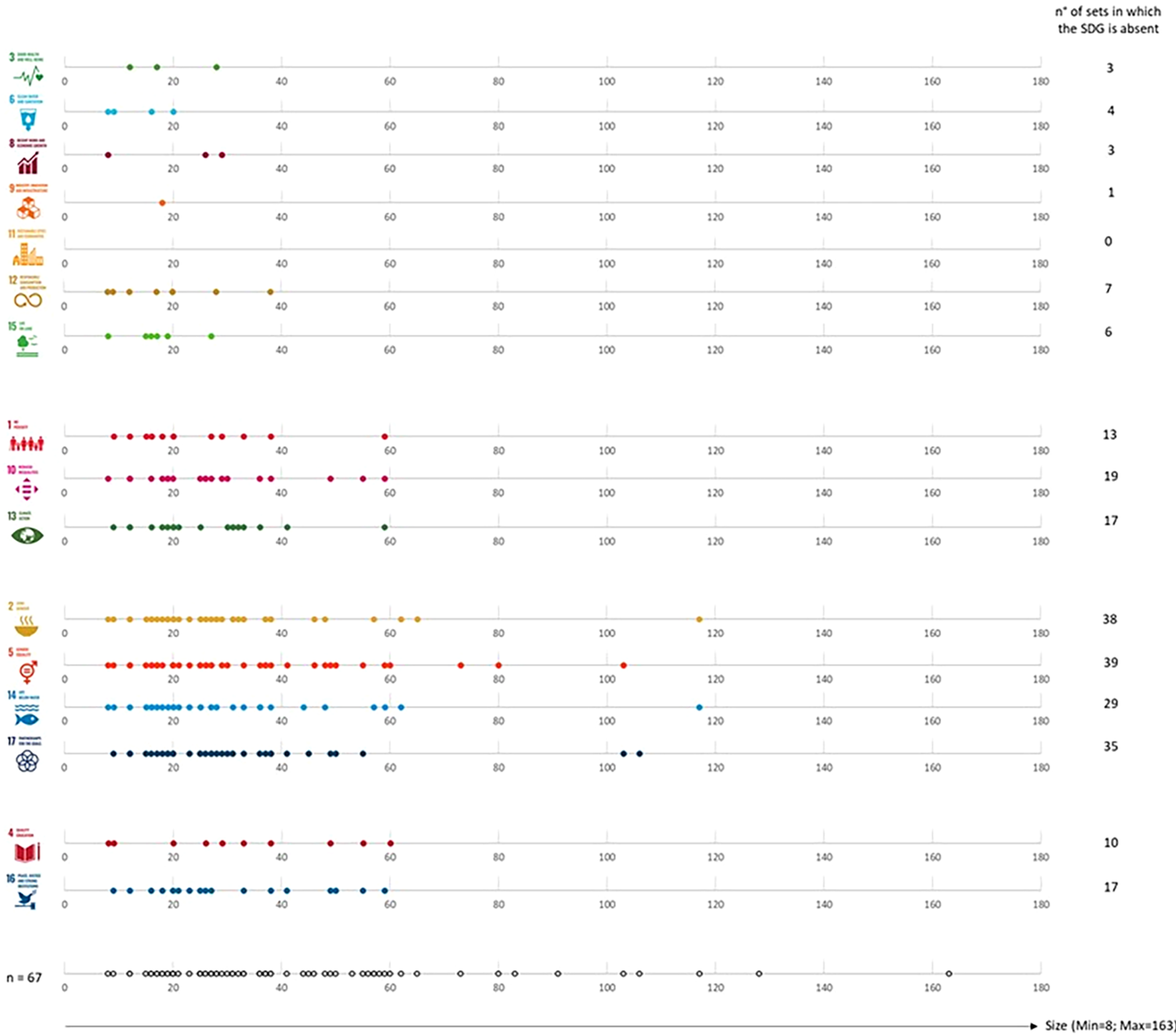

Fig. 10. Cases in which a given SDG is absent from an indicator set. Each filled circle represents an indicator set in which the SDG is neglected (hence, for instance, SDG4 has 10 filled circles, meaning that it is absent from 10 indicator sets, of which the smallest is comprised of eight indicators and the largest has 60). Sets are ranked by size. The axis at the bottom of the figure includes all 67 sets of the sample and must be understood as a reference to better judge the coverage of each SDG.

Second, the level of comparability is generally higher in those sets that have been implemented in more than one city. That being said, beyond this binary comparison (one city/multiple cities), we do not observe a correlation between comparability and the number of cities in which a set has been implemented. In other words, there is a simple distinction in the level of comparability between sets that are developed with a single city in mind and those developed with the intent to compare cities (be it 2, 10 or 100 cities).

- **Lesson #4a**: Trying to keep an indicator set below a certain size might lead set developer(s) to prioritize the most common indicators of urban sustainability at the expense of context-specific indicators.
- **Lesson #4b**: Measuring sustainability in only one city allows set developers more freedom to use more context-specific indicators.

Observation #5: The attention paid to sustainability domains and system-components differs across geographical contexts.

This observation might be illustrated by comparing the results obtained for three of the most represented countries in our sample: China (n = 6), USA (n = 7) and Canada (n = 9). As illustrated in Fig. 12, the indicator sets from the two North American countries have more in common than those developed in China in terms of both sustainability domains (STEEP categories) and MONET types. More concretely, whereas social issues receive clearly more attention in North American than Chinese sets, the latter put more emphasis on technology and economy. In terms of the MONET typology, whereas indicator sets in both Canada and USA allocate a majority of indicators to address current individual and social needs (*level* category), Chinese sets focus on the status and potential of resources (*capital*) and pay much more attention to *efficiency* indicators. The results illustrate how the concept of urban sustainability is interpreted differently depending on context-specific preferences (e.g., cultural contexts) and current key challenges.

- **Lesson #5**: An effort should always be made to adapt indicator sets to local idiosyncrasies.

4.4. Lessons regarding the tension between complexity and simplicity

Observation #6: Indicator sets tend to prioritize frameworks based on simple logics

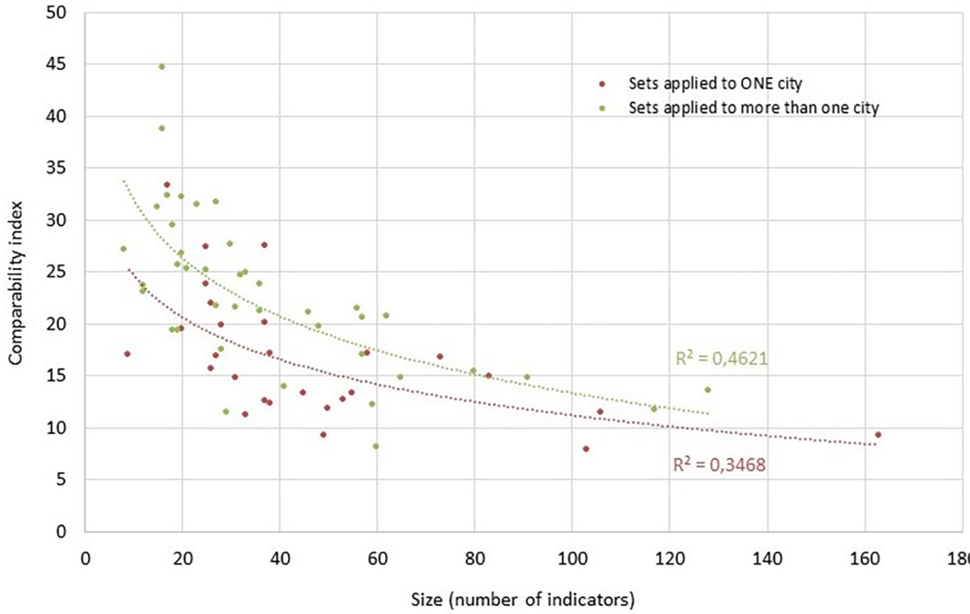

Fig. 11. Comparability level by size.

The conceptual frameworks used for classifying indicators among our sample of sets range from the classical three pillars-based divisions to sophisticated system science-based frameworks; however, the latter type represents a clear minority (i.e., only six sets out of the 67 included in the sample, all of which were developed by scholars). In the majority of cases, the conceptual frameworks are structured using simple domain-based (i.e., economy, society, environment, etc.; e.g., Alpopi et al., 2011; Musa et al., 2018) or issue-based logics (i.e., energy, transport, housing, etc.; e.g., Istat, 2015; City of Surrey, 2016; ISO, 2018a; LEED, 2019), or a two-level hierarchical structure combining these two logics (e.g., Zoeteman et al., 2015; UN Habitat, 2016; Cercle Indicateurs, 2017; Arcadis, 2018). Among the few cases within our sample that employ a more complex logic for framing the urban system, Wang et al. (2013) relied on a structure similar to the DPSIR framework (Smeets & Weterings, 1999), Wu et al. (2018) added indicator categories explicitly to the interfaces between the different domains, and Yigitcanlar et al. (2015) used a framework that identified indicators at two scalar levels (micro- and mezzo-levels).

The popularity of conceptual frameworks based on sustainability domains and/or issues testifies to their advantage of being intuitive and immediately understandable by non-experts. However, such frameworks arguably fail to integrate the complexity that characterizes urban systems (McPhearson et al., 2016; Webb et al., 2018; etc.). In addition, regardless of the framework used, urban sustainability components (domains, topics, etc.) are most often separated as if they were detachable pieces, thereby ignoring what happens at the interface of these elements and how they specifically relate to each other (e.g., Wiek & Binder, 2005; Binder et al., 2010).

- **Lesson #6**: Although being the common *modus operandi* in practice,

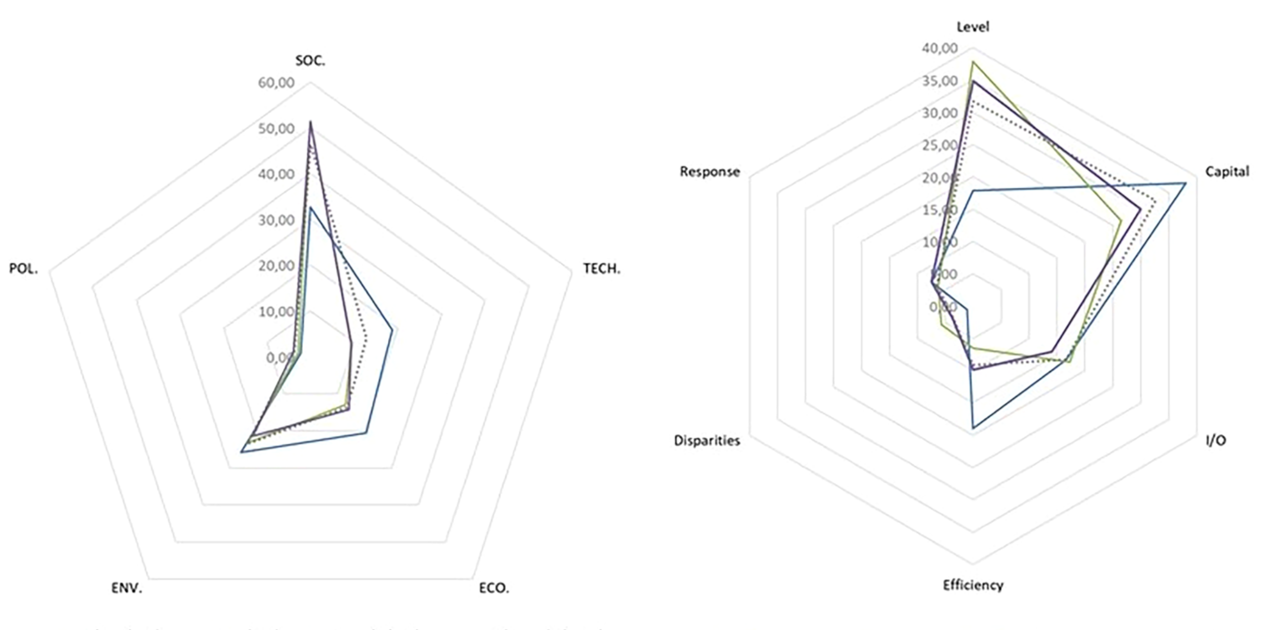

Fig. 12. Average attention paid to STEEP and MONET categories in indicator sets developed in the USA, Canada and China.

		Level	Capital	Input-Output	Efficiency	Disparities	Response
1. No poverty	SDG 1	91,6%	41,0%	2,0%	0,0%	18,9%	9,2%
2. No hunger	SDG 2	50,8%	36,5%	9,5%	1,6%	0,0%	14,3%
3. Good health and well-being	SDG 3	75,1%	35,2%	10,8%	5,9%	2,4%	8,1%
4. Quality Education	SDG 4	58,3%	66,3%	16,0%	0,5%	8,6%	2,7%
5. Gender Equality	SDG 5	62,3%	23,0%	0,0%	0,0%	75,4%	0,0%
6. Clean Water & Sanitation	SDG 6	19,4%	57,5%	22,3%	20,1%	0,0%	26,7%
7. Affordable & Clean Energy	SDG 7	9,7%	21,4%	31,2%	51,9%	0,6%	37,0%
8. Decent Work & Economic Growth	SDG 8	49,2%	31,1%	20,5%	2,9%	9,7%	1,1%
9. Industry, Innovation & Infrastructures	SDG 9	25,6%	52,4%	19,2%	20,1%	0,6%	15,6%
10. Reduced Inequalities	SDG 10	47,1%	20,7%	13,2%	0,0%	60,3%	2,5%
11. Sustainable Cities and Communities	SDG 11	49,5%	55,0%	8,4%	11,7%	2,0%	12,0%
12. Responsible Consumption & Production	SDG 12	2,5%	16,4%	29,4%	50,2%	0,0%	54,2%
13. Climate Action	SDG 13	17,1%	28,2%	36,8%	12,8%	0,0%	28,2%
14. Life below Water	SDG 14	1,2%	76,5%	8,6%	3,7%	0,0%	42,0%
15. Life on Land	SDG 15	9,7%	83,1%	11,8%	5,1%	0,0%	17,3%
16. Peace, Justice & Strong Institutions	SDG 16	55,7%	42,3%	3,1%	3,1%	10,8%	1,5%
17. Partnerships for the Goals	SDG 17	33,7%	82,6%	17,4%	2,3%	0,0%	2,3%

0-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70% and more

Fig. 13. Heatmap illustrating how each SDG is understood from a systemic perspective in the 67 sets included in the sample (on average). Cells express the percentage of indicators relating to the SDG that refer to the respective systemic component.

disaggregating sustainability into a list of discrete topics or dimensions can excessively simplify the systemic complexity, interconnections and trade-offs involved in urban sustainability.

Observation #7: Cross-typological analyses provide deeper insights on the ways that indicators are distributed across different aspects of urban sustainability.

Viewing the data through a cross-typology lens allows us to engage in a more detailed analysis of the distribution of indicators across different aspects of urban sustainability. For instance, simply crossing the SDGs with the MONET typology is sufficient to reveal to what extent different systemic aspects (as defined by the MONET categories) are taken into account for each of the SDGs or vice versa. As Fig. 13 illustrates, both the quantity and quality of the information elucidated by such a cross-typology framework is clearly higher than what is presented in Figs. 5 and 7, where each typology was considered individually (see Section 4.1). For example, the analysis reveals that indicators related to environmental issues (e.g., SDGs 6, 13, 14, 15) largely ignore the *disparities* component, thereby disregarding political ecology concerns about the access to and the management of natural resources. In the same way, while climate-related indicators (SDG13) most often focus on flows (i.e., I/O indicators such as *CO_2 emissions*), the bulk of water- and land-related indicators (SDGs 6, 14 and 15) refer to the quality and availability of natural resources (i.e., *capital* indicators). Overall, we observe from the numbers in Fig. 13 that shifting from one sustainability goal to another generally also involves a shift from one systemic aspect to another, whether consciously or not. Whatever the reason, such a variation can only be elicited by crossing different logics.

- **Lesson #7**: Crossing multiple logics in a matrix-like structure is a simple and powerful method for the development and analysis of indicator sets

5. Discussion

As discussed in Section 2.1, indicators perform a conceptual role that goes beyond their use as mere data carriers. In that sense, our analysis clarifies how the underlying concept of urban sustainability is understood (and *de facto* defined) by practitioners and scholars through the use of indicators. The results show that urban sustainability on average is strongly defined by social aspects (STEEP typology), the satisfaction of current needs as well as the status of different forms of *capital* resources (MONET typology), and the issues under SDG11 (e.g., sustainable urbanization, access to transport systems). To some extent, these emphases naturally derive from the object (cities) being measured as well as the geographical context of our sample (mainly Western initiatives). However, reviewing them with a critical eye can also reveal gaps in current approaches to promote urban sustainability; for example, as demonstrated above, the attention paid to distributional concerns, gender issues and governance matters is generally marginal.

Our analysis highlights several lessons for the future development of indicator sets for urban sustainability. First, concerning the tension between parsimony and comprehensiveness (Section 4.2), the tendency of small indicator sets to be less comprehensive in their coverage of sustainability issues **(Lesson #1)** can be mitigated with a careful selection of indicators **(Lesson #2)**. In addition, some specific issues that are likely to be ignored even with larger sets require particular attention **(Lesson #3)**. On that basis, the following recommendations may be addressed to future indicator set developers:

- Dedicate explicit effort to the elaboration of a conceptual framework at the very beginning of the set development process. The use of such a framework as a mapping tool in the selection of indicators is valuable for signaling potential gaps and identifying existing redundancies, thereby serving to optimize the tradeoff between parsimony and comprehensiveness. Frameworks also enable the comparison of indicator sets with regard to their respective emphases and coverage of different sustainability aspects.
- Base the indicator selection process on both (i) criteria referring to indicators individually considered (e.g., data availability, understandability) and (ii) criteria considering the indicator set as a whole (e.g., parsimony, comprehensiveness). An unbalanced emphasis on the former might result in incomplete coverage and/or superfluous metrics.
- Think twice before using already existing composite indexes (e.g., the Inclusive Wealth Index, Human Development Index, Ecological

Footprint) that condense several aspects of sustainability into aggregate metrics. This strategy can indeed enable to cover more aspects of sustainability (i.e., increasing comprehensiveness) without raising the number of indicators in a set (i.e., increasing parsimony). However, it is important to note that such synthetic indexes might be difficult to 'decrypt' due to the contrasting values they blend and the aggregative procedures on which they rely (Bockstaller & Girardin, 2003; Sébastien & Bauler, 2013).

Related to the tension of comparability vs. specificity (Section 4.3), keeping the size of an indicator set small tends to lead to the use of more standard indicators **(Lesson #4a)**, potentially at the expense of novelty and resonance at the local scale. Additionally, sets applied in more than one city tend to contain more well-established metrics **(Lesson #4b)**, most likely because the need to have comparable data available across cities pushes set developers to prioritize most usual indicators. A third lesson related to this tension states that transferring indicator sets directly from one city to another may not be appropriate **(Lesson #5)**, as different geographical regions display differing emphases on the various categories of urban sustainability. These lessons lead us to make the following recommendations to future set developers:

- Consider including both (i) a core list with standard indicators for the purpose of comparability and (ii) a sub-set of indicators that are particularly pertinent for the urban area in question (see for instance: Moller & MacLeod, 2013; Feleki et al., 2020).
- Be cautious in using carbon copies of past indicator sets, as this strategy may result in contextually inappropriate assessments, and it also inhibits any innovation needed to integrate emerging issues.

Finally, concerning the tension between complexity and simplicity, our analysis demonstrates that future indicator sets, as opposed to current practice, should consider using frameworks that better integrate the complexity characterizing urban systems **(Lesson #6)**. One way of doing this is to combine two or more different logics in a multidimensional framework **(Lesson #7)**. For instance, combining a thematic logic with a systemic one can help to select the most pertinent indicators; i.e., those covering not only all the important topics (e.g., water), but also more specifically those aspects that make each topic a core element within a specific system (e.g., water accessibility, water quality, water consumption, etc.). In other words, this combination of logics reveals not only *what* is important, but also *why* and *how* it actually becomes a key stake given a particular context (see Merino-Saum et al., 2018).

Three key recommendations for future indicator sets might be put forward:

- Do not view schemes such as that in Fig. 13 as homework checklists that must be entirely filled in, as this would easily lead to excessively large sets (Tanguay et al., 2010; Verma & Raghubanshi, 2018). These structures are rather multidimensional maps through which (i) set developers and other involved actors might identify pertinent stakes and key priorities (e.g., Altwegg et al., 2004) and (ii) such prioritization is made transparent to the general public.
- When crossing different logics into multidimensional frameworks, keep in mind that frameworks must also be accessible to a variety of users. From our point of view, a bi-dimensional framework based on dissimilar logics represents an interesting equilibrium between complexity and simplicity, and is already able to reveal the possible presence of significant gaps and redundancies.
- Despite their unprecedented popularity in the field of sustainability indicators, do not use SDGs either to replace existing frameworks or to inhibit future frameworks from being developed. Rather, the SDG framework could be combined with other types of frameworks (e.g., systemic).

6. Conclusion

The project reported in this paper began with a keen interest in collecting and mapping the immense number of urban sustainability indicators that exists within the various initiatives dedicated to this crucial and timely topic. The two research questions defined for the project aimed at: (i) on the one hand, analyzing how current indicator sets translate the concept of urban sustainability into metrics; and (ii) on the other hand, drawing lessons to guide the development of new indicator sets.

The significance of our results firstly derives from the extensive size of our sample (67 indicator sets, 2847 indicators), which includes a fair balance of initiatives promoted by both international and local actors. Although the sampling was limited to initiatives with documentation in English, French, German, Italian or Spanish, which may constitute a geographical bias in the results, the sheer number of initiatives included in the analysis nevertheless offers an unprecedently comprehensive view on the status of indicator-based urban sustainability initiatives. Secondly, the methodology employed in the project (see Fig. 2), and the team's methodical screening process aimed at elevating the analysis from pure subjectivity to a degree of intersubjectivity, thereby increasing the reliability of the results.

The results of our review provide a comprehensive overview of the emphases that current indicator initiatives attribute to different aspects and categories of urban sustainability. In fact, by clarifying how indicator sets are translating the concept of urban sustainability into metrics, our analysis reveals a *de facto* definition of this often-fuzzy concept. According to the results, the meaning of urban sustainability is largely constituted by social aspects, satisfaction of current needs, the status of capital stocks, and topics encompassed in SDG11 (Make cities and human settlements inclusive, safe, resilient and sustainable).

In addition, our work illustrates some of the central tensions that indicator set developers inevitably face and contributes seven key lessons for managing them. With these lessons in mind, developers can better optimize decisions regarding the size, comparability and complexity of their indicator sets.

Further research could expand the analysis presented herein to other countries and regions that are not included into our sample. In the same sense, exploring how the use of indicators for urban sustainability is evolving over time could enrich our results (however, a larger temporal scale would be needed). Further analysis could also address additional tensions that might emerge in the process of developing an indicator set for sustainability. As previously stated (see Section 2.3), the tensions analyzed in the present paper are among those most frequently faced in the field; however, they are certainly not the only ones.

All in all, we believe that our work significantly advances the knowledge on urban sustainability indicators and substantially supports their use as tools for guiding decision-making towards more sustainable cities. Due to their nature as hubs of human activities and their roles as nodes in global socioeconomic networks, cities are central drivers of global environmental change; however, they also often bear the burdens of the earth's system perturbations. Therefore, in a world faced with accelerating climate change, increasing economic instability and escalating resource scarcities, progress in designing multidimensional indicator sets at the urban level is urgently required to support and guide a global transition towards sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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