EPFL

Thèse n° 8909

From metrics towards meaningful assessments of urban sustainability - exploring visions, frameworks and indicators

Présentée le 21 octobre 2021

Faculté de l'environnement naturel, architectural et construit
Laboratoire de relations humaines-environnementales dans les systèmes urbains
Programme doctoral en génie civil et environnement

pour l'obtention du grade de Docteur ès Sciences

par

Pekka Jaakko HALLA

Acceptée sur proposition du jury

Prof. Ph. Thalmann, président du jury
Prof. C. R. Binder Signer, Dr A. Merino, directeurs de thèse
Dr J. Lyytimäki, rapporteur
Prof. C. Rozenblat, rapporteuse
Dr E. Cogato Lanza, rapporteuse

École
polytechnique
fédérale
de Lausanne

2021

Acknowledgements

No man is an island, and no thesis is written alone. Therefore, I would like to begin this thesis report by acknowledging those who have contributed to the accomplishment of this work.

I want to thank, first, my supervisor Claudia R. Binder for giving me the chance to work on this topic, for her guidance along the way, and for her sharp and insightful feedback that led not only to an increased quality of the present thesis, but also to many learnings at the personal level.

I owe a great debt of gratitude to my co-supervisor Albert Merino-Saum for his tirelessness in providing both substantive and moral support, for the shared moments spent pondering ideas, and for the many entertaining discussions on the ups and downs of the *Colchoneros*.

I would also like to thank the members of my thesis jury, Elena Cogato Lanza, Jari Lyytimäki, Céline Rozenblat, and Philippe Thalmann for their valuable feedback on the thesis, all given in a critical yet constructive spirit, and for their inspiring and encouraging comments during the thesis examination.

In preparing the manuscripts contained in this thesis I have had the chance to collaborate with many smart and inspiring people. In this regard, I would like to thank Romano Wyss, Valeria Superti, Anne Boesch, Aristide Athanassiadis, Guillaume Drevon, Michael U. Hensel, Vincent Kaufmann, Shin Alexandre Koseki, Catalina Turcu and Ulli Vilsmaier. Thank you also to the interviewees that granted me their time and insights during the case study conducted in Geneva.

I am grateful for having been part of a brilliant group of people at HERUS – including Anna, Anne, Albert, Aristide, Caroline, Emanuele, Franziska, Gloria, Ivo, João, Livia, Maria, Matteo, Melissa, Rafael, Romano, Silvia, Stefanie, Suse, Thorsten and Valeria – whom I consider not just as colleagues, but also as friends. Furthermore, from the EPFL administration, I would like to extend my gratitude to Caroline Bühler, Emma Sorrentino and Sandra Roux for helping out with many practical matters.

I count myself lucky in terms of the friends I have had around me in Lausanne and elsewhere. I would especially like to thank Massimo for the much-needed sessions of musical and ping pong therapy. Heartfelt thanks go also to Jenny, who supported me through some of the most difficult moments of this project. Of my HERUS friends, thank you especially to Anna, Albert, Livia, Ivo, Matteo and Valeria for the extracurricular activities, particularly valuable during the period of working from home.

Thank you also to my family in Finland – my parents and their partners, and my brothers and their families – for their continuing support and encouragement that, despite the distance, is strongly felt.

A special thank you goes to Elena for her unreserved support, for her kindness and patience, especially during the final thesis writing, and for miraculously managing to listen to my rambling monologues.

Finally, I acknowledge that I have been fortunate to benefit from an enormous amount of support from the institutions of organized society, beginning from the free healthcare and education that I received as a child, all the way to the academic environment at EPFL and the funding received through the Swiss Mobiliar Chair for Urban Ecology and Sustainable Living. I hope to be able to pay some of the debt accrued back in the coming years.

Pekka Halla - Lausanne, 30.07.2021

Abstract

Problem statement. Cities hold a central role in global efforts towards sustainability, and integrating sustainability concerns into the governance of cities constitutes an increasingly urgent challenge. One avenue holding promise in this respect concerns methodologies under the banner of 'sustainability assessment'. Indeed, various assessment initiatives, promoted by actors from local to global scales, have been developed in recent years, often based on sets of indicators that allow for the monitoring and benchmarking of cities across different aspects of sustainability. However, important shortcomings and gaps in knowledge remain, among them a lack of comprehensive guidelines for supporting the reflexive and contextually-relevant design of such assessments, and for ensuring their potential for influence in urban governance processes.

Research objective. This thesis aims to support the reflexive development of indicator-based sustainability assessments that are contextually appropriate and salient for local urban governance.

Methodology. In addressing the overarching research objective, the thesis was divided into three parallel research modules, each module with a particular thematic objective and dedicated research methodology. The first module used collaborative workshops among academics to investigate visions of urban sustainability. The second module collected a comprehensive empirical sample of urban assessments to analyze the indicators and conceptual frameworks in use in the field. The third module employed a case study methodology to develop an assessment approach aimed at enhancing the salience of such assessments.

Results. Across the three modules, the thesis makes conceptual, methodological and empirical contributions for different aspects of the design of indicator-based urban sustainability assessments. Firstly, it elaborates on the meaning of visions of urban sustainability, and provides tools and ideas for engaging with such visions in sustainability assessments. Secondly, the thesis elaborates on the conceptual frameworks and indicators available for the design of urban assessments, as well as on the critical areas where future initiatives can improve compared to current practice. Thirdly, the thesis contributes to knowledge for increasing the salience of indicator-based assessments for governance by proposing and demonstrating an assessment approach that systematically embeds the assessed indicators into their contexts.

Conclusion. Three transversal themes carry through the contributions and insights discussed in this thesis. First, the construction of an assessment of urban sustainability should be seen equally as a construction and clarification of the meaning of the concept, connecting concrete indicators to aspirational visions. Second, the choices related to the design of assessments should reflexively draw from the available options, in order to tailor them to specific contexts and purposes. Third, assessments should not be seen merely as technical exercises, but as occasions for creating narratives around sustainability that connect to the everyday challenges of relevant stakeholders. By contributing tools and insights for the design of assessments that acknowledge these three themes, this thesis encourages assessment practice that is both useful and meaningful for those involved in local urban governance, and that can thereby contribute to transforming cities towards sustainability.

Keywords: urban sustainability, urban system, sustainability assessment, vision, conceptual framework, indicator

Résumé

Problématique. Les villes jouent un rôle central dans les efforts mondiaux en faveur du développement durable, et l'intégration des enjeux de durabilité dans leur gouvernance présente un défi toujours plus pressant. L'une des pistes prometteuses à cet égard concerne les méthodologies d'évaluation regroupées sous le titre "*sustainability assessment*". En effet, diverses initiatives d'évaluation de ce type ont été développées récemment à différentes échelles, souvent sur la base d'indicateurs qui permettent le suivi et le référencement des villes selon différents aspects de la durabilité. Cependant, d'importantes lacunes subsistent dans cette littérature. Il manque notamment des principes de base sur lesquels pourrait reposer la conception réflexive et contextuelle des évaluations futures ; permettant ainsi de décupler l'impact de ces évaluations en termes de gouvernance.

Objectif. La thèse vise à soutenir le développement réflexif portant sur des évaluations de durabilité qui soient adaptées au contexte local et qui favorisent pertinemment la gouvernance urbaine.

Méthodologie. En vue d'atteindre cet objectif, la thèse a été divisée en trois modules parallèles de recherche, chaque module ayant un objectif thématique particulier et une méthodologie de recherche spécifique. Le premier module a mis en œuvre des ateliers collaboratifs entre scientifiques pour étudier les visions de la durabilité urbaine. Le deuxième module a recueilli un échantillon empirique extensif d'évaluations urbaines pour analyser leurs indicateurs et les cadres conceptuels employés. Le troisième module a utilisé une étude de cas pour développer une approche d'évaluation visant à renforcer la pertinence de ce type d'évaluations.

Résultats. À travers ces trois modules, la thèse apporte des contributions conceptuelles, méthodologiques et empiriques à la conception des évaluations. Premièrement, elle élucide et structure les visions plurielles de la durabilité urbaine, tout en fournissant des outils pour intégrer et articuler ces visions dans les processus d'évaluation. Deuxièmement, la thèse étudie et compare les cadres conceptuels et les indicateurs disponibles pour la conception d'évaluations de durabilité urbaine. Elle identifie par ailleurs les pratiques à améliorer dans les évaluations futures. Troisièmement, la thèse contribue aux connaissances sur la pertinence des évaluations vis-à-vis de la gouvernance locale en proposant une approche qui intègre systématiquement les indicateurs évalués dans leur contexte.

Conclusion. Trois thèmes transversaux se retrouvent dans les contributions et les idées de la thèse. Premièrement, la conception d'une évaluation de la durabilité urbaine doit être considérée comme une clarification de la signification du concept, reliant des indicateurs concrets à des visions souhaitées. Deuxièmement, les choix liés à la conception des évaluations devraient s'appuyer de manière réflexive sur les options disponibles, afin de les adapter à des contextes et des objectifs spécifiques. Troisièmement, les évaluations ne doivent pas être considérées uniquement comme des exercices techniques, mais comme des occasions de créer des récits qui se rapportent aux défis quotidiens des parties prenantes concernées. En fournissant des outils qui reconnaissent ces trois thèmes, cette thèse encourage une pratique d'évaluation qui est utile et significative pour les parties prenantes, et qui peut ainsi contribuer à orienter les villes vers la durabilité.

Mots-clés.: durabilité urbaine, système urbain, évaluation de la durabilité, vision, cadre conceptuel, indicateur

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Part I : Synopsis

1. Introduction

1.1 Background

Sustainability[1] is a concept ubiquitously found in societal discourses, scientific research, and the strategies of various public and private sector actors (Kates et al., 2005; Waas et al., 2011). While the concept is not new – its roots in literature can be traced back to 1713, when the German mining administrator von Carlowitz used it to discuss forest management around the mines in Saxony (Grober, 2007) – it is arguably currently imbued with unforeseen gravity and urgency. In particular, the exponential growth witnessed during the last century in human populations and in the scale of economic activity means that for the first time in history the challenge of sustainability is no longer confined to the kind of local settings that von Carlowitz was concerned about, but instead has now reached the global scale (MEA, 2005; Steffen et al., 2015).

At its core, the challenge of sustainability contains a tension between human developmental demands and the need to secure the integrity of the Earth's ecological systems (Rockström et al., 2009; Raworth, 2012; Gibson, 2016). Perhaps the most quoted definition of sustainability, from the so-called 'Brundtland report', reflects this tension in stating that sustainability consists of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43). In other words, sustainability requires the careful balancing of environmental protection against not only the urgent need to address global poverty and economic inequality (WCED, 1987; UN, 2015), but also against the ingrained modern ideal of perpetual economic growth (Norgaard, 2009).

Awareness of the sustainability challenge began to gain ground during the latter half of the twentieth century, following the contributions of such pioneers as Carson (1962), Boulding (1966) and the Club of Rome (Meadows et al., 1972), whose work pointed to the emerging environmental issues associated with the rapid post-war economic development of the Western world. This increasing awareness led the United Nations (UN) in 1972 to organize the first global conference dealing with the environment, the Stockholm Conference on the Human Environment, which paved the way for subsequent creation of multilateral international treaties on the theme (Jabbour et al., 2012). A decade later, commissioned by the UN, the Brundtland report played a key role in mainstreaming the concept of sustainability (Redclift, 2005), and since then, the number of sustainability-related initiatives has exploded in both the public and private domains. International landmarks in the field include the UN's Agenda 21 from 1992, the Millennium Development Goals adopted in 2000, the 1997 Kyoto and 2016 Paris agreements dealing with the looming threat of climate change, and the UN's Sustainable Development Goals (SDGs) adopted in 2015.

Within the challenge of sustainability, cities hold distinct significance (Parnell, 2016; Castán Broto, 2017), as the last century has seen the world undergo a tremendous urban transformation, with an increasing majority of humans now living in cities (UN, 2019). Consequently, today the majority of

[1] Note that this thesis follows the increasingly common practice of using the terms 'sustainability' and 'sustainable development' interchangeably. This decision is based on the insight that sustainability is a dynamic and not a static state, involving constant development in response to changing circumstances (Waas et al., 2011; Gibson, 2016), which effectively removes any difference in connotation between the two terms.

global resource consumption occurs in cities; for example, urban areas are responsible for an estimated 75% of final energy use (GEA, 2012; Wu et al., 2020). Meanwhile, cities are also hotbeds of social and technological innovation, as well as hubs in the world economy (Sassen, 2005; UN-Habitat, 2016; Balland et al., 2020). Indeed, approximately 80% of the global gross domestic product (GDP) can be attributed to cities (IPCC, 2014). Given this dual role of cities as both principal resource consumers and value creators, it can be said that the development of both already existing and future cities constitutes a crucial determinant of all dimensions of sustainable development globally. As an upshot, the concept of 'urban sustainability' has been occupying an increasingly central position of interest in both the political and academic domains[2] (UN, 2017a; Lobo et al., 2020).

In the political domain, a major milestone in advancing awareness for the need for sustainability-related policymaking at the local level was the UN's Agenda 21, whose Chapter 28 called for the formulation of a local Agenda 21 (Selman, 1998). Since then, reflecting the advancing urbanization of the world, much of the focus dedicated to local initiatives has revolved especially around cities. At the UN's Habitat III conference in 2016, this focus culminated in the elaboration of the New Urban Agenda (UN, 2017a) as a global guideline for sustainable urban development. The importance of cities is also visible in the existence of a dedicated goal for 'Sustainable Cities and Communities' among the UN's 17 Sustainable Development Goals (UN, 2015). Beyond initiatives at the national and international scales, cities themselves are also emerging as proactive agents in the field of sustainability, with collaborative networks such as C40 and ICLEI providing a forum for local scale actors to collaborate and share knowledge on sustainability-related policymaking (Giest and Howlett, 2013).

Complementing these developments in the political sphere, within the academic community research into urban sustainability has proliferated since the 1990s (Alberti, 1996; Maclaren, 1996; Finco and Nijkamp, 2001). Notably, the concept has recently inspired attempts to create analytical frameworks and methodologies for a globally generalizable 'urban science' (McPhearson et al., 2016; Lobo et al., 2020). Rather than departing from traditional disciplinary perspectives, these attempts place the city itself at the center of attention, which, given the intertwined socioeconomic, ecological and infrastructural facets that cities possess, essentially requires the development of interdisciplinary approaches and knowledge (Acuto et al., 2018; Contestabile, 2018).

Within this increasing importance accorded to urban sustainability, specific attention has been given to the development of approaches that allow for its assessment (Wiek and Binder, 2005; Cohen, 2017; Kaur and Garg, 2019). The overarching aim of these assessment methodologies is, first, to translate the otherwise abstract concept to an operational form (e.g., in terms of specific goals and metrics), and second, to produce knowledge that can assist different actors in understanding the sustainability status of their cities, and in formulating and evaluating their sustainability-related policies and strategies (Waas et al., 2014; Bond et al., 2015). Many of these methodologies use so-called sustainability indicators that attempt to capture the different aspects of urban sustainability into observable metrics (Meadows, 1998; Waas et al., 2014; Verma and Raghubanshi, 2018). By now, a

[2] Note that several definitions exist for, first, distinguishing urban areas from rural areas, and second, distinguishing between the terms 'city' and 'urban' (UN, 2019). As this discussion is beyond the scope of this thesis, the decision is taken to assume that within this work 'urban' refers simply to areas with a high density of human populations, and that a 'city' is an area that contains a cluster of contiguous urban parcels that in total reach a certain threshold sum of population (see: Dijkstra et al., 2020). In practice it means that the terms 'urban' and 'city' are used interchangeably throughout the thesis.

great number of such indicator-based urban sustainability assessment frameworks exist. These initiatives originate not only from academia or from international organizations (Tanguay et al., 2010; Mori and Christodoulou, 2012; ISO, 2018; Global Platform for Sustainable Cities, 2018), but in an increasing number of cases local governments have also taken upon themselves to construct indicator sets for assessing the sustainability of their cities (e.g., City of Sapporo, 2013; City of Surrey, 2016; City of Sydney, 2016).

1.2 Persisting challenges

Despite the prominent efforts dedicated towards the theme of sustainability, much remains to be achieved, both in terms of human-induced pressure on global ecosystems (Turner, 2008; Steffen et al., 2015; Zeng et al., 2020) and in terms of ensuring a decent quality of life for all (Milanovic, 2012; Diffenbaugh and Burke, 2019). By many measures the urgency to act is exacerbated in cities; evidence shows that although cities in principle hold the promise of higher efficiency in satisfying human needs (Bettencourt et al., 2007; Wu et al., 2020), in practice urban residents often consume more than their fair share of resources (Heinonen and Junnila, 2011; Pang et al., 2019). In addition, research shows that poverty is concentrating in cities (Ravallion et al., 2007) despite the disproportionately high share of global GDP that they produce (IPCC, 2014). It suggests that concerted efforts must be spent to distribute these benefits equitably among urban residents. Given these urban challenges, a globally crucial task moving towards the future is to ensure that sustainability is integrated as a central principle into the governance of cities (Bulkeley and Betsill, 2005; van Zeijl-Rozema et al., 2008). Here, the kind of indicator-based sustainability assessment methodologies mentioned above can play a central role in concretizing the concept, thus making it more actionable for local governance processes (Hak et al., 2012).

In order to serve this important purpose, however, assessment methodologies must tackle significant challenges, two of which in particular are pertinent for motivating the research of this thesis. The first challenge relates to understanding and operationalizing the concept of 'urban sustainability'. This challenge derives not only from possible technical issues (e.g., defining appropriate metrics, and collecting and analyzing data), but more fundamentally from the fact that the concept itself is multidimensional, value-laden, contextually specific, and entails complex interconnections between socioeconomic and ecological systems (Alberti, 1996; Finco and Nijkamp, 2001; Dempsey et al., 2011). In fact, to be precise, the problem is not a shortage of assessment frameworks and indicators (King et al., 2000; Pintér et al., 2005). Rather, it is in making sure that the available tools are employed reflexively and purposefully to construct assessments that are tailored to match local key governance challenges (Innes and Booher, 2000; Hartmuth et al., 2008), as well as adequately inclusive of the concerns and goals of those having a stake in the assessment (O'Connor and Spangenberg, 2008; Turcu, 2013; Gutierrez et al., 2018).

The second important challenge facing sustainability assessment methodologies is the coupling of the information that they produce into local governance processes (Holden, 2013; Dizdaroglu, 2017). As has been observed by several authors, the production of data does not automatically translate to influence in real-world governance (Gudmundsson et al., 2009b; Sébastien et al., 2014). Therefore, the challenge consists in designing the assessments so that the information they produce is salient for their potential users and the complex real-world challenges and decision-making situations they face (Cash et al., 2003; Parris and Kates, 2003; Hák et al., 2016).

1.3 Overarching objective of thesis

To summarize, the point of departure for the thesis is the increasingly central position that cities assume in the global sustainability challenge. In fact, while cities exert heavy loads on their surrounding environments, as hotbeds of social, economic and scientific activities they also possess the potential for facilitating global transitions towards sustainable ways of living. To unleash this positive potential and to limit the negative impacts of cities, methodologies like sustainability assessment are needed to translate the concept of sustainability to the operational level of local urban governance. Here, the two challenges mentioned above in the construction of indicator-based assessments motivate the research of this thesis: (i) designing assessments that operationalize the concept of urban sustainability in a reflexive, contextually appropriate manner, using the range of options available, and, (ii) designing assessments that provide information in a form that is salient for local governance processes.

Based on the above, the overarching objective of this thesis can be expressed as:

> *Supporting the reflexive development of indicator-based sustainability assessments that are contextually appropriate and salient for local urban governance*

The objective is based on the belief that when sustainability assessments are developed reflexively, tailoring them to particular contextual specificities and stakeholder concerns, as well as paying attention to the form of the information that they provide, these assessments have the potential to contribute to the integration of sustainability as a central strategic principle into the governance of cities. This, however, is not a trivial task, and supporting tools and guidelines are urgently needed.

1.4 Structure of thesis

This thesis is a 'thesis by publication', meaning that its principal contributions are contained in five manuscripts submitted for publication. The manuscripts are listed below in Table 1-1. The thesis consists of three parts, as follows:

Part I provides a synopsis of the thesis. More specifically, Chapter 2 reviews relevant literature on the subject matter of the thesis, and highlights the relevant gaps in current scientific knowledge that the thesis addresses. Chapter 3 presents an overview of the structure, objectives and research questions of the thesis. Chapter 4 clarifies the conceptual approach that undergirds the research of the thesis. Chapter 5 is dedicated to presenting the methodological approach of the thesis. Chapter 6 summarizes the main results and insights of the research reported in the five manuscripts. Chapter 7 provides a discussion of the thesis, including its scientific contributions, recommendations drawn for practice, limitations, and possible subsequent research avenues. Finally, Chapter 8 briefly lays out the main conclusions of the thesis.

Part II contains the five manuscripts listed in Table 1-1. They include one chapter published in an edited volume on urban sustainability assessment (Manuscript 1), one article published in *Ecological Indicators* (Manuscript 3), and three journal articles (Manuscripts 2, 4 and 5) whose publication is pending at the time of this writing. The precise contributions of the candidate are described at the beginning of each manuscript.

Part III contains supplementary material for the methodological chapter and the manuscripts.

Table 1-1. The manuscripts constituting the body of the thesis.

#	**Reference**
1	**Halla, P**., Wyss, R., Binder, C.R., 2020. Conceptualizing Urban Systems for Sustainability Assessment: Four Powerful Metaphors, in: Binder, C.R., Wyss, R., Massaro, E. (Eds.), Sustainability Assessment of Urban Systems. Cambridge University Press, Cambridge, pp. 241–260. https://doi.org/10.1017/9781108574334.012
2	**Halla, P**., Wyss, R., Athanassiadis, A., Drevon, G., Hensel, M.U., Kaufmann, V., Koseki, S.A., Turcu, C., Vilsmaier, U., Binder, C.R., *forthcoming*. Using metaphors for addressing urban sustainability. Publication pending. (Preprint: https://doi.org/10.31235/osf.io/kdzxt)
3	Merino-Saum, A., **Halla, P**., Superti, V., Boesch, A., Binder, C.R., 2020. Indicators for urban sustainability: Key lessons from a systematic analysis of 67 measurement initiatives. Ecological Indicators, 119, 106879. https://doi.org/10.1016/j.ecolind.2020.106879
4	**Halla, P**., Merino-Saum, A., *forthcoming*. Conceptual frameworks for urban sustainability indicators - an empirical analysis. Publication pending. (Preprint: https://doi.org/10.31235/osf.io/vayq7)
5	**Halla, P**., Merino-Saum, A., Binder, C.R., *forthcoming*. Contextually rich sustainability assessment for supporting local urban governance - connecting indicators to institutions and controversies. Publication pending. (Preprint: https://doi.org/10.31235/osf.io/m4vz7)

2. Theoretical background and pertinent gaps in current literature

As described in the introduction, the challenges that motivate the research of this thesis concern, firstly, the reflexive operationalization of the complex concept of urban sustainability in sustainability assessments, and secondly, coupling the output of such assessments to local urban governance processes. Accordingly, the purpose of this chapter is to provide an overview of current scientific understanding on the central themes of these challenges, including urban sustainability, sustainability assessment (and in particular *urban* sustainability assessment), and the potential influence of assessments. Throughout the chapter, the presentation also points to gaps that remain in existing knowledge and that currently hinder the potential of urban sustainability assessments for addressing the above challenges. These gaps are summarized at the end of the chapter, and they form the basis for the formulation of the research objectives and questions described in the following Chapter 3.

2.1 Urban sustainability

As presented in the introduction, during the last half a century the concept of sustainability has increasingly captured the attention of researchers, politicians and the general public alike. During this time, the concept has been the object of lively research and debate that have progressively shaped its meaning (Redclift, 2005; Du Pisani, 2006). The debate has not, however, converged into a precisely defined, single understanding of what sustainability entails and how it is to be achieved, but instead the concept has evolved to encompass a number of parallel discourses and approaches (Waas et al., 2011; White, 2013; Patterson et al., 2017). Often, then, attempts at providing definitions for sustainability remain at the level of abstract principles (Gibson et al., 2005; Waas et al., 2011; Christen and Schmidt, 2012), such as the Brundtland report's definition quoted in Section 1.1 (WCED, 1987), or the commonly used idea of the three parallel pillars of sustainability (Purvis et al., 2019)[3].

When dealing with specific problems or decision-making situations related to sustainability, however, there is a need to operationalize the concept into more concrete goals, metrics and actions (Rydin, 2007; Hak et al., 2012; Elgert, 2018). These operationalizations, in turn, are bound to reflect (i) the characteristics of the specific sustainability problem at hand (e.g., sustainable energy), and, (ii) the specificities of the context (e.g., Switzerland in the year 2021) where the problem is considered (Kates et al., 2005; Hartmuth et al., 2008). One such more specific problem is *urban* sustainability, which, as already mentioned, constitutes a particularly significant theme within the overarching global sustainability challenge (UN, 2017a; Lobo et al., 2020).

Corresponding with point (i) above, definitions of urban sustainability (see, e.g., Shen et al., 2011; Mori and Christodoulou, 2012; Huang et al., 2015) typically reflect the particular character and role of cities in the world (Sassen, 2005; Balland et al., 2020; Meirelles et al., 2020)[4]. Indeed, as hubs of people and

[3] One the one hand, this persisting fuzziness around the concept may render it vulnerable to misuses (Hickel, 2015; Marquis et al., 2016). On the other hand, however, the vagueness also allows for the concept to act as an assembling umbrella term that mediates interactions between different actors and positions, thereby allowing it to have wider political and scientific traction (Lélé, 1991).

[4] For example, UN-Habitat states that "[s]ustainable urbanization requires that cities generate adequate income and decent employment opportunities; provide the necessary infrastructure for water and sanitation, energy, transportation and communication; ensure equitable access to housing and services; minimize the number of people living in slums; and preserve a healthy environment within the city and surrounding areas" (UN, 2019, p. 2).

socioeconomic activity, urban sustainability involves satisfying a complex set of parallel requirements (Finco and Nijkamp, 2001; Dempsey et al., 2011; Ramaswami et al., 2012; Hamman, 2017). Here, two features in particular can be highlighted that make urban sustainability distinct from sustainability in general. First, cities themselves possess a set of characteristics, including their ability to utilize agglomeration effects to produce economic gains and innovation (Scott and Storper, 2003; Bettencourt et al., 2007). In addition, cities are characterized by high social complexity (Blok and Farias, 2016; Opp, 2017) – i.e., the co-presence of a multiplicity of people, values, subcultures, etc. – as well as a high density of human-built infrastructures, technologies and artifacts (Sahely et al., 2005). Second, cities have a particular relationship with their surroundings, since in terms of ecosystem services they are mainly sites of consumption (Mori and Christodoulou, 2012; Turcu, 2013). In other words, the concern is for cities to limit the externalities and resource demands they impose on their surroundings (Kennedy et al., 2014). In fact, it is sometimes argued that urban sustainability is an oxymoron, since cities will always have to rely on their hinterlands for resource inputs (Rees, 1997). Overall, then, *internal* urban sustainability has a particularly strong emphasis on the economic, social and infrastructural aspects of sustainability, while *external* urban sustainability consists of balancing the negative impacts (e.g., burdens on ecosystems) and positive impacts (e.g., production of economic value, and creation of technological and social innovation) that cities have towards other systems.

Corresponding with point (ii) above, operationalizations of urban sustainability can be expected to reflect contextual specificities (Kates et al., 2005). Such context-specificity may appear in at least two ways. First, the specific local circumstances (climate, geography, etc.) and the particular evolutionary stage of a city result in a distinct set of sustainability problems (Hartmuth et al., 2008). For example, as Bai and Imura (2000) show, urban challenges typically evolve along the developmental trajectory of a city, at first from poverty to production-related issues, and then on to consumption-related issues. Second, interpretations of urban sustainability reflect particular local preferences (Turcu, 2013; Gutierrez et al., 2018), which are rooted in culturally defined expectations and worldviews (Jasanoff and Kim, 2015). For example, different historical periods have witnessed varying popular and scientific conceptions of what makes a city 'good' (Lynch, 1984; Bettencourt, 2015).

However, beyond this general basis – the points (i) and (ii) discussed above – a considerable variety of parallel perspectives to urban sustainability exists across different fields and scientific disciplines. The variety pertains not only to the necessary criteria for urban sustainability, but more fundamentally also reflects different ideas about the very nature and building blocks of cities (Portugali, 2011; Cook and Swyngedouw, 2012). These perspectives can be decidedly contrasting or even antagonistic towards each other; for example, perspectives that emphasize efficiency as a yardstick of urban sustainability may clash with requirements for resilience (Elmqvist et al., 2019), which, in turn, may be an unappealing concept to those attuned to social science (Olsson et al., 2015). However, rather than being a problem to solve definitively, this is merely a reflection of the nature of cities as quintessential complex systems that contain a multitude of interconnected concerns and competing goals (de Roo et al., 2012; Bettencourt, 2015; Portugali, 2016). For such systems, several legitimate descriptions exist in parallel, with each description dissecting the system from a different perspective and along a different set of axes (Cilliers, 2008; Wells, 2012).

To summarize, urban sustainability is a multidimensional concept whose operationalizations reflect both the particular characteristics of cities and contextual specificities. At the same time, a degree of ambiguity concerning the concept remains, owing in part to the complexity of cities that leads to

multiple parallel perspectives to them and their sustainability. In this situation, arguably, what becomes equally important to the task of advancing science towards new, more detailed knowledge about cities is the task of collecting, organizing and comparing the already-existing knowledge in a way that makes it understandable and accessible to practitioners and decision-makers**.** At the moment, work towards such comprehensive interdisciplinary approaches is only nascent, and important conceptual and methodological gaps remain (Acuto et al., 2018; Contestabile, 2018).

2.2 Sustainability assessment

2.2.1 History and definitions

As a response to the need to operationalize sustainability more concretely, a plethora of approaches under the banner of 'sustainability assessment' have been developed since the 1990s (Bond et al., 2012; Gibson, 2016; Pope et al., 2017). In terms of origins, the term can be associated in particular with two fields of science and practice: impact assessment and sustainability science. Within the impact assessment tradition[5], sustainability assessment represents the third generation (Gibson et al., 2005; Bond et al., 2015) following environmental impact assessment (EIA) and strategic environmental assessment (SEA), both of which are today enshrined in legal instruments around the world (Morgan, 2012). Historically, the impact assessment tradition stretches back to the 1960s (Glasson et al., 2013), and its focus has since then progressively expanded from its original scope on assessing the environmental impacts of particular projects to also assessments of higher-level strategic plans and programmes (Bond et al., 2015). What makes sustainability assessment distinct within the tradition is, as Pope et al. put it, that "some attempt is made to engage with the concept of sustainability in all its complexity" (2017, p. 206). Consequently, sustainability assessments are distinguished from other forms of impact assessments with their particular focus on the comprehensive coverage of different dimensions of the assessed object, as well as an acknowledgment of the value-laden character of the knowledge being produced (Sala et al., 2015).

In realizing this distinction, sustainability assessment methodologies often incorporate insights and methods that are central to the field of sustainability science (Audouin et al., 2015). The latter has emerged as a prominent field during the last two decades, based on the explicit goal to develop rigorous scientific knowledge around the complex problem of sustainability (Kates et al., 2001; Kates, 2011). Transdisciplinarity, i.e., knowledge co-production between scientific disciplines as well as between scientists and other social actors, features centrally in sustainability science as a means to cope with the inherently multidimensional and value-laden character of sustainability (Osorio et al., 2009; Norström et al., 2020). In addition, compared to traditional conceptions of the character of science as a neutral endeavor, sustainability scientists typically assume a more active role in effectuating change in the real world (Wiek et al., 2012).

The position of sustainability assessment at the confluence of the impact assessment tradition and sustainability science is reflected in how it is typically defined. For example, according to Bond et al., "sustainability assessment can be simply defined as any process that directs decision-making towards sustainability" (2015, p. 3). Similarly, Gibson states that "[s]ustainability assessment is essentially an

[5] Impact assessment is defined as "the process of identifying the future consequences of a current or proposed action" (IAIA, 2009).

organized approach to deliberation and decision making [which] overlaps with, and plays a role in, governance for sustainability" (2016, p. 16). Waas et al. (2014) in turn define sustainability assessment as any process that aims at (i) creating understanding about the meaning of sustainability; (ii) structuring sustainability-related information in view of making it accessible in decision-making; (iii) fostering sustainability goals. In other words, instead of being defined by a particular tool or procedure, sustainability assessment is considered first and foremost as a deliberative forum for learning about and operationalizing the complex concept of sustainability into governance (Gibson, 2009; Scerri and James, 2010; Bond et al., 2012), potentially applied to a broad range of objects from individual products to entire systems, such as cities (Gibson, 2016; Pope et al., 2017).

2.2.2 Principles, dimensions and tools

To give some structure to the multitude of approaches that fit within the above definitions, a number of analyses, both descriptive and prescriptive in nature, have attempted to synthesize general meta-frameworks of sustainability assessment (Gibson et al., 2005; Lee, 2006; Bond et al., 2012; Pintér et al., 2012; Waas et al., 2014; Sala et al., 2015; Pope et al., 2017). From this literature, roughly three broad areas of concern can be identified. Firstly, some authors have sought to specify sets of ideal principles to guide the design of sustainability assessments (Pintér et al., 2012; Waas et al., 2014). Example principles include adopting a guiding vision, having an adequate scope, following transparent and participatory processes, communicating results to induce learning, etc. The second area of concern refers to the assessment itself; here, a distinction can be made, for example, between the normative (i.e., the sustainability goals and targets against which the assessment is made), systemic (i.e., the representation of the object being assessed with, for example, sets of indicators) and procedural (i.e., the steps and participants of the assessment) dimensions of the assessment (Wiek and Binder, 2005; Binder et al., 2010). Thirdly, some of the literature suggests for assessments to explicitly consider dimensions related to the assessment context (Lee, 2006; Sala et al., 2015; Pope et al., 2017). Among these dimensions are the stakeholders and responsible parties, the general objectives and decision-making rules applicable to the assessment, and the formal and informal institutions weighing upon the assessment (Reed et al., 2006; Pahl-Wostl, 2009).

Within the above (ideal) principles and dimensions, sustainability assessments deploy a broad collection of possible tools, depending on the particular problem setting and approach taken. The available tools can be categorized according to different typologies (Ness et al., 2007; Gasparatos and Scolobig, 2012; Singh et al., 2012). For example, Ness et al. (2007) identify three categories, namely, (i) indicators and indices; (ii) product-related assessment tools; (iii) integrated assessment tools. This thesis focuses particularly on sustainability assessments that are based on indicators (Meadows, 1998; Waas et al., 2014; Verma and Raghubanshi, 2018). Gallopin defines indicators as “variables that summarize or otherwise simplify relevant information, make visible or perceptible phenomena of interest, and quantify, measure, and communicate relevant information” (1996, p. 108). As Waas et al. (2014) describe, indicators have both a 'systemic' aspect, in that indicators are simplified reflections of attributes of complex systems and phenomena (Bossel, 1996; Maclaren, 1996), and also a 'technical' aspect, in that indicators are variables that acquire a specific meaning when related to a reference point (Lancker and Nijkamp, 2000).

A specific component in sustainability assessments that is central for the research conducted within this thesis is the accompanying conceptual framework (Maclaren, 1996; Lyytimäki and Rosenström,

2008; Pintér et al., 2012). Such frameworks play an important yet often undervalued role in sustainability assessments. In particular, by disaggregating the overarching assessment problem into more specific categories, frameworks help to define the problem in more concrete terms, and subsequently guide the development and selection of pertinent goals and metrics (Bossel, 1999). Conversely, by anchoring metrics into broader concepts, frameworks elevate them from mere data points to indicators with a more complete and relatable meaning (Maggino, 2017). Furthermore, conceptual frameworks perform an important management purpose in that they provide a structure for organizing the multitude of information related to the assessed problem, thus helping to make this information intelligible (Gallopín, 1997; van Zeijl-Rozema and Martens, 2010).

2.2.3 Urban sustainability assessment

Within the literature on sustainability assessment, an increasingly rich reservoir of approaches exists dedicated specifically for the sustainability assessment of cities (Alberti, 1996; Maclaren, 1996; Cohen, 2017). Some of these approaches aim to assess cities in their entirety, while others zoom in on the scale of neighborhoods or on specific sub-subsystems, such as transport or housing (Sharifi and Murayama, 2013; Kaur and Garg, 2019). These approaches do not uniquely originate in the academic domain, as many governmental actors from the local to the international level have also developed their own preferred approaches for assessing urban sustainability (Shen et al., 2011; FSO, 2017; UN, 2017b; Global Platform for Sustainable Cities, 2018). Also, by now a number of certification standards exist for sustainable urban development (Sharifi and Murayama, 2013; ISO, 2018; Kaur and Garg, 2019). As with sustainability assessments in general, indicators are the most commonly used tools for assessing urban sustainability (Tanguay et al., 2010; Cohen, 2017; Verma and Raghubanshi, 2018). Some approaches prefer to present these indicators as disaggregated dashboards (Kitchin et al., 2015), while others develop different methods for their aggregation into indices or multi-criteria assessments (Mori and Christodoulou, 2012; Merino-Saum, 2020).

As presented in Section 2.1, the concept of urban sustainability entails a level of ambiguity that lends itself to the presence of different interpretations about its meaning. This ambiguity becomes visible and concrete in the variety of ways it is operationalized in different assessment approaches. In indicator-based assessments, this variety appears not only in the explicit goals and indicators selected for the assessments (Tanguay et al., 2010), but also in the conceptual frameworks developed for the assessments (Maclaren, 1996) and in the (implicit or explicit) value-based visions of urban sustainability that guide the design of the assessments (Pintér et al., 2012). As Vatn (2009) argues, each assessment approach can be considered as a 'value-articulating institution'; in other words, the choices made in the design of assessments are not neutral, but privilege certain values and interests over others (Gasparatos, 2010). In fact, as Meadows (1998) points out, not only are these choices influenced by what we consider important, but also, in an inverse fashion, the outcomes of the choices end up shaping our sense of what is important. The unavoidable normativity embedded in assessment approaches brings forth the requirement to construct them through transparent and reflexive processes (Kemp and Martens, 2007; Pintér et al., 2012; Popa et al., 2015). To fulfill this challenging requirement, clear guidelines are needed for instructing developers of urban sustainability assessments in their choices. Such guidelines, however, are currently lacking in several respects.

At the level of guiding visions of urban sustainability, although the formulation of such a vision is underlined by several authors as an important early step in the design of sustainability assessments,

the literature does not specify how exactly this may be done, or what such visions even consist of (Meadows, 1998; McCool and Stankey, 2004; Pintér et al., 2012). This lack of means for engagement with such visions means that sustainability assessments, first, often lack explicit connection to deeper meanings and values, and second, miss out on creating a dialogue between the different fundamental perspectives to urban sustainability that the relevant stakeholders may possess.

In terms of conceptual frameworks for indicators, a number of authors have discussed different types of such frameworks for urban sustainability (Maclaren, 1996; Olalla-Tárraga, 2006; Nathan and Reddy, 2012). However, an overview of current practice is lacking, and guidance in literature is scarce for how to develop these conceptual frameworks and why certain kinds of frameworks should be preferred over others (Burgass et al., 2017). The lack of guidance is problematic given the several purposes that conceptual frameworks serve in sustainability assessments (see Section 2.2.2). For example, an imprecise or inappropriate conceptual framework can lead to a haphazard selection of indicators (Pintér et al., 2005; Montmollin and Scheller, 2007), as well as to the inadequate anchoring of indicators to conceptual foundations (Maggino, 2017).

When it comes to indicators, reviews of assessment methods have shown that not only is there a lack of consensus on the metrics to be used for indicating urban sustainability (Tanguay et al., 2010), but also that important variation can be detected in the emphasis accorded to different dimensions of urban sustainability (Braulio-Gonzalo et al., 2015; Kaur and Garg, 2019). Part of the variance is due to the inherent context-dependency of urban sustainability (Hartmuth et al., 2008; Turcu, 2013). Nevertheless, arguably, some of it can also be attributed to the aforementioned lack of solid conceptual frames to guide the indicator selection (Cohen, 2017), and the lack of practical guidelines for navigating the existing 'indicator industry' (King et al., 2000) and the multitude of sustainability indicators developed during the last decades.

The lack of overview and guidance for making sense of the range of the options for visions, conceptual frameworks and indicators can be considered particularly problematic in the case of urban sustainability, since its multidimensional and context-specific character means that adequately capturing it in assessments is a demanding task (Finco and Nijkamp, 2001; Dempsey et al., 2011). Yet, instead of copying from past practice, assessments should be tailored consciously and reflexively for each application in order to attain resonance with local governance and to adequately consider the concerns of different stakeholders present in local urban contexts (Reed et al., 2006; Turcu, 2013; Gutierrez et al., 2018).

2.2.4 The use and influence of sustainability indicators

As presented in Section 2.1.2, a consensus exists in literature that the purpose of sustainability assessment is not merely producing sustainability-related information, but also ultimately fostering sustainability objectives in decision-making. Producing information with indicators does not, however, automatically lead to influence[6] (Gudmundsson et al., 2009b; Sébastien et al., 2014; Lehtonen et al.,

[6] Note that the terminology here follows Rich (1997) in distinguishing between 'impact' (information has led to a concrete action), 'influence' (information has *contributed* to a decision or a way of understanding a problem) and 'use' (information has been treated in some way, without necessarily leading to influence). As researching impacts in this sense is beyond the scope of this thesis, the discussion focuses on the use of indicator-based information, and how under favorable conditions use may lead to influence.

2016). Indeed, Innes and Booher observed already in 2000 that "millions of dollars and much time of many talented people has been wasted on preparing national, state and local indicator reports that remain on the shelf gathering dust" (2000, p. 174). Furthermore, the influence that sustainability indicators and their assessment manage to achieve is rarely direct, and the information they produce "more often interacts with policies through indirect and largely unforeseen pathways, for instance, by gradually shaping frameworks of thought or by serving as ammunition in political battles" (Sébastien et al., 2014, p. 318).

Past scholarship has elaborated on the question of influence of indicator-based assessments in three specific ways. Firstly, literature identifies different functions that indicators can play in governance, with each function targeting different audiences and processes of governance from the identification of possible issues to the design and evaluation of policies (Innes and Booher, 2000; Gudmundsson, 2004; Hezri, 2004). For example, Innes and Booher (2000) propose a three-tiered hierarchy of indicator functions. At the first level, system performance indicators provide a general overview of how the assessed system is working, and therefore target the general public (Gudmundsson (2004) calls these 'headline' indicators). The second tier is made up of policy and program indicators. These indicators are mainly targeting policy analysts or policymakers themselves, typically focus on a subsystem (e.g., transport, housing, etc.), and may be assessed either ex-ante or ex-post (Gudmundsson, 2004). The final tier of Innes and Booher's hierarchy concerns so-called rapid feedback indicators, which target all kinds of actors with constant up-to-date information, and thereby aim to enable the self-organizing properties of the assessed system.

Secondly, different types of indicator use (and potential influence) have been identified in literature, including instrumental, conceptual and political use[7] (Gudmundsson et al., 2009b; Sébastien et al., 2014). Instrumental use entails applying the information that the indicators carry for making decisions and for guiding actions (Gudmundsson et al., 2009b). Conceptual use, in contrast, concerns the shaping of mental models and definitions, and is therefore more indirect than instrumental use (Sébastien et al., 2014). Political use, in turn, concerns deploying the indicators to legitimize decisions or using them as part of political wheeling and dealing (Boulanger, 2007; Gudmundsson et al., 2009b). In addition, an important fourth type of use (and potential influence) occurs during the development indicators and assessment, in what is called their 'process use' (Holden, 2008; Sébastien et al., 2014). It shifts focus from the end results to the social learning and networking that takes place among the actors involved in the process of developing indicator-based assessments.

Thirdly, literature has elaborated on the factors that determine how much influence indicators may wield (Innes, 1990; Sébastien et al., 2014; Borgnäs, 2016). For example, Gudmundsson et al. (2009b) discuss factors related to the indicators themselves, their users, and the policies being assessed. For this thesis, factors related to indicators are particularly interesting[8], and three such factors are often cited as important determinants of their possible influence: scientific credibility, salience and legitimacy (Cash et al., 2003; Parris and Kates, 2003; Hák et al., 2016). While the first of these is best addressed by experts, according to literature, enhanced the salience and legitimacy of indicators and

[7] Political use can be further broken down to the sub-types of legitimization use, tactical use, and symbolic use (Hezri, 2004; Gudmundsson et al., 2009b).

[8] An extensive literature exists providing factors that determine not only their potential for having influence, but their quality in general (Niemeijer and de Groot, 2008; van Oudenhoven et al., 2012).

the related assessments can be achieved by broad participation of stakeholders in the development phase (Reed et al., 2006; Bond et al., 2012; Turcu, 2013).

Remarkably, research on sustainability indicators and assessments continues to primarily focus on the factor of scientific credibility by developing new, technically sophisticated measurement and data analysis methods, while overlooking the parallel sociopolitical factors of salience and legitimacy (Turcu, 2013; Waas et al., 2014; Hák et al., 2016; Lehtonen et al., 2016). Particularly, the factor of salience remains "the most underdeveloped and neglected issue" (Hák et al., 2016, p. 568). This undermines the effectiveness of the assessments in coupling into governance, not only in terms of concrete policymaking but also in terms of broader social learning processes (Hezri, 2005; Shen et al., 2011; Bond et al., 2012).

2.3 Summary of pertinent gaps in literature

Throughout the discussion of the theoretical background presented in this chapter, a number of research needs have been discussed that are pertinent for fulfilling the overarching objective of the thesis to *support the reflexive development of indicator-based sustainability assessments that are contextually appropriate and salient for local urban governance*. In particular, the intention of the thesis is to address the following gaps in existing scholarship:

- Firstly, a gap exists in means for making explicit and comparing different visions of the concept of urban sustainability (See Section 2.1). The consequence is a lack of reflexive engagement with different perspectives to the concept, and a lack of understanding and communication of the underlying meanings and values driving the assessments.

- Secondly, there is a gap in having an updated overview and critical analysis of indicators and conceptual frameworks used in the flourishing field of urban sustainability assessment (See Section 2.2.3). The consequence is a lack of learning from current practice and a lack of guidelines for making use of the range of options when constructing urban sustainability assessments.

- Thirdly, a gap in knowledge exists concerning the ways in which sustainability assessments can be designed to enhance their salience for the governance of cities (See Section 2.2.4). The consequence is that the information provided by assessments remains limited in influence.

Addressing the two first gaps aims to support more reflexive development of indicator-based assessments, leading to designs that are appropriate for the context and purposes of each application. Addressing the third gap aims to inspire designs of assessments that enhance their salience for local urban governance. Taken together, then, the work aims to push the practice of indicator-based urban sustainability assessment towards more reflexive, real-world relevant designs.

3. Research modules, objectives and questions

The overarching objective of the thesis (Chapter 1), and the related gaps that were identified in current scientific knowledge (Chapter 2) guided the formulation of the objectives and research questions of this thesis. These objectives and questions were divided into three parallel research modules, as presented in Fig. 3-1. In addition, prior to the three research modules, conceptual work was performed to prepare the grounds for the work of each of the modules; this theoretical basis is described in Chapter 4. The objectives of the modules are further elaborated into more specific research questions (RQ) in Table 3-1, which also links the modules with the manuscripts of the thesis.

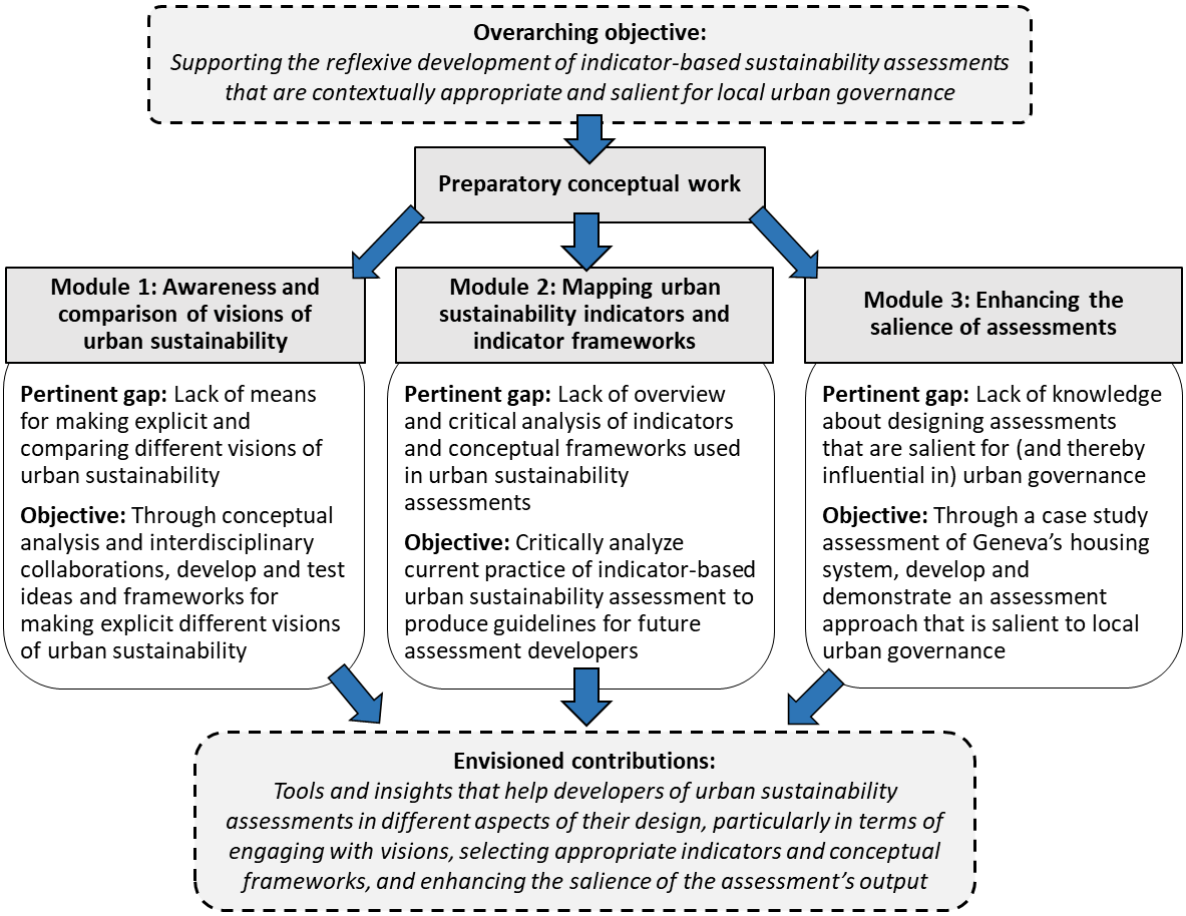

Fig. 3-1. The research modules of the thesis.

Table 3-1. The research questions (RQ) of the three research modules of the thesis.

Module	Research questions	Manuscripts
1	• RQ1.1: How can visions of urban sustainability be represented, characterized and compared? • RQ1.2: What are the implications of different visions for urban sustainability assessment?	*# 1, 2*
2	• RQ2.1: How do current indicator initiatives translate urban sustainability into metrics? • RQ2.2: What kind of conceptual frameworks do the indicator initiatives employ? • RQ2.3: What does the analysis of current practice imply for the development of future indicator sets for urban sustainability?	*# 3, 4*
3	• RQ3.1: How to increase the salience of indicator-based assessments for the concrete challenges and decision-making situations of local urban governance?	*# 5*

As described in Fig. 3-1 and Table 3-1, the objective of Module 1 is to explore means for representing, characterizing and comparing different fundamental visions that explicitly or implicitly guide the approaches of different stakeholders involved in urban sustainability. The intention is also to clarify the implications that the visions have in particular for the sustainability assessment of cities. The objective of Module 2 is critically analyzing how the concept of urban sustainability is operationalized in current assessment practice through indicators and indicator frameworks, in order to draw instructive lessons for future indicator set developers concerning the many choices that they face. The insights gained from Module 2, especially concerning the pros and cons of different types of indicator frameworks, also inform the work of Module 3, whose objective is to develop an assessment approach expressly aiming to enhance the salience of the information it produces to local urban governance. The research of Module 3 was conducted through a case study of assessing the City of Geneva's housing system.

As Fig. 3-1 illustrates, the three research modules are parallel to each other, rather than sequential. In other words, they contribute to the overall objective from different angles. While Module 1 addresses more fundamental and abstract questions concerning visions of urban sustainability, the work of Module 2 complements this at the more concrete level of indicators and indicator frameworks. Module 3, in turn, adds another layer by proposing a particular approach for the design of indicator-based sustainability assessments that expressly aims for enhanced salience for local urban governance. Taken together, the modules of the thesis aim to contribute tools and ideas for different aspects in the design of indicator-based urban sustainability assessments.

To specify further the intended scope of the research, this thesis focuses on indicator-based assessments that take as their object either the city in its entirety or one of its principal sub-systems (e.g., housing, transport, energy, or food), and that aim for a broad coverage all dimensions of sustainability. In other words, the focus is on assessments used for high-level issue identification and agenda setting at the early stage of a policy process (EEA, 2005; Hezri, 2005; Loorbach, 2010). The target audience and potential participants of this kind of assessments include both persons directly involved in policymaking as well as urban stakeholders more generally (Innes and Booher, 2000).

4. Conceptual approach

As mentioned in the previous chapter, prior to commencing work on the three research modules, there was a need for preparatory work to clarify the conceptual basis and particular angle of the ensuing research within the three research modules. This conceptual basis is presented in this chapter. In part it draws from the literature review presented in Chapter 2, and it involves the following elements: (i) urban sustainability and its three levels of interpretation; (ii) sustainability assessment and its relationship to urban governance. The conceptual approach is integrated and summarized at the end of the chapter and connected to the three research modules presented in the previous chapter.

4.1 (Urban) sustainability – principles and interpretations

To begin, it is essential to clarify the understanding of the concept of 'sustainability' that underlies the research of this thesis. Since the overarching objective of the work relates to the connection between sustainability assessment and urban governance, the thesis takes its cue from Patterson et al. who state that "public policy and planning theory approaches to sustainability emphasize the social, institutional, economic and environmental aspects of sustainability within a framework that seeks to achieve a 'balance' or an 'integration' of these factors" (2017, p. 20). Aligned with this idea, for this thesis it is assumed that sustainability entails considering simultaneously an adequately broad range of stakeholder concerns and goals, and striving to find a reasonable balance between them. It means that in order to contribute effectively to sustainability-related local governance, operationalizations of sustainability must respect the 'principle of representative diversity' (O'Connor and Spangenberg, 2008).

Furthermore, following the discussion of Section 2.1, '*urban* sustainability' specifically is assumed to consist of concerns and goals deriving from (i) the particular characteristics of cities (which have both an internal and an external dimension), and, (ii) contextual specificities, including local circumstances and developmental stage of the city (Bai and Imura, 2000; Hartmuth et al., 2008), as well as specific local priorities and cultural expectations (Turcu, 2013; Jasanoff and Kim, 2015).

As have been discussed in the preceding chapters, dealing with tangible challenges in urban governance requires moving beyond the kind of abstract principles of urban sustainability presented above to operationalizing the concept more concretely. This thesis puts forward the idea that, when it comes to sustainability assessments, the operationalization occurs (and can be analyzed) at three distinct interpretative levels, i.e., visions, conceptual frameworks and indicators. The three levels exist at different degrees of concreteness, with visions representing the most abstract and indicators most tangible interpretations of urban sustainability.

The first interpretative level concerns fundamental 'visions' of urban sustainability[9]. Indeed, having a guiding vision of sustainability has been mentioned as a central requirement for the construction of meaningful sustainability assessments, without, however, specifying what such visions may consist of (Meadows, 1998; McCool and Stankey, 2004; Pintér et al., 2012). In other words, the research of Module 1 aims to elaborate on the meaning, characteristics and implications of such visions in the context of urban sustainability and sustainability assessment. To begin, some inspiration may be

[9] A vision can be defined simply as "an idea or mental image of something" (Cambridge Dictionary, 2021).

received from authors in the so-called 'sustainability transitions' field, where the concept of visions has been discussed to some detail (Rotmans et al., 2001; Smith et al., 2005; Kemp and Martens, 2007). For example, Smith et al. (2005, p. 1506) mention five functions of visions: identifying a possibility space, acting as a heuristic for problem definition, framing target setting and monitoring of progress, specifying and connecting relevant actors, and describing a narrative that attracts resources. In other words, visions imply more than mere targets, and extend also to influencing the definition of a problem.

The idea explored in this thesis is that commonly used metaphors of cities and urban phenomena can represent *archetypal* visions of urban sustainability. Consequently, analyzing and comparing such metaphors can prove a fruitful exercise for making explicit the range of visions that exists concerning urban sustainability. In general, the use of metaphors permeates our language, both in everyday expressions and in science (Klamer and Leonard, 1994; Lakoff and Johnson, 2003). By invoking the imagery of familiar phenomena, metaphors provide a cognitive mechanism that facilitates and structures our interpretation of other, unknown and complex phenomena (Barnes and Duncan, 1992; Smith and Katz, 1993). Indeed, metaphors are also omnipresent in our language of cities (Nientied, 2016) – e.g., urban *metabolism*, *smart* city, etc. – and have provided both analytical lenses and aspirational images for urban development through history (Lynch, 1984; Bettencourt, 2015) .

The second interpretative level pertinent to sustainability assessment, and addressed in Module 2, concerns conceptual frameworks (Ravitch and Riggan, 2017). In the context of this thesis, the focus is more particularly on conceptual frameworks that create a representation of the problem under assessment and thereby support the selection and structuring of indicators[10]. Different definitions of such conceptual frameworks for indicators exist, with different authors describing them as 'models' (Becker, 2005), 'structures' (Nathan and Reddy, 2012) or 'networks of interrelated concepts' (Pope et al., 2017). In this thesis, conceptual frameworks for indicators are understood as structures that disaggregate an overarching concept (e.g., 'urban sustainability') into categories, specify the relationships between these categories, and connect them to concrete metrics. In other words, conceptual frameworks have a dual function; on the one hand, they are conveyors of conceptual meaning as more specific definitions of abstract concepts; on the other hand, they are conveyors of empirical information in connecting metrics and data to these concepts (Bossel, 1999; Maggino, 2017).

The third interpretative level, also addressed by Module 2 of this thesis, concerns indicators, i.e., variables that make perceptible (an attribute of) a phenomenon of interest (e.g., 'urban sustainability'). What distinguishes an indicator from a mere metric is the presence of a reference value and an association to a category within a conceptual framework (Gallopín, 1997; Lancker and Nijkamp, 2000; Waas et al., 2014; Maggino, 2017). Identically to conceptual frameworks, this thesis understands the nature of purpose of indicators simultaneously from two distinct perspectives. Firstly, indicators are carriers of data, and as such have the purpose of serving decision-making (Gudmundsson, 2003; Boulanger, 2007). Secondly, indicators are also carriers of messages and meanings (Bell and Morse, 2001; Lehtonen et al., 2016), i.e., signals that operate at the conceptual level, shaping existing mental models and understandings. In other words, instead of simply neutrally conveying an underlying

[10] Other kind of frameworks pertinent in the context of sustainability assessment include policy frameworks and procedural frameworks (Gudmundsson, 2003; Lyytimäki and Rosenström, 2008).

phenomenon, indicators also help to construct the very meaning that the phenomenon acquires (Astleithner and Hamedinger, 2003).

To summarize, the idea put forward in this thesis is that the construction of urban sustainability assessments draws from choices made at three interpretative levels of urban sustainability – visions, conceptual frameworks and indicators. Therefore, engaging in the analysis of these levels can make the options more explicit, and thereby support the reflexive design of indicator-based assessments (Kemp and Martens, 2007; Pintér et al., 2012; Popa et al., 2015). This is particularly important as choices made at these three levels, rather than being neutral reflections of a pre-existing objective concept, represent a *de facto* definition of it that prioritizes certain values and interests over others (Vatn, 2009; Gasparatos, 2010).

4.2 Sustainability assessment and urban governance

With regard to the concept of 'sustainability assessment', following the presentation of Section 2.2.1, this thesis assumes that it is a distinct form of assessment that attempts to engage with sustainability in all its complexity. Furthermore, instead of being based on a specific tool or method, it is first and foremost a vehicle for creating problem-specific and contextually appropriate understanding about sustainability and for integrating sustainability objectives into local governance. Moreover, in accordance with the discussion of Section 2.2.4, each sustainability assessment should also be constructed having in mind its particular purpose and target audience. Among the different approach to sustainability assessment, in alignment with the public policy-oriented definition of sustainability assumed (Patterson et al., 2017), this thesis focuses principally on indicator-based assessments used for high-level issue identification and agenda setting at the early stage of a policy process (EEA, 2005; Hezri, 2005; Loorbach, 2010), and which assess either the city in its entirety or one of its principal sub-systems (e.g., housing, transport).

Next, given the importance accorded to the coupling of sustainability assessments to governance, it is necessary to clarify what the latter is taken to mean in the context of this thesis. For a definition of 'governance', the thesis follows van Zeijl-Rozema et al., who state that it "can be seen as a collection of rules, stakeholder involvement and processes to realize a common goal" (2008, p. 411). Importantly, they also distinguish between two dimensions of governance, which are both subsumed within the understanding of the term assumed in this thesis: 'hierarchical governance' which consists of mainly top-down decision-making, and which emphasizes planning and control; and 'deliberative governance', which entails a broad sharing of governing power, and an emphasis on dialogue and social learning (van Zeijl-Rozema et al., 2008). In addition, ‘urban governance’, in particular, can be seen to occur at multiple scales from local to global (Bulkeley and Betsill, 2005; Webb et al., 2018).

Importantly, a bidirectional relationship is assumed to exist between sustainability assessments and the governance context in which they are conducted. On the one hand, the governance context mediates the precise way in which the overarching problem (‘urban sustainability’) is operationalized into assessments, depending on the stakeholders and institutions present in the context (Hartmuth et al., 2008). On the other hand, the governance context determines how (and whether) the information produced by the assessments is interpreted and implemented (Astleithner et al., 2004; Holman, 2009). In other words, assessments are constructed in a context, and they also gain their meaning in a context.

Based on this insight, to tackle the objective and research question of Module 3, this thesis proposes that a systematic embedding of the indicators of an assessment into the governance context can increase its salience, i.e., "the relevance of the assessment to the needs of decision makers" (Cash et al., 2003, p. 8086). In particular, the assumption taken and tested is that this embedding can be achieved with the support of a dedicated conceptual framework that incorporates relevant contextual elements into the analysis of the selected indicators.

The approach is an attempt to upgrade the quality of the assessment's output from mere information to deeper knowledge and wisdom (Ackoff, 1989; Stanners et al., 2007). The point is to see indicators as more than mere data points, in order to make them less abstract and to increase their salience for the ongoing governance issues and debates of given contexts (Bell and Morse, 2001; O'Connor and Spangenberg, 2008). In other words, this perspective moves away from a singular focus on quantifying indicators as an end goal of assessments, instead pointing equal attention to the analysis of their contextual meaning. This perspective is aligned with the dual understanding of indicators discussed in Section 4.1 (indicators as both data carriers and as conceptual messages). It is furthermore aligned with the understanding of sustainability assessment adopted in this section, which urges sustainability assessments to take on an explicitly educational role concerning the meaning of sustainability, and to focus not only on the decision-making aspect of governance, but also on broader processes of societal learning and dialogue (Hezri, 2004; Scerri and James, 2010).

4.3 Overview of conceptual approach

The conceptual approach adopted for this thesis, as discussed in this chapter, is summarized and illustrated in Fig. 4-1.

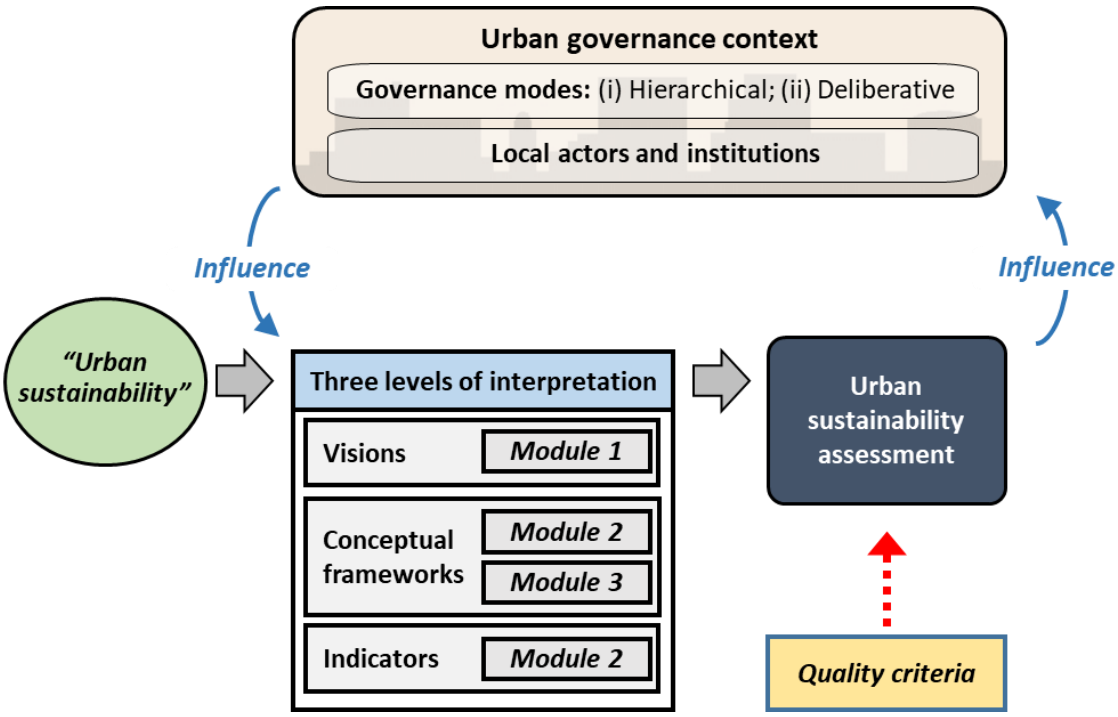

Fig. 4-1. Overview of the conceptual approach of the thesis.

As the figure depicts, the thesis is interested in the operationalization of the concept of urban sustainability, with the help of the three interpretative levels – visions, conceptual frameworks and indicators – into urban sustainability assessments. This operationalization is mediated by the governance context in which the assessment is constructed. The assessment itself (ideally) feeds back into the governance context, which determines how (and whether) the results of the assessment are interpreted and implemented. The choices made at the three interpretative levels in the operationalization of urban sustainability, rather than being neutral reflections of a pre-existing objective reality, shape the concept by establishing a de facto definition for it. The quality of the resulting assessment can be subjected to evaluation against certain quality criteria, drawn from the discussion presented above and summarized in Table 4-1. In fact, another way of expressing the overarching objective of the work in this thesis is to provide tools and insights that help developers of assessments to meet the quality criteria presented in Table 4-1.

Table 4-1. The quality criteria for evaluating an indicator-based urban sustainability assessment.

1) Incorporating an adequately broad range of stakeholder concerns and goals
2) Reflecting particular characteristics of cities
3) Reflecting contextual specificities, including:
    i) Local circumstances and developmental stage of the city
    ii) Community priorities and cultural expectations
4) Tailored for particular purposes and target audiences
5) Salience of output to the needs of stakeholders

As illustrated in Fig. 4-1, the research of Module 1 relates to the level of interpretation dealing with visions, and in particular tests leveraging metaphors as representatives of such visions, while Module 2 relates to understanding the options available at the other two levels of interpretation. Module 3 also addresses the level of conceptual frameworks by developing a dedicated framework to support the salience of assessments. As mentioned above, together the contributions of the three modules aim to support the design of indicator-based urban sustainability assessments that meet the quality criteria laid out in Table 4-1.

5. Methodological approach

This chapter describes the methodological approach taken to pursue the research objectives and questions of the three modules of the thesis. When considering the methodological approach of a research project, the discussion is never limited solely to the concrete methods employed or the data collected, but extends also to questions concerning particular research paradigms and their underlying values and philosophical assumptions (Crotty, 1998; Alvesson and Sköldberg, 2009; Creswell and Plano Clark, 2011). Put differently, choices related to the construction of a research approach "reflect a commitment (explicit or implicit) to a particular model of how the world works" (Silverman, 2005, p. 6). Therefore, it is apt to begin the chapter by clarifying the 'commitment' that the thesis is premised upon before presenting the more concrete methods of data collection and analysis. This allows to better explain the methodological choices taken, and to reflect upon the coherence of these choices given the fundamental purpose of the research.

5.1 Research purpose and paradigm

When constructing the methodological approach of a given research project, authors typically emphasize the primacy of the project's *purpose* in guiding the related choices (Patton, 1990; Silverman, 2011). As Patton puts it, "decisions about design, measurement, analysis, and reporting all flow from purpose" (1990, p. 150). Five fundamental types of purpose can be distinguished for research, of which 'applied research' best describes the research conducted within this thesis (the other four types being basic research, summative and formative evaluation research, and action research; Patton, 1990). In general, the aim of applied research is to illuminate a particular real-world problem, and to produce knowledge that can help more effectively dealing with it. Indeed, complying with this general understanding, the stance taken from the very beginning of this thesis work was to consider the main objects of the research ('urban sustainability', 'sustainability assessment' and 'governance') as real-world problems, for which urgent support is required in practice. This fundamental purpose subsequently guided the formulation of the research modules presented in the previous chapters, with each module addressing the overall problem from different angles, and with different objectives and challenges in mind.

Given the problem-centered stance adopted for this thesis, and its overarching objective to support managing the problem in practice, the research can be located within the paradigm of 'pragmatism', which focuses on "the consequences of research, on the primary importance of the question asked rather than the methods, and on the use of multiple methods of data collection to inform the problems under study" (Creswell and Plano Clark, 2011, p. 41). Thomas Kuhn (1962) famously described that such paradigms consist of sets of shared generalizations, beliefs and values of particular communities of actors. In research, inscribing oneself to a particular paradigm is reflected, among other things, in three kinds of assumptions: (i) ontological assumptions (*What is the nature of the objects of research?*); (ii) epistemological assumptions (*What can we know about them?*); (iii) methodological assumptions (*What is the preferred logic of inquiry to create that knowledge?*) (Crotty, 1998; Creswell and Plano Clark, 2011).

In terms of ontological and epistemological assumptions, the pragmatist paradigm can be seen as a special case. Instead of committing to a fixed position, it suggests adapting the assumptions to the overarching objective of producing practical knowledge for dealing with the particular problem under

scrutiny (Creswell, 2009). Accordingly, ontologically this research is located between the polar opposites of relativism and realism, incorporating aspects of both of these positions (Moon and Blackman, 2014). The relativist aspect relates to the main objects of the research, 'urban sustainability', 'sustainability assessment' and 'governance'. The nature of these objects – their form, meaning and importance – is to a considerable extent a matter of social agreement and negotiation, which is a hallmark of a relativist ontological position. For example, as was presented in Section 3.1, a central purpose of sustainability assessment is to create understanding of the meaning of 'urban sustainability'. Stated differently, it means that parts of the ontology of this object is being constructed through the assessment process. The realist aspect of the thesis, in turn, relates especially to some of the material imperatives of urban sustainability (e.g., the energy and material footprints of urban dwellers), which cannot simply be 'agreed away'. This aspect can be seen, for example, in the formulation of a set of general principles defining urban sustainability (see Table 4-1).

Epistemologically, the thesis is located primarily within the constructionist position, which states that knowledge emerges from the interplay between the knower and the object of knowledge (Crotty, 1998). This position is taken to emphasize, on the one hand, the central role of the concepts and conceptual frameworks that the researcher chooses to employ in interpreting empirical observations in knowledge creation processes, and on other hand, to acknowledge the power that such conceptual tools can have in helping to give structure to complex objects like 'urban sustainability', thus bestowing their users (whether academics or practitioners) with the practical capability to act upon the problem in question. In other words, this epistemological position is congruent with the overarching pragmatist objective for research, i.e., learning to cope with the world and its complex problems (Creswell and Plano Clark, 2011).

Concerning methodology, as already mentioned above, adopting a pragmatist worldview in research implies the flexible application of multiple research methods depending on the problems under scrutiny (Creswell and Plano Clark, 2011). In this thesis this assumption is concretized in the use of different methodologies and methods depending on the objectives and research questions of the respective research modules. In addition, the general logic of inquiry of the thesis is characterized by a pragmatic compromise between (empirical) inductive reasoning and (rational) deductive reasoning in a process of 'iterative theory building' (Kerssens-van Drongelen, 2001). In the methodology of this thesis it means in particular that, depending on the research question being pursued and the data at hand, either pre-existing conceptual frameworks were used to guide data collection and interpretation, or such frameworks were inductively formed, or as a third option, pre-existing frameworks were used as a starting point while also allowing for the possibility of the empirical observations to challenge and refine those frameworks.

5.2 Research methodology

Table 5-1 presents an overview of the methodologies applied across the three research modules of the thesis. In brief, Module 1 applied a collaborative research procedure among academics for developing conceptual tools and ideas for making explicit and creating dialogue about visions of urban sustainability. Module 2, in turn, applied a collaborative research methodology to critically analyzing existing approaches to urban sustainability at the more concrete level of indicators and indicator frameworks. The insights gained from Module 2 also informed the work of Module 3, in which, through a case study methodology employing multiple complementary research methods (Yin, 2014), an

assessment approach was developed and demonstrated that aimed at enhancing the relevance of the assessment for local urban governance. The methodologies of each module are outlined in the following sections; more detailed descriptions can be found in the respective manuscripts found in Part II of this thesis.

Table 5-1. Overview of the methodological approach of the three research modules.

Research module	Methodology

Module 1: Awareness and comparison of visions of urban sustainability	• Methodology: Collaborative conceptual development through workshops
	  • Stage 1: 3 academics (Manuscript 1)
	  • Stage 2: 10 academics (Manuscript 2)

Module 2: Mapping urban sustainability indicators and indicator frameworks	• Methodology: Collaborative content analysis of an empirical sample of 67 urban sustainability indicator initiatives
	  • Stage 1: *Quantitative* content analysis (4 researchers; Manuscript 3)
	  • Stage 2: *Qualitative* content analysis (2 researchers; Manuscript 4)

Module 3: Enhancing the salience of assessments	• Methodology: Case study
	• Multiple methods and sources of empirical data:
	  • Stakeholder interviews (14 stakeholders)
	  • Literature review (grey and academic literature)
	  • Discussions with 8 academic experts
	  • Stakeholder questionnaire

5.2.1 Module 1

The research conducted within Module 1 was initiated based on the objective of developing and testing means for making explicit different visions of urban sustainability, and the idea in particular that commonly used metaphors of cities and urban phenomena could be used as representatives of such visions. From the beginning, the work was conceived to be largely conceptual in nature; however, the ambition was for the work to be conducted following a collaborative methodology of knowledge co-construction (Norström et al., 2020), in order to both enrich the argumentation and to instill into the conceptual analysis a degree of intersubjectivity, thereby increasing the reliability of the results (Morgan, 2007). This collaborative work occurred within a rough framing designed by the doctoral candidate.

The first stage of the work of this research module included the doctoral candidate and two other researchers, and led to the preparation of Manuscript 1. In this stage, four metaphors ('machine', 'organism', 'network' and 'melting pot') were selected to represent distinct and complementary visions of urban sustainability, and through desk research, their metaphorical use in literature for urban contexts was explored. For facilitating the analysis and comparison of these metaphor-based visions, an analytical framework was devised based on systems theory (Bossel, 1999; Hester and Adams, 2017). The framework allowed to elaborate the metaphors into full-blown ideal-typical visions of cities and their sustainability. In practice, the analysis took place in a workshop among the three researchers (Ørngreen and Levinsen, 2017), and proceeded by the researchers collaboratively filling in the boxes of the analytical framework for each metaphor-based vision, thereby constructing and negotiating their meaning.

The second stage of the module, which led to the preparation of Manuscript 2, explored further the potential use of metaphors in efforts towards urban sustainability. It expanded the participating group to ten academics, with specialists from different disciplines and with different experiences in academia and practice selected to broaden the scope of inputs to the collaborative work[11]. The work among the group began with a set of tentative ideas identified by the three initiating researchers that had been involved in the first stage of the work, and evolved through a series of eight workshops over a period of nine months (Ørngreen and Levinsen, 2017) in a process that can be described as collaborative and iterative theory building (Kerssens-van Drongelen, 2001). During this process, ample space was given to discussions and interdisciplinary exchange that not only provided material for responding to the initial research questions, but also refined and added to those research questions. The inductive analysis of this material (mostly in the form of notes and recordings) by the initiating group of researchers (Mayring, 2000), combined with the writing tasks given to sub-groups of two to three participants between the workshops, progressively led to the formulation of three core theses concerning the potential productive role of metaphors in efforts towards urban sustainability. Supplementary information on the methodology of Manuscript 2 can be found in Appendix A.

5.2.2 Module 2

As described in Chapter 4, the objective of the research of Module 2 was to complement Module 1 by critically analyzing existing approaches to urban sustainability at the more concrete level of indicators and indicator frameworks, and based on this, draw instructive lessons for future indicator-based sustainability assessments. Again, the research relied on a collaborative methodology, but this time the participating researchers were on equal footing in framing and conducting the research.

Also, in contrast to the conceptual work of Module 1, the work in Module 2 consisted of empirical analysis, namely, of a sample of 67 urban sustainability indicator initiatives from both academia and practice. The sampling of these initiatives was accomplished in two steps: first, a pool of candidate initiatives (n=891) was identified through a Scopus search targeting academic literature, and a mixed Google-search and snowball sampling method targeting grey literature; second, a criterion-based sampling (Patton, 1990) was applied to the pool of candidate initiatives to arrive at the final set of 67 initiatives. The criteria for selection to the final sample stated that an initiative had to: (i) be empirically applied; (ii) be recently active; (iii) explicitly intend to measure sustainability (and not, e.g., well-being, greenness, etc.), and all its dimensions; (iv) have focus on the urban scale (and not, e.g., the regional scale); and (v) contain a defined set of indicators.

The analysis of the sample proceeded over two stages. The first stage (four researchers) consisted of a 'quantitative content analysis' (Silverman, 2011), in which the importance given by the indicator initiatives to different aspects of urban sustainability was evaluated based on the number of indicators referring to said sustainability aspect. Accordingly, an indicator categorization scheme was first

[11] The participants' disciplinary backgrounds included geography, sociology, economics, urban studies, urban planning, environmental sciences and architecture.

established. To allow for a multidimensional analysis, three parallel category typologies were selected, including the 17 SDGs, the STEEP[12] framework, and the MONET[13] framework. These three typologies were chosen based mainly on considerations of operationality and resonance for both academia and practice. Then, through an iterative process of screening the indicators collected from the indicator initiatives against the three typologies, a set of coding rules were developed for assigning the indicators to particular categories. The process included all four researchers, and alternated between individual work and group discussions for harmonizing decisions and coding rules. The multi-person involvement was a way to enhance the reliability of the screening process and the subsequent results (Silverman, 2011). Importantly, the coding rules were not applied automatically, but each indicator was considered individually to discover possible latent meanings. Most notably such meanings were interpreted from the conceptual categories with which the indicators were associated within a given initiative. Once this reflexive process was completed and all indicators associated with particular categories (2847 indicators across the 67 indicator initiatives), the generated data was analyzed with descriptive statistical analyses (Agresti and Finlay, 2009) using a Python code constructed for the purpose. Supplementary information on the methodology can be found in Appendix B.

The second stage of Module 2, which was undertaken by two researchers, involved a 'qualitative content analysis' (Mayring, 2000) of the conceptual frameworks used by the same sample of indicator initiatives. The analysis consisted of two steps. In the first step, a typology of conceptual frameworks was developed inductively from the analyzed sample, each type defined by a specific logic of categorizing indicators (e.g., domain-based, goal-based, etc.). The typology emerged from an iterative and negotiated process among the two researchers. Once the typology was defined with a set of distinct framework types, in a second step, the analysis focused one by one on each framework type, resulting in an elaboration of their internal structure and sub-types. Finally, the strengths and weaknesses of each framework type were discussed in terms of a theory-based set of purposes that indicator frameworks should serve. This set of purposes was defined based on a review of pertinent literature.

5.2.3 Module 3

The objective of the work in Module 3 was to develop and demonstrate an indicator-based assessment approach utilizing a conceptual framework designed expressly to enhance the assessment's salience for local urban governance processes. In developing the approach, the research followed the logic of iterative theory generation (Kerssens-van Drongelen, 2001) as an interplay between pre-existing theoretical frames and new ideas emerging from empirical evidence. The work was based on a case study methodology, with the housing system of the City of Geneva as the object of the case study assessment[14]. The rationale for turning to a case study methodology hinged on the belief that an in-

[12] The STEEP framework consists of categories for social, technological, economic, environmental and political indicators (Bradfield et al., 2005).

[13] The MONET framework consists of categories for level, capital, input/output, efficiency, disparity and response indicators (de Montmollin and Scheller, 2007).

[14] Here, a case study is understood as research where "the investigator explores a real-life, contemporary bounded system (a case) or multiple bounded systems (cases) […] through detailed, in-depth data collection involving multiple sources of information" (Creswell, 2013, p. 97). A distinct characteristic of a case study is also that the phenomenon under investigation is studied "within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident" (Yin, 2014, p. 16).

depth study of one case would be fruitful for the kind of iterative theory generation mentioned above. As such, the thesis aligns with Flyvbjerg (2006), who argues that, especially when it comes to researching complex real-world phenomena, the power of richly described exemplars in inducing knowledge is often underestimated, both in the inductive (generating new theories and hypotheses) and deductive (testing hypotheses) senses.

The selection of the particular case study object (i.e., the housing system of Geneva) was based on a logic of purposeful sampling of a typical and potentially information-rich case (Patton, 1990). Housing is a key topic for the sustainability of cities (UNECE, 2015), traversing all dimensions of sustainability and involving various types of stakeholders (Marcuse, 1998; Feige et al., 2011). Furthermore, the City of Geneva in particular, with its growing and diverse population, densely built urban area, and ageing building stock (FSO, 2020, 2019), presented an interesting and timely setting for a case study on housing sustainability. These factors rendered the housing system of Geneva a promising and challenging case study object for testing ideas for and demonstrating the developed assessment approach, as the latter aimed particularly to support such complex local urban governance challenges.

The design of the case study assessment followed two guiding principles. Firstly, the participation of local stakeholders was given emphasis, in order to tailor the assessment to local specificities and stakeholder preferences (Reed et al., 2006). Secondly, to increase the internal validity of the research, the case study design made use of triangulation (Meijer et al., 2002), i.e., the use of multiple methods and sources of evidence.

In the end, the assessment procedure entailed three main phases. The first phase began with fourteen explorative qualitative semi-structured interviews (Kvale and Brinkmann, 2009), conducted with a group of local stakeholders that were sampled to represent a broad range of viewpoints on the assessed problem (the housing system of Geneva)[15]. In the interviews, the stakeholders were asked to share their understanding of what constitutes a sustainable housing system, as well as of the challenges that Geneva's housing system is facing. The interviews lasted up to one hour, and they were recorded, transcribed, and subjected to qualitative content analysis (Mayring, 2000) with the help of the MAXQDA software. It was at this point that most of the iterative procedure of refining the conceptual framework occurred, driven by the need to find an appropriate conceptual structure for organizing and making sense of the rich interview data. Several framings (and related coding schemes) were attempted before the final conceptual framework emerged. The information gained from the interviews was then complemented by analyzing a collection of relevant grey literature[16], which also further served to solidify the conceptual framework and to test its usefulness in structuring the

[15] See Appendix D for further information on the interviews, including the interview guide and a list of interviewees.

[16] The archive of analyzed grey literature can be found in Appendix E. The archive was collected through a snowball sampling method. Importantly, the interview data was given primacy in determining the themes to be included in the analysis; the grey literature was therefore limited to only those documents pertaining to these themes. Furthermore, in the collection of the grey literature archive, the principle of saturation was applied for deciding when to cease adding new documents (Teddlie and Yu, 2007).

collected data and its analysis. Apart from producing knowledge about the contextual setting and its current challenges, the analysis of the first phase elaborated thirteen goals against which the housing system would be evaluated, and a list of sub-themes under each goal[17]. For expressing these goals, as a final step of the first phase, a pool of candidate indicators was collected from the same archive of grey literature, from the indicators collected and analyzed in the work of Module 2, from databases of federal and cantonal statistical offices, and by reviewing academic literature on indicators for housing sustainability[18].

The second phase of the research aimed to refine and validate the thirteen goals identified in the first phase of analysis, and to select for each goal the final indicators from the pool of candidate indicators. The phase included two steps, the first of which included discussions (maximum one hour) with eight academics, whose topical expertise together covered the thirteen goals. In the discussions, the experts were asked to review whether the analysis thus far had any obvious omissions in terms of the goals and sub-themes discovered. With the academics, six indicators were also shortlisted for representing each of the thirteen goals[19]. As a second step of this phase, the earlier stakeholder-interviewees were contacted again to fill in an online questionnaire[20], in which they could express their opinions on the relative importance of the thirteen goals in the context of Geneva[21]. Also, the stakeholders were asked to make a prioritization among the six shortlisted indicators for each goal, again particularly having the context of Geneva in mind. In this manner, the final indicators used in the assessment were identified.

The third and final phase of the research concerned the assessment itself. It involved specifying a precise metric for the indicators selected in the previous phase (two indicators for each of the thirteen goals), searching for data[22], and benchmarking the results for Geneva against both its historical values and two other Swiss cities (Zürich and Basel), provided that data was available. Then, the indicators and the values that they displayed were connected systematically to the contextual dimensions analyzed in the first phase of the study, thus providing as the final output the contextually-rich assessment that the work of Module 3 had as its motivating objective.

[17] E.g., the goal 'safe neighborhoods' contained a sub-theme 'crime', etc. The decision to use a goal-based framework drew from the insights gained through the work of Module 2 concerning the advantages of this type of frameworks (see Table 6-5).

[18] See Appendix F for further information on the collection of sustainability indicators for housing from academic literature..

[19] The shortlisted indicators can be found in Appendix G.

[20] The details and results of the questionnaire can be found in Appendix H.

[21] The purpose of inquiring for the relative importance was not to establish any kind of quantitative basis for assessing them, but simply to validate the set of goals. For example, had several stakeholders expressed one of the thirteen goals as less important than the other goals, it would have provided a reason to reconsidering its presence in the set of goals. However, this was not the case for any of the goals.

[22] Notes on the indicators and data sources can be found in Appendix I.

6 Summary of results

The purpose of this chapter is to provide a descriptive summary of the results produced during the research for the thesis. More detailed accounts can be found in the manuscripts contained in Part II of the thesis.

6.1 Module 1: Awareness and comparison of visions of urban sustainability

The objective of Module 1 was to explore ways to make explicit and compare different visions of urban sustainability. As described in Chapter 4, metaphors used to describe cities and urban phenomena were selected as vehicles for representing archetypal versions of such visions. The work of this module consisted of two stages, leading to the preparation of Manuscripts 1 and 2, respectively.

6.1.1 Stage 1: Analyzing metaphors as archetypal visions of urban sustainability

In the first stage of Module 1, a selected set of four metaphorical terms (the city as a 'machine', 'organism', 'network' and 'melting pot') were analyzed as archetypal visions of urban sustainability. To facilitate the systematic analysis and comparison of these metaphorical visions, an analytical framework was devised based on systems theory (Bossel, 1999; Hester and Adams, 2017). The framework included eleven system aspects (across four themes) that together facilitated a comprehensive characterization of the analyzed metaphor-based visions. For demonstrative purposes, a part of the analytical framework can be seen in Table 6-1, including two of the analyzed metaphors as an example. Full versions of both the analytical framework and its application are found in Manuscript 1.

Table 6-1. Characterizing metaphors of cities; example with two metaphors (adapted from Halla et al., 2020).

Theme	System aspects	***Machine***	***Organism***
Delimiting the system	Boundary	*Administrative*	*Functional*
	Environment	*Decoupled*	*Rooted*
	Inputs/ outputs	*In: materials and energy; Out: products*	*In: materials and energy; Out: secondary resources*
Under-standing the system	Purposes	*Satisfaction of practical needs*	*Survival and reproduction*
	Functions	*Production*	*Metabolism*
Analyzing the system	Elements	*Artificial and tangible materials and components*	*Natural and artificial; tangible materials and organs*
	Organization	*Hierarchical, designed, static, and clear units*	*Hierarchical structures; spontaneously but slowly evolving units*
	Dynamics	*Linear and predictable*	*Evolutionary and homeostatic*
Governing the system	Monitoring	*Objects: inputs and outputs; Criteria: efficiency*	*Objects: organ functions; Criteria: health and resilience*
	Information	*Objective quantitative data; general laws*	*Objective quantitative and qualitative data; general principles*
	Decision-making	*Mode: top-down control; Aim: process optimization*	*Mode: top-down influence; Aim: learning, adaptation and remediation*

As the comparison of Table 6-1 demonstrates, metaphors can powerfully capture distinct archetypal visions of cities. It also demonstrates the extent to which such visions contrast with each other in their basic understanding of what a city is. For example, while the machine-inspired vision sees the city as a clearly delimited unit, the vision of the city as an organism sees it as inseparably rooted into its environment. Also, while the machine vision suggests to focus on optimizing the efficiency of the city's production functions, the organism function urges to pay more attention to the health and long-term resilience of the city system. It should be noted that the characterizations of 'machine' or 'organism' cities presented in Table 6-1 should not be taken as to represent definitive and objective definitions for these terms; rather, they represent particular understandings of these terms by certain analysts at a certain point in time, elicited with the goal of producing awareness of different possible visions.

Based on the insights gained from the characterization of the four metaphors, the analysis proceeded to derive and compare the implications that each metaphor-based vision of cities has for assessing their sustainability. In particular, these implications were found to pertain to four aspects of sustainability assessment: (i) the purpose of sustainability assessment; (ii) the selection of participants; (iii) the evaluative principles of sustainability; (iv) the central constituent parts of the system model. The comparison is reproduced in Table 6-2. It makes explicit a range of possible stances concerning the design of urban sustainability assessments.

Table 6-2. Implications of the metaphorical visions for the sustainability assessment of cities (Halla et al., 2020).

Metaphor	Purpose of assessment	Participation	Sustainability principles	Model of the system
Machine	Optimization	Based on utility	Efficiency	Practical functions within an administrative boundary
Organism	Learning and adaptation	Based on decision-making authority and substantive expertise	Health and resilience	Metabolic functions within a functional boundary
Network	Provision of information	Based on voluntary interest and social connections	Connectivity	Connections and flows within an ad hoc boundary
Melting pot	Conflict resolution	Broad participation of government and community representatives	Harmony, equity, innovation	Social and political processes within a boundary defined by social interactions

6.1.2 Stage 2: Clarifying the value of metaphors for urban sustainability

The second stage of work on Module 1 built upon and complemented the insights of the first stage, in particular by specifying further the value and possible role of metaphors in attempts to identify, compare and bring into dialogue different fundamental visions of urban sustainability. To support the conceptual argumentation, the participating group of researchers discussed and jointly completed a comparative table[23] (see Table 1 of Manuscript 2), this time using the urban metaphors 'metabolism', 'rhythm' and 'smart' as examples. As an outcome, three theses were formulated (Halla et al., *forthcoming*):

[23] The comparative table used in the second stage was a variation of Table 6-2. It consisted of the following categories over which the three metaphors were compared: 1. Implied requirements for a sustainable city; 2. Characteristic sustainability indicators; 3. Examples of use in science and practice; 4. Urban issues in focus; 5. Context when most appropriate.

- *Thesis 1: Metaphors can clarify and represent different aspects of urban sustainability*
- *Thesis 2: Metaphors can facilitate transdisciplinary approaches to urban sustainability by clarifying focuses and boundaries of forms of knowledge and know-how*
- *Thesis 3: Metaphors can convey visions of urban sustainability that are appropriate for particular contexts*

Thesis 1 refers to the ability of metaphors to act as orientational terms that help to imagine and express different aspects and requirements of urban sustainability. Therefore, metaphors can support generating comprehensive understanding and agreement on the meaning of the concept. Thesis 2 refers to the possible role of metaphors in bringing into dialogue different fields of knowledge, in view of constructing transdisciplinary approaches for addressing the multitude of requirements of urban sustainability. In particular, discussing and analyzing urban metaphors could be used to clarify the focal points, limits and relative positions of the fields of knowledge associated with these metaphors (e.g., urban metabolism, rhythmanalysis of cities, smart cities, etc.), which is a necessary first step towards their integration. Thesis 3 points to the potential of metaphors to capture contextually variable meanings of urban sustainability. In particular, different metaphors could be used to illustrate particular aspirational visions of cities depending on their historical and geographical contexts. It should be noted that despite these advantages the use of metaphors entails certain potential pitfalls. In particular, taking metaphors too literally or ignoring their evolving meaning over time may lead to simplistic and caricatural representations.

The work of the second stage concluded by suggesting three particular pathways for supporting efforts towards urban sustainability: (i) employing metaphors in collaborations between citizens, policymakers and scientists, in particular by using them as boundary objects that provide easily relatable images of different interpretations of urban sustainability, thereby facilitating communication between actors from different backgrounds; (ii) constructing urban sustainability assessment frameworks with metaphors as rubrics for categories of indicators, thereby anchoring these indicators into expressive visions that can better communicate their meaning; (iii) investigating the (explicit or implicit) influence of different metaphors of cities in approaches to urban development, and critically evaluating their pertinence or obsoleteness for describing present-day or anticipated future urban challenges.

6.1.3 Key outputs and insights of Module 1

The underlying motivation behind the work of this module was to support the reflexive and transparent operationalization of the concept of urban sustainability in sustainability assessments. The particular gap addressed by the work of this module is the lack of means for comprehensively identifying and comparing different visions of urban sustainability. To that end, the work produced a number of outputs presented above and summarized in Table 6-3.

First, the work elaborated two types of conceptual frameworks, one for analyzing and comparing visions of cities (Table 6-1), and one for comparing the implications of such visions for applications of sustainability assessment (Table 6-2). The frameworks make explicit, firstly, what these visions consist of (concretely: the categories of these tables), and secondly, facilitate systematic and explicit reflection on the focal points and blind spots of different visions of cities and the impacts that such visions explicitly or implicitly have on urban sustainability assessments. It can be noted that although these

two frameworks were in this thesis applied particularly to the analysis of metaphors as archetypal visions, in principle the same frameworks can be applied equally to analyzing and reflecting on other objects, including theoretical models of cities (in the case of Table 6-1) or concrete instances of urban sustainability assessments (in the case of Table 6-2).

Table 6-3. Key outputs and insights of Module 1.

Outputs	Insights

• A systems theory-based framework for analyzing and comparing visions of cities (Table 6-1)
  ○ Application of the framework to produce a metaphor-based typology of visions of cities (the *content* of Table 6-1)
• A framework for analyzing and comparing instances of sustainability assessments (Table 6-2)
  ○ Application of the framework to produce a metaphor-based typology of approaches to urban sustainability assessment (the *content* of Table 6-2)
• Three theses concerning the value of metaphors for efforts towards urban sustainability, and three suggested future research pathways for leveraging on the value
	• Engaging at the level of visions can support the reflexive design and practice of urban sustainability assessments
	• Metaphors, in particular, can be productively employed to represent such visions

The application of the two conceptual frameworks to the analysis of a number of metaphors elaborated a typology of archetypal perspectives to cities (the content of Table 6-1) and their sustainability assessment (the content of Table 6-2). This archetypal typology can be deployed to reflect on and compare approaches to cities and their assessment. For example, the typology displayed in Table 6-2 can be used to support the design of sustainability assessment as it reveals different options that exist in terms of the purpose of the assessment, participation, sustainability principles considered, and the conceptualization of the assessed system. In addition, to further clarify the particular ways in which engaging with metaphors can be valuable for efforts targeting urban sustainability, the research of this module also elaborated and argued for three theses that aim to provoke experiments in using them.

The key insight gained from the research conducted within Module 1 is that engaging with visions of urban sustainability, whether using metaphors as archetypes of such visions or otherwise, can generate value in terms of supporting more reflexive design and practice of urban sustainability assessments. Particularly, it can help to ensure that the assessments are based on a clear and comprehensive understanding of the concept of urban sustainability, that different aspects and requirements related to the concept are given their due acknowledgement, and that participants representing different backgrounds can be identified and brought into productive dialogue.

6.2 Module 2: Mapping urban sustainability indicators and indicator frameworks

The objective of Module 2 was to critically analyze current practice in indicator-based urban sustainability assessments, in order to produce guidelines for future indicator set developers. As explained in Section 5.2.2, the research analyzed a sample of recent indicator initiatives, which all had the self-declared intention to cover the concept of urban sustainability in its entirety (as opposed to targeting a more specific theme, such as sustainable housing, or sustainable mobility). The work consisted of two stages, the first stage analyzing the indicators used by the initiatives (Manuscript 3), and the second stage focusing on their conceptual frameworks (Manuscript 4).

6.2.1 Stage 1: Analyzing urban sustainability indicators

The analysis of the indicators in the first stage of Module 2 produced several interesting findings, especially given that the relatively large sample size (67 indicator sets; 2847 indicators) gave a comprehensive vantage point to indicator-based urban sustainability assessments. The first observation relates to the indicators most commonly found in the indicator sets (Fig. 6-1). Only two indicators were found to appear in at least half of the indicator sets, and only a further nine in more than a third of the sets. The result is a demonstration of the ambiguity of the concept of urban sustainability, and the plurality of interpretations that it is given by the analyzed indicator initiatives.

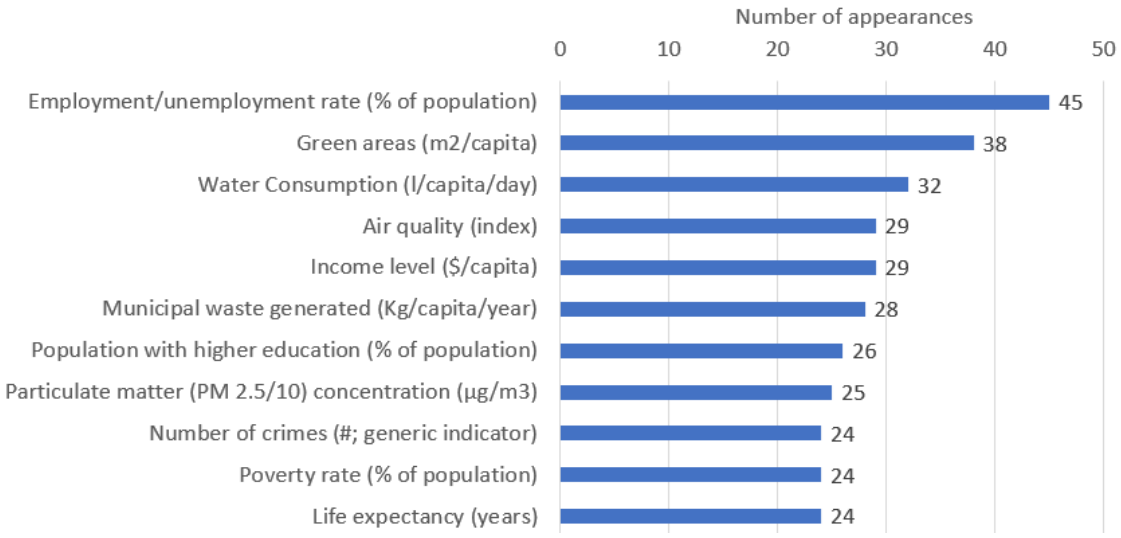

Fig. 6-1. The most common urban sustainability indicators. Shown are indicators appearing in more than a third of the analyzed 67 indicator sets (adapted from Merino-Saum et al., 2020).

Concerning the sustainability aspects covered by the indicator sets, the results of the analysis for the three typologies (SDGs, STEEP, MONET) are illustrated in Fig. 6-2. The first observation to make from the figure is the significant variability that exists among the indicator sets, which, again, testifies to the plurality of interpretations of urban sustainability. In terms of the SDGs, the most prominent among the 17 goals is unsurprisingly SDG 11 ('Sustainable cities and communities') with an average attention of 29%. At the other end of the spectrum, several SDGs receive only marginal attention, in particular SDG 2 ('Zero hunger'), SDG 5 ('Gender equality'), SDG 13 ('Climate action'), SDG 14 ('Life below water') and SDG 17 ('Partnerships for the goals'). In terms of the STEEP typology, the social dimension receives the most attention by a clear margin at an average of 46%, while the political dimension is covered with only an average of 4% of the indicators. In terms of the MONET typology, the categories of level and capital are the most prominent aspects of urban sustainability, both with an average attention of slightly over 30%. At the same time, the disparities, efficiency and response categories are referred to by less than 10% of the indicators on average.

The use of multiple typologies in parallel also allowed for a cross-typological consideration of the indicators used by the indicator initiatives of the sample. The example shown in Fig. 6-3 demonstrates the added depth of such cross-typological analysis. As an example, the analysis reveals how the question of disparities is for the most part neglected by indicators referring to environment-related SDGs (e.g., SDG 6, SDG 13, SDG 14, SDG 15).

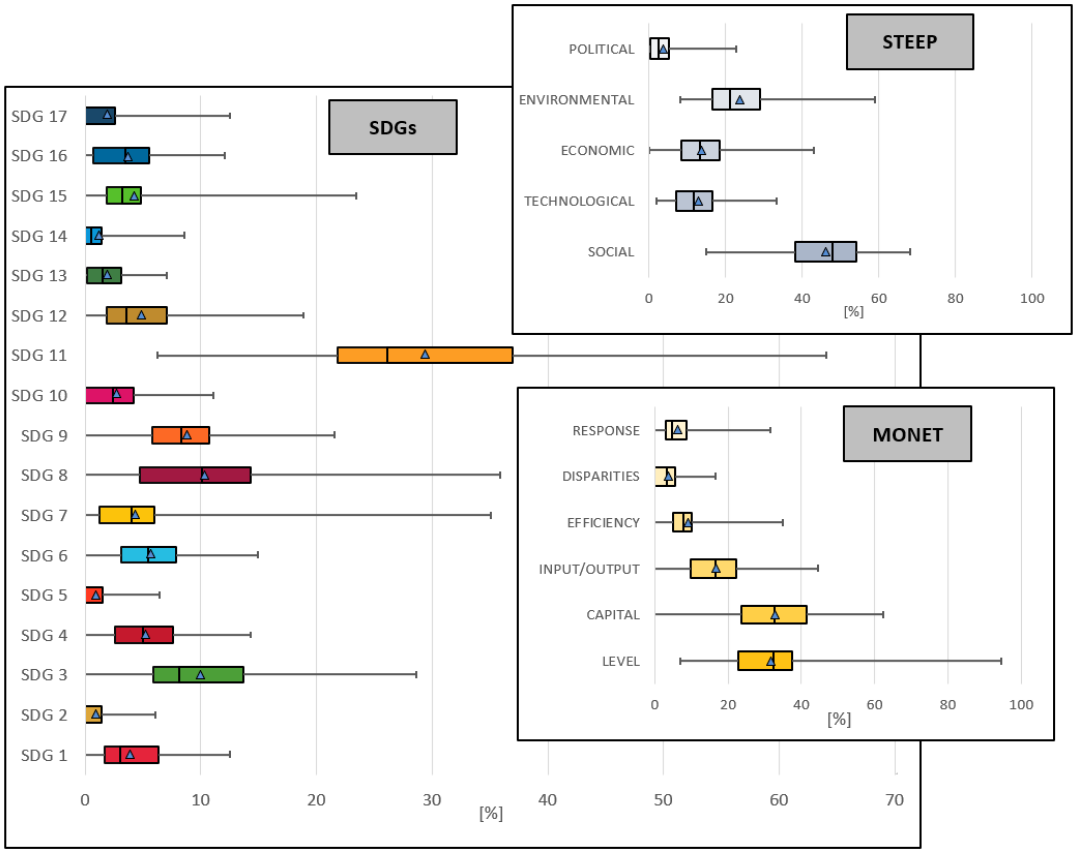

Fig. 6-2. The relative importance given to different categories of urban sustainability (across three typologies), expressed as the percentage of indicators within an indicator set referring to a particular category. The box plots depict the 67 indicator sets in quartiles, with the triangles marking mean values (adapted from Merino-Saum et al., 2020).

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

Fig. 6-3. Heatmap illustrating a cross-typological analysis of the collected 2847 indicators. The cells express the percentage of indicators relating to a particular combination of SDGs (vertical axis) and MONET categories (horizontal axis) (adapted from Merino-Saum et al., 2020).

Finally, the analysis of the sample of indicator sets in the first stage of Module 2 made a number of observations related to three common tensions that indicator set developers must invariably face. The first tension – parsimony vs. comprehensiveness – pertains to the simultaneous need to cover as many aspects of urban sustainability as possible but with as few indicators (and, therefore, resources) as possible. What was observed in the analyzed sample was that although sets containing a higher number of indicators also covered on average a higher number of aspects of urban sustainability, this relationship was far from being universal. In other words, the comprehensiveness of an indicator set can be increased not only by increasing the number of indicators (thereby reducing parsimony), but also through a prudent and structured selection of indicators that avoids redundancy.

The second tension – context-specificity vs. comparability – concerns finding a balance between, on the one hand, selecting indicators that express particular locally important sustainability challenges, and on the other hand, selecting indicators that enable comparability across cities. The analysis made two observations in particular. First, smaller indicator sets, as well as indicator sets developed for more than one city, generally consisted of more commonly used indicators. In other words, a preference for small sets that are applicable in several cities comes with the peril of losing novelty and resonance with local specificities. Second, the attention lent to different categories varied depending on the geographical origin of the indicator initiatives, which demonstrates the local variability of interpretations of urban sustainability, and therefore reminds of the need to consider local idiosyncrasies when developing and applying indicator sets.

The third tension – complexity vs. simplicity – concerns the challenge of representing the assessed object (e.g., a city) with enough detail and scientific credibility while also retaining sufficient understandability for all the related stakeholders. Here, the observation was that the indicator sets clearly tended towards conceptual frameworks based on simple domain- or theme-based categories of indicators (an observation that was expanded upon in the following second stage of Module 2). One way to counter this tendency towards simplicity could be to use such cross-typological frameworks as the one presented in Fig. 6-3, which was observed to provide a relatively simple yet powerful means for providing a more detailed characterization of the object of assessment.

6.2.2 Stage 2: Analyzing conceptual frameworks for urban sustainability indicators

The second stage of the research on Module 2 focused on the analysis of the conceptual frameworks used by the sample of indicator initiatives. Again, the large number of indicator initiatives collected in the sample allowed for the analysis to provide a thorough review of the kind of conceptual frameworks used in the field. The typology of frameworks discovered and formulated inductively from the empirical sample is presented in Table 6-4. Each framework type is defined by a particular logic according to which its internal categories are determined. The typology consists of six types of categorization logics, and an additional hybrid type combining multiple logics in a single framework.

All but one of the analyzed initiatives were found to use a conceptual framework of some kind. In terms of the number of initiatives using a particular framework type[24], the theme-based logic was clearly the

[24] Note that the use of hybrid frameworks explains why the sum of frequencies shown in Table 6-4 is higher than the sample size of 67. For example, a popular hybrid framework found in the sample used a hierarchical structure whereby domains were used as upper-level categories embedding a second level of categories based on themes.

most frequent, with 52 of the analyzed 67 cases making use of this categorization logic. Domain-based (34 cases) and goal-based (18) frameworks were also popular, while systemic (5), spatial (3) and epistemological (3) categorizations were merely exceptions. Furthermore, almost three quarters (49 out of 67 cases) of the analyzed conceptual frameworks were structured using a hybrid logic combining two or more of the six basic logics.

Table 6-4. Typology of indicator frameworks (adapted from Halla and Merino-Saum, *forthcoming*).

Type	Definition	Frequency
Domain	Categorization based on the most general perspectives or sub-systems pertinent to sustainability and reducible only to the overarching concept	34/67
Theme	Categorization based on topics and challenges pertinent to sustainability	52/67
Goal	Categorization based on outcomes seen as desirable for sustainability	18/67
Systemic	Categorization based on a model that explicitly defines the relationships between indicator categories	5/67
Spatial	Categorization based on physical location or scale	3/67
Epistemological	Categorization based on kinds of knowledge	3/67
Hybrid	Categorization combining several of the above logics through either hierarchization, juxtaposition, assimilation or matrix-like integration	49/67

The analysis also elaborated on the internal structure of the framework types, and enumerated lists of potential categories for each type. For the domain type, eleven different categories were identified, with the traditional three pillars ('environment', 'economy' and 'society') by far the most frequently used. For the theme type, a two-tiered internal structure of categories was identified, with the first level consisting of fairly generic topics (e.g., 'transport'; 38 examples found in total), and the second level referring to more specific challenges (e.g., 'congestion'; 140 examples). Goal-based frameworks were found to express their categories by referring to a particular object (either a domain or a theme, such as 'transport'; 43 examples), combined with an action (e.g., 'promote'; 20 examples) and/or an attribute (e.g., 'accessible'; 42 examples)[25]. Among the frameworks representing the systemic type, two sub-types were found. The first differentiated its internal categories in terms of the functional roles they play within the system (e.g., the DPSIR framework used by Wang et al., 2013), while the second used dedicated categories at the interfaces of primary categories to elaborate on the relationships between the latter. As for the spatial type, the distinction between categories were made either in terms of scale (e.g., separating between indicators at the building/parcel, neighborhood and city scales) or in terms of geography (e.g., 'urban' and 'rural' indicator categories). Finally, all the frameworks of the epistemological type differentiated between quantitative and qualitative indicators.

The framework types can be contrasted against each other in different ways. For example, a progressive increase in the level of detail can be seen beginning with domains (e.g., 'economy'), via

[25] Complete lists of categories found in the sample for domain-, theme-, and goal-based types can be found in Appendix C.

themes (e.g., 'economic growth'), and on to goal-based categorizations (e.g., 'promote competitive local economic development'). Also, by capturing the interconnections between indicator categories, the systemic framework type displays a more dynamic understanding of the concept of urban sustainability than, e.g., the domain and theme types that limit themselves to listing discrete areas of sustainability. Furthermore, the framework types differ in terms of their level of normativity. The goal type, by explicitly defining desirable outcomes, represents the highest degree of normativity, while the domain type, by virtue of remaining non-specific, also remains more neutral.

Based on these inherent characteristics of the different framework types, the analysis proceeded to draw comparisons as to the ability of the framework types to satisfy different purposes that conceptual frameworks are expected to serve. To systematize the comparison, a set of six purposes were defined based on a review of pertinent literature. The purposes are described in Table 6-5, along with the most suitable framework type(s) for each purpose[26]. As shown by the table, goal-based frameworks can be considered most suitable for four purposes. Nevertheless, even they do not perfectly serve all the purposes. This highlights the need to consider the particular aims, context and target audience of each initiative, and to tailor the design of a conceptual framework accordingly.

Table 6-5. Purposes of conceptual frameworks (adapted from Halla and Merino-Saum, *forthcoming)*.

Purpose	Function	Type most suitable
Mind map	(Re-)Defining the overarching concept to be monitored	Goal-based
Radar	Guiding indicator selection and development	Goal-based
Skeleton	Structuring information	Theme-based, Goal-based
Scale model	Representing how a phenomenon functions	Systemic
Anchor	Putting metrics into context	Theme-based, Goal-based
Business card	Communicating with the target audience	Domain-based, Theme-based

6.2.3 Key outputs and insights of Module 2

As with Module 1, the motivation behind the objectives and research questions pursued in Module 2 was to support reflexivity in the design of indicator-based urban sustainability assessments. The particular gap in current knowledge that the research addressed was the lack of (critical) overview of indicators and conceptual frameworks used in current practice in the field. The research conducted within the module yielded the results listed in Table 6-6.

At the level of indicators, the analysis revealed the uneven coverage accorded to different aspects of urban sustainability. For example, while the issues related to basic urban services (i.e., SDG 11) are well covered, distributional concerns, gender issues and governance matters are currently

[26] Note that only four of the most frequent framework types (domain, theme, goal, systemic) were considered in the comparison. The team of researchers were not confident including the two remaining types (spatial, epistemological) in the comparison due to the low number of examples pertaining to these types found in the sample.

underrepresented. In general, the analysis pointed to the utility of conceptual frameworks for guiding the selection of indicators to construct sets that are comprehensive in their coverage yet also parsimonious in the number of indicators. At the level of conceptual frameworks, the work produced an empirically-based typology of frameworks, and observed a tendency towards simple conceptualization of urban sustainability. Indeed, a majority of the initiatives preferred to conceptualize the indicator categories as discrete areas of concern (either themes or domains). Meanwhile, only around a quarter expressed explicitly goal-based categories, and more complex systemic or spatially explicit framings were merely exceptions in the sample. The analysis also elaborated on the internal structure and possible categories of each framework type. The work also produced a comparison of the strengths and weaknesses of the framework types in terms of their ability to serve six important purposes of frameworks discerned from literature. The analysis can thus support future indicator set developers to make more conscious decisions in constructing their conceptual frameworks, depending on their particular intended purposes.

Overall, the key insights acquired through the work of Module 2 concern the need for structured approaches to designing indicator-based urban sustainability assessments. Currently, a considerable variance exists between such assessments, important omissions can be detected in terms of coverage of aspects, and although all but one of the initiatives used some kind of a conceptual framework, in general there is a tendency towards simple conceptualizations of urban sustainability. Partly these observations can be explained by differences in the purposes and contexts of the analyzed initiatives, but, most probably, they are also caused by the lack of attention given to the conscious design of the initiatives. The outputs produced over the course of the research of this module can go some way in mitigating the situation, firstly in terms of simply promoting awareness of the need for reflexivity in the development of assessments, and secondly in terms of laying out different options available for future indicator set developers.

Table 6-6. Key outputs and insights of Module 2.

Outputs	Insights
• A quantitative review of most common indicators, as well as emphases and gaps in attention accorded to different aspects (categories) of urban sustainability • An empirically-based typology of conceptual frameworks for indicators ○ Comparison of the framework types in terms of serving six central purposes	• A large variance exists between indicator-based urban sustainability assessments; important omissions can be found in their coverage of sustainability aspects; the assessments tend towards simple conceptualizations of urban sustainability • There is a need for conscious and structured approaches to the design of urban sustainability assessments

6.3 Module 3: Enhancing the salience of assessments

The objective of Module 3 was to develop and demonstrate an assessment approach that is salient to local urban governance. For this purpose, a case study assessment of Geneva's housing system was conducted. The work led to the preparation of Manuscript 5.

The central research question pursued within this module was how to increase the salience of indicator-based assessments for the concrete challenges and decision-making situations of local urban governance. As described in Section 4.2, the proposed solution was to embed the indicators into the context of the assessment, and to do this systematically with the help of a designated conceptual

framework to guide the collection and analysis of the relevant contextual information. In the course of the case study, this conceptual framework was iteratively developed to reach its final form presented in Fig. 6-4. The challenge in developing the framework was to, on the one hand, include enough conceptual categories to elevate the informational value provided by the assessment, but at the same time, make sure that the framework was operational in practice and understandable for all possible stakeholders.

The final proposed framework contains two primary parts, the assessment model and the assessment context. The assessment model contains the indicators selected for the assessment (e.g., 'amount of low speed limit zones') and a conceptual structure that links the indicators to specific system dimensions to be covered by the assessment (e.g., 'buildings', 'neighborhoods'), a set of goals that describe the desired qualities of these dimensions (e.g., 'safe neighborhoods'), as well as related sub-themes (e.g., 'traffic safety', 'crime'). The second part of the framework refers to the assessment context, and specifically identifies stakeholders (Reed, 2008), regulative and normative institutions, as well as cultural-cognitive institutions (Scott, 2014) as the relevant elements to consider. These elements represent central drivers of the indicators (and the issues that they reflect), and as such largely determine the opportunities for acting upon any results gained from the indicators.

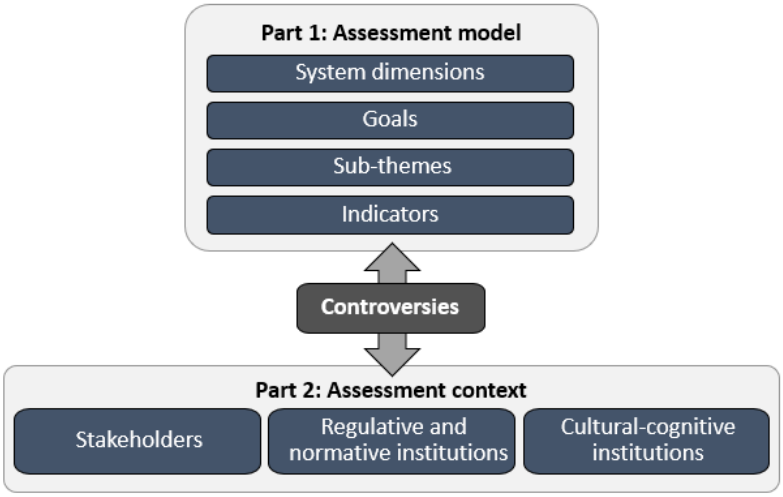

Fig. 6-4. Conceptual framework for contextually rich sustainability assessment.

Apart from the two primary parts of the framework, the final element of the framework refers to current 'controversies' related to the assessed problem (Latour, 2007; Marres, 2007). Here, this term denotes contentious challenges, policies, projects, etc., that give rise to public debates and that reveal tradeoffs between different goals and indicators. They are also occasions in which people become assigned to different stakeholder groups, and in which established social institutions (regulative, normative and cultural-cognitive) are subjected to explicit re-evaluation and possible change. In the course of the case study, it was discovered that the analysis of such controversies made visible connections and tradeoffs between different goals and indicators of the assessment model, as well as between the indicators and the elements of the assessment context, thereby offering an avenue for the kind of systematic contextual embedding of the indicators that was sought with the approach.

Applying the conceptual framework to the assessment of Geneva's housing system, i.e., populating the elements of the framework with empirical content, was achieved through the methodological steps described in Section 5.2.3. As a first output, the study produced the assessment model shown in

Table 6-7[27]. The model enumerates thirteen goals across five dimensions (dwellings, buildings, neighborhoods, markets, and culture). The table also lists the indicators selected through the participatory procedure involving local stakeholders, as well as the concrete metrics with which the indicators were operationalized. For some indicators it was not possible to find suitable metrics and data (within the scope of the study), which is a signal for the need to develop such metrics for these aspects of the housing system in order not to overlook them in future policymaking.

Table 6-7**.** The assessment model for Geneva's housing system (adapted from Halla et al., *forthcoming*).

Goal	Indicators	Metric [unit, year]	Value	Evolution	Benchmark
1. Comfortable and healthy dwellings	1.1 Noise	Share of population disturbed at night by > 55 dB(A) [%, 2015]	42.2	N/A	Zürich - 15.1 Basel - 13.9
	1.2 Natural light	*To be operationalized*			
2. Durable and adaptable buildings	2.1 Investments in maintenance, renovation or conversion	Investments in expansions, transformations and demolitions per capita [CHF, 2018]; data for cantons	3,786	2 941 [2013]	Zürich - 2,640 Basel – 4,847
	2.2 Ease of refurbishing installations	Price of renovating installations [index, 2020]; data for cantons	100.5	100 [2015]	Zürich - 92.0 National - 91.3
3. Buildings with low energy and material footprint	3.1 Energetic efficiency of buildings	Average heat consumption index [MJ/(m^2a), 2019]	486	507 [2014]	Cantonal target: 350 by 2030
	3.2 Share of renewable energy	Share of residential buildings with wood, electricity, heat pumps or solar collectors for heating; (if including district heating) [%, 2015]; data for cantons	10.8; (11.7)	8.8; (9.5) [2010]	Zürich - 24.4 (27.6); Basel - 1.7 (31.7)
4. Buildings and neighborhoods in harmony with their physical surroundings	4.1 Construction considering the natural conditions of the site	*To be operationalized*			
	4.2 Percentage of green coverage	Share of wooded and recreational areas [%, 2013-18]	18.6	18.9 [2004-09]	Zürich - 35.5 Basel - 12.6
5. Safe neighborhoods	5.1 Pedestrian and low speed limit zones	Share of moderated traffic zones [%, 2017]	40.9	34.9 [2013]	Zürich - 55.4 Basel - 72.6
	5.2 Existence of risk maps	Binary indicator for existence of risk maps [yes/no; 2021]	Yes	N/A	Zürich – Yes Basel - Yes
6. Participatory neighborhoods	6.1 Availability of community facilities	Number of neighborhood centers [1/10 000 inhabitants, 2020]	0.54	N/A	Zürich - 0.43 Basel - 0.87
	6.2 Membership in community associations	Population (>15 years) involved in a communal or neighborhood association [%, 2020]; regional data	6.2	N/A	Zürich - 4.2 National - 5.4
7. Connected neighborhoods	7.1 Capacity of public transport system	Amount of public transport stops [1/1000 inhabitants, 2019]	0.7	0.8 [2015]	Zürich - 1.1 Basel - 1.0
	7.2 Soft mobility infrastructure	Bicycle friendliness [index points, 2019]	3 pts	N/A	Zürich - 2 pts Basel - 8 pts
8. Convivial neighborhoods	8.1 Architecture encouraging social links	*To be operationalized*			
	8.2 Amount of public spaces	Density of public benches [1/ha, 2020]	1.17	N/A	N/A

[27] For presentation purposes, the assessment model shown here is a simplified version that leaves out the sub-themes of the model. For a full version see Fig. 3 in Manuscript 5.

Table 6-7 (Cont.). The assessment model for Geneva's housing system (adapted from Halla et al., *forthcoming*).

Goal	Indicators	Metric [unit, year]	Value	Evolution	Benchmark
9. Diverse neighborhoods	9.1 Age distribution of residents	Dependency ratio: Number of residents outside working age per those in working age; (std. dev. between neighborhoods) [%, 2020]	50.9; (9.8)	51.7; (10.1) [2011]	Zürich - 47.6 (14.3) Basel - 56.1 (11.9)
	9.2 Share of residents receiving social benefits	Share of residents receiving social subsidies; (std. dev between neighborhoods) [%, 2017]	11.2; (8.7)	10.8 [2011]	Geneva Canton - 9.7
10. Economically viable markets	10.1 Cost of maintenance and retrofitting	Price of renovations and transformations [index, 2020]; data for cantons	101.4	100 [2015]	Zürich - 98.0 National - 98.0
	10.2 Access to funding for investment	*To be operationalized*			
11. Accessible and fair markets	11.1 Average rental price per m^2	Average rent (CHF) per net floor space [CHF/(m^2month), 2017]	29.8	19.8 [2005]	Zürich - 25.7 Basel - 18.9
	11.2 Subsidized housing ratio	Share of subsidized dwellings of total number of dwellings [%, 2019]	9.8	10.0 [2015]	Geneva Canton - 8.0
12. Markets with adequate supply	12.1 Construction rate relative to population growth	Ratio of new dwellings to new residents [dwellings/persons, 2015-2019]	0.38	0.26 [2011-2015]	Zürich – 0.43; Basel – 0.91
	12.2 Vacancy rate	Dwelling vacancy rate [%, 2019]	0.6	0.3 [2011]	Zürich - 0.1; Basel - 1.0
13. Cultural and aesthetic value	13.1 Preservation of local characteristics and identity	*To be operationalized*			
	13.2 Satisfaction with aesthetics of surrounding architecture	*To be operationalized*			

The assessment proceeded by quantifying the indicators for Geneva and benchmarking the values against their historical evolution, against comparable Swiss cities (Zürich and Basel), and/or against policy targets. The results highlighted a number of critical issues concerning the sustainability of Geneva's housing system. These related in particular to: (i) the energetic performance of the housing stock (Indicators 3.1 and 3.2); (ii) supply of housing (Indicators 12.1 and 12.2), especially in terms of affordable housing (Indicators 11.1 and 11.2); (iii) certain aspects of the urban environment, including noise and traffic (Indicators 1.1 and 5.1), the amount of green areas (Indicator 4.2), and mobility (Indicators 7.1 and 7.2). This initial indicator-based assessment was then elaborated by connecting the indicators to the contextual elements of the conceptual framework of Fig. 6-4, in particular through the analysis of controversies. Fig. 6-5 presents an example of such an analysis for the controversy that surrounds efforts to densify the built environment in Geneva.

The example of Fig. 6-5 demonstrates how the proposed approach can elucidate a more complete picture around the assessed indicators and the sustainability challenges that they point to, such as the low construction and vacancy rates (Indicators 12.1 and 12.2). In particular, the analysis: (i) reveals how these indicators (and the goals that they represent) are tied to certain tradeoffs and to certain stakeholder groups; (ii) highlights the regulative and normative structures within which local governance must maneuver when acting on the challenges revealed by the indicators, and which typically extend beyond the powers of local authorities and stakeholders; (iii) elicits the underlying

taken-for-granted assumptions and values at play. In this manner, by defining and structuring the challenges identified by the indicators, the approach offers more complete support for the governance of the sustainability problem in question, and thus prepares the way for ensuing dialogue and policymaking on the subject.

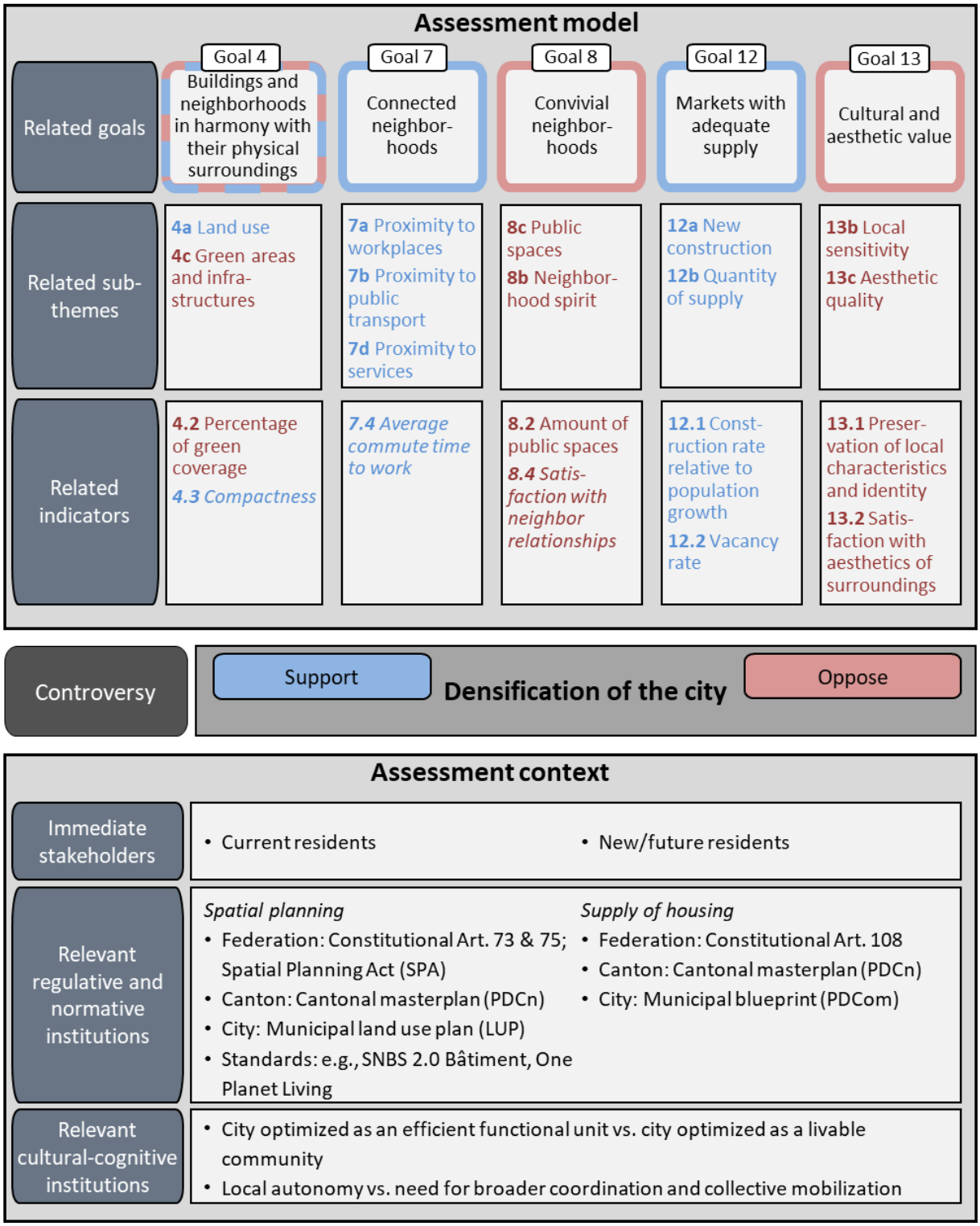

Fig. 6-5. Diagram of the densification of the city controversy (Halla et al., *forthcoming*). The blue-and-red color-coding marks a supporting link between the goals, sub-themes and indicators, and the two positions on the controversy (blue for 'support' and red for 'oppose'). The indicators marked in *italics* were not among those selected by the stakeholders, but which would, however, be pertinent for the controversy in question.

6.3.1 Key outputs and insights of Module 3

The underlying motivation behind the work of this module was to respond to the challenge of designing salient sustainability assessments that couple to local urban governance processes. In particular, the gap addressed by this module related to the lack of understanding on how to design and conduct sustainability assessments in ways that enhance their salience for the governance of cities. The outputs produced in the course of the work of the module are summarized in Table 6-8.

Table 6-8. Key outputs and insights of Module 3.

Outputs	Insights
• Development and demonstration of an assessment approach with enhanced salience for local urban governance • A comprehensive model for assessing the sustainability of an urban housing system • Sustainability assessment of the housing system of Geneva	• Embedding indicators into contextual elements can considerably enhance the informational value of sustainability assessments • Assessments can tell 'stories', instead of simply offering facts, thus making the latter more relatable for urban stakeholders

The principal output of the research of this module was the description and demonstration of an assessment approach designed expressly to increase the relevance of the information produced by the assessment for the governance of cities. Specifically, the approach is guided by a conceptual framework that structures the incorporation and analysis of contextual aspects in an indicator-based assessment. As demonstrated by the case study, the proposed approach can elucidate a richer picture of the challenges identified in the assessment than an analysis solely based on indicators. The approach is an attempt to look beyond the numbers displayed by the indicators with a systematic discussion of their meanings and of possible ways for influencing them.

Through the case study, the work of Module 3 also produced outputs specifically related to the topic of housing. In particular, by employing a participatory methodology that collected inputs from different stakeholders, the work produced a comprehensive assessment model for housing. The model elucidates the range of goals, from the scale of individual dwellings to neighborhoods and on to housing markets, that need to be balanced for the housing system to be sustainable. Furthermore, the case study assessment of Geneva's housing system produced knowledge about the particular current challenges and controversies related to its sustainability.

The main insight offered by the work of the module is that moving away from a singular focus on indicators, and instead lending attention also to the analysis of the underlying sociopolitical settings in which the indicators are embedded, can enhance the informational value of assessments. In other words, instead of simply producing indicator-based facts, assessments can weave the indicators into broader 'stories', thus making them more relevant for decision-making and learning processes related to local urban governance. In particular, performing the contextual embedding of indicators through ongoing controversies can be a fruitful exercise that makes the otherwise abstract indicators and assessments more relatable and concrete to local stakeholders, since such controversies represent occasions through which most people in practice engage with issues related to sustainability.

7 Discussion

The purpose of this chapter is three-fold. First, it discusses the scientific contributions made across the three research modules, and integrates them into a unified picture. Second, it formulates a set of recommendations for urban sustainability assessment practice based on the insights generated by the work. Third, some reflections on the overall approach and methodology are offered, pointing to certain limitations of this thesis and to future avenues for complementing and building on it.

7.1 Scientific contributions of thesis

7.1.1 Module 1

The work of Module 1 set out to explore different visions that exist concerning the concept of urban sustainability. More specifically, the first research question of the module (RQ1.1: *How can visions of urban sustainability be represented, characterized and compared?*) entailed establishing means for making such visions explicit and therefore enabling their structured analysis and comparison. This was achieved by a systems theory-based framework (Table 6-1) that allows to characterize and discuss these visions more specifically, not only in terms of their positions concerning the idea of urban sustainability (i.e., 'What is a sustainable city?'), but, even more fundamentally, concerning their view of the very nature of cities (i.e., 'What is a city?'). Furthermore, the possibility and value of using common metaphors of cities and urban phenomena as archetypal visions was explored; indeed, applying the aforementioned framework to the analysis of a set of city metaphors shone a light on the breadth of possible visions. For example, while one vision (the city as a *machine*) may see the city as an independent unit whose sustainability depends mainly on the efficiency of its production processes, another vision (the city as an *organism*) reminds that a city is deeply rooted in its surroundings, and its sustainability concerns the health and resilience of its organs.

Engaging with metaphors also allowed to answer the second research question of the first module (RQ1.2: *What are the implications of different visions for urban sustainability assessment?*). In particular, based on the insights from the comparative analysis of metaphor-based visions (Table 6-1), another comparative table was formulated (Table 6-2), which shows that such visions do not differ merely in terms of the criteria that they imply for assessing cities (e.g., efficiency vs. resilience), but also in their approaches to the purpose and participants of the assessment, and to the conceptualization of the assessed system. The metaphor-based, archetypal set of approaches to sustainability assessment can therefore be used as a reflective tool for understanding the range of options that exist in the design of such assessments.

Overall, then, the work of the module contributes to an enhanced understanding of the meaning and possible use of 'visions' in the context of urban sustainability assessment. Defining a guiding vision is emphasized by several authors as a necessary early step in the design of assessments in order to clarify the underlying values and expectations related to the assessment (Meadows, 1998; McCool and Stankey, 2004; Weaver and Rotmans, 2006; Pintér et al., 2012; Sala et al., 2015; Cohen, 2017). In relating the contributions of this module to this existing literature, three points can be mentioned.

First, the work of this thesis contributes to making clearer what exactly such visions may consist of. As the categories of Table 6-1 express, visions can be characterized by how they delimit a system, understand its purposes and functions, analyze it, and suggest that it is governed. Furthermore, as

Table 6-2 shows, visions can be characterized by their implications for the design of sustainability assessments, including their purpose, participants and evaluative principles. In other words, visions entail not only a normative aspect (e.g., the evaluative criteria and the mode of governance they suggest for the assessed system), but also a descriptive aspect through the way they suggest to conceptualize the assessed system. In that sense, this thesis understands the concept of a vision roughly as it is understood in the sustainability transitions literature, where it is discussed as a means for inspiring action towards systemic change by acting as a heuristic for problem definition, target setting and stakeholder identification (Smith et al., 2005; Kemp and Martens, 2007).

Second, in addition to making the possible components of a guiding vision more explicit, the above specification of its meaning also makes it broader compared to previous literature on sustainability assessment. For example, literature on 'integrated sustainability assessment' prescribes that a specific stage of scoping (i.e., problem definition) should precede the stage of envisioning desirable future states of the assessed system (Weaver and Rotmans, 2006; Bohunovsky et al., 2011). In contrast, the understanding of a vision put forward in this thesis takes the position that separating these stages is artificial, as the scoping already draws from particular visions[28].

Third, the work of Module 1 proposes to cross-fertilize the scholarship on sustainability assessment with that on (urban) metaphors (Lynch, 1984; Newell and Cousins, 2015; Nientied, 2016). Such metaphors can be used as archetypes that elicit the range of possible visions of (urban) sustainability. Also, they can provide an easily relatable heuristic image, and thereby enable exchange on the respective visions of actors from various backgrounds. In other words, metaphors can facilitate reflexive and participatory engagement with visions as an initial step in the design of assessments.

7.1.2 Module 2

The research Module 2 of the thesis intended to complement the work of Module 1 in supporting the reflexive development of urban sustainability assessments by focusing on the more concrete levels of indicators and indicator frameworks. The first research question (RQ2.1: *How do current indicator initiatives translate urban sustainability into metrics?*) was answered through a systematic review of a large number of indicator initiatives for urban sustainability from the last decade. As an answer to the question, the analysis identified first a list of most common indicators of urban sustainability (Fig. 6-1) and then used a multi-typological lens to elicit a picture of how the indicators used by the initiatives cover different aspects of urban sustainability (Fig. 6-2). The analysis revealed a large variance between the initiatives. Important omissions were also found in the coverage; for example, distributional concerns, gender, and governance were given only marginal attention. Furthermore, the analysis made a number of observations concerning three common tensions in indicator set development, and based on these, formulated recommendations for dealing with them.

The work complements existing literature that has mapped indicators of urban sustainability (e.g., Tanguay et al., 2010; Shen et al., 2011; Braulio-Gonzalo et al., 2015; Kaur and Garg, 2019). Compared

[28] Incidentally, this definitional clarification also allows to make a distinction between a 'vision' and the adjacent concept of a 'scenario', which "describes a hypothetical *future state* of a system and provides information on its development up to this state" (Scholz and Tietje, 2002, p. 80; emphasis added). In other words, scenarios may be based on visions or combinations of them (both in terms of how a vision conceptualizes a system and envisions its future), but these two terms should not be confounded.

to these authors, the work reported in this thesis was able to produce an unprecedentedly comprehensive overview of the field, given the large number of indicator initiatives (67 initiatives consisting of 2847 indicators in total) included in the analyzed sample. It therefore gives a strong quantitative basis for evaluating current practice in indicator-based urban sustainability assessment, including the focal points and gaps in attention accorded to different aspects of urban sustainability, and for formulating recommendations for improving this practice in the future. The comprehensiveness of the overview is further augmented by the use of three complementary parallel typologies in the analysis (SDGs, STEEP and MONET). The sample also includes several initiatives developed at the local level (22 initiatives), which distinguishes it from earlier scholarship that has focused mostly on international standards.

The second research question (RQ2.2: *What kind of conceptual frameworks do the indicator initiatives employ*?) was answered through the analysis of the same sample of indicator sets. Through the analysis, a typology of conceptual frameworks was inductively constructed, with each type defined by a particular logic of categorizing indicators. Six distinct types were identified (in order of popularity: theme, domain, goal, systemic, spatial, epistemological), joined by a hybrid type combining two or more of the other logics. Overall, a tendency towards simple conceptualizations was detected, as the majority of the initiatives preferred to conceptualize the indicator categories as discrete areas of concern (either themes or domains).

The analysis can be contrasted with earlier literature on conceptual frameworks for sustainability indicators (Maclaren, 1996; Gallopín, 1997; Pintér et al., 2005; Olalla-Tárraga, 2006; Lyytimäki and Rosenström, 2008; Nathan and Reddy, 2012). Compared to these authors the present work makes several novel contributions. First, in contrast to earlier scholarship on the topic, which has considered types of frameworks on a theoretical basis or based on individual examples, the research of this thesis represents a first empirical investigation of a large number of indicator initiatives. This allows the thesis to not only make observations concerning the relative popularity of types of conceptual frameworks, but also to deepen the existing knowledge of these types, to provide a clear definition for each type, and to elaborate on their internal structure and categories. Furthermore, the work also contributes novelty to existing literature by discussing the ability of different indicator framework types to serve particular purposes, thus providing much-needed guidance for future developers of indicator-based assessments (Burgass et al., 2017).

Several lessons can be discerned from the results and insights produced by the work of Module 2 (RQ2.3: *What does the analysis of current practice imply for the development of future indicator sets for urban sustainability?*). As highlighted by the variance between initiatives at the indicator level, the range of different types of conceptual frameworks available, as well as the gaps in coverage of different aspects, urban sustainability is a highly ambiguous concept. Therefore, the central lesson is the need for indicator-based urban sustainability assessments to be constructed carefully and consciously from the range of options available, in order to make sure that important aspects are not omitted, and that the conceptual representations used are not overly simplistic. Furthermore, it is also to make sure that the assessment is tailored to the specific purpose and context of the assessment, since assessment developers should not settle for simply copying indicator sets from earlier examples. The practical recommendations formulated on the basis of the work to support future assessment developers are elaborated further below in Section 7.2.

As described in Section 4.1, the approach taken in this thesis to indicators and indicator frameworks sees them not only as carriers of data, but also as carriers of messages and meanings. In performing such a conceptual role, indicators and indicator frameworks used in assessments of urban sustainability represent practical *de facto* definitions of the complex concept. From this perspective, the systematic collection and analysis of indicator initiatives – the conceptual framings and indicator categories that they use, and the aspects that they cover and do not cover with indicators – helps mapping the components of a sustainable city, and thereby also contributes to literature discussing the meaning of the concept[29] (Finco and Nijkamp, 2001; Mori and Christodoulou, 2012; Cohen, 2017; Hamman, 2017; Dizdaroglu, 2017; Zhang and Li, 2018). At the same time, the de facto definition displayed by the initiatives can also be subjected to a critical evaluation to see whether there is a discrepancy between this operational understanding of the concept and theoretically derived expectations, such as the principles listed in Table 4-1.

According to the results of the analysis at the indicator level (see Fig. 6-2), urban sustainability is on average understood as a strongly social concept (STEEP typology), with a focus on the level of satisfaction of urban residents' needs and different capital resources (MONET typology), as well as on the issues encompassed by SDG 11 (e.g., sustainable urbanization, access to transport systems). To a considerable extent, these emphases do match with the expectations mentioned above. Specifically, since cities are characterized in particular by a high density of humans and infrastructures (Sahely et al., 2005; Dempsey et al., 2011), these aspects can also be expected to be given emphasis in urban sustainability assessments. However, important omissions also remain, especially when it comes to such aspects of urban sustainability as distributional concerns, gender issues and urban governance.

At the level of conceptual framing (see Table 6-4), the indicator initiatives understand urban sustainability mostly as a matter of different discrete areas of concern, including domains (the three pillars, in particular) and themes, and more rarely as an explicitly value-laden concept tied to specific goals, or as a systemic concept with dynamic interconnections between the areas of concern (Wiek and Binder, 2005). In addition, spatial aspects, both when it comes to the important relationship between cities and their surroundings (Rees and Wackernagel, 1996; Kennedy et al., 2007), as well as to different scales within a city, are poorly represented by the conceptual framings found in the analyzed sample. The same can be said for temporal considerations, which were found completely absent at the conceptual framings of the analyzed sample (for examples of such temporal conceptual framings see, e.g., UN, 2014; Alderton et al., 2019).

In other words, current practice of urban sustainability assessment tends towards simplistic framings, only partly compensated by the complexity added by the common use of hybrid frameworks, and as such contrasts with the increasingly complex frameworks of cities found in scientific literature (Ramaswami et al., 2012; McPhearson et al., 2016; Webb et al., 2018; Zhou et al., 2021). Of course, in making comparisons between the conceptual frameworks used in connection with indicator sets against those developed expressly for scientific analysis, it must be remembered that the former must reconcile scientific accuracy with the requirement of being communicable to a broader audience.

[29] As described in Section 5.2.2, an explicit focus on urban sustainability (instead of any adjacent concept, such as well-being) was one of the criteria for an indicator initiative to be selected in the analyzed sample. This allows for the discussion to make statements about the meaning accorded specifically to this concept.

In contrast, the large number of thematic categories (see Table 2 in Manuscript 4) discovered in the sample reflects well the role of cities as functionally complex hubs of people, infrastructures and economy (Mori and Christodoulou, 2012; Meirelles et al., 2020; Lobo et al., 2020). Indeed, disregarding this multiplicity, and evaluating the sustainability of cities for example only on their environmental records would mean ignoring the positive role that cities potentially play in the socioeconomic aspects of sustainability (Bettencourt et al., 2007; Balland et al., 2020).

7.1.3 Module 3

The research of Module 3 had as its objective to investigate an approach to sustainability assessment that would specifically pay attention to the coupling of the assessment to local urban governance. Specifically, the research question (RQ3.1: *How to increase the salience of indicator-based assessments for the concrete challenges and decision-making situations of local urban governance?*) focused on the salience of the assessment's output for the needs of the stakeholders involved in the governance of the assessed system. As a response to the question, an assessment approach based on a dedicated conceptual framework was developed and demonstrated with a case study in the City of Geneva. The approach systematically embeds the assessed indicators into their local sociopolitical context. This allows for the assessment to go beyond the indicators as disconnected pieces of information, thereby producing output that better meets the needs of the assessment's users in facing their real-word challenges and decision-making situations. In particular, connecting the assessment of indicators to the analysis of ongoing controversies related to the assessed system elevates the indicators from mere data points to more complete 'stories'. Thus, it concerns upgrading the output of the assessment, in Ackoff's (1989) terms, from mere information to understanding (i.e., from pure descriptions to explanations), or even on to wisdom (i.e., connecting information to values).

This approach serves two purposes in particular for local urban governance. First, by combining breadth (i.e., including in a single assessment the concerns of a broad range of stakeholders) with depth (i.e., enriching the analysis of indicators with contextual information), it constructs a basis for learning, dialogue and networking among local stakeholders. Thus, it serves to build the kind of social foundation crucially required for supporting the sustainability transformations of cities (Hezri, 2004; van Zeijl-Rozema et al., 2008). In particular, connecting the assessment to ongoing controversies and debates can be valuable, as it renders the indicators and the challenges identified through them more relatable for local stakeholders. Second, the approach can serve at a preliminary agenda-setting stage, prior to policymaking, in which the assessed sustainability problem is defined and structured more holistically, and the main challenges facing policymaking are identified (EEA, 2005; Hezri, 2005). Thus, it sets the stage for policymaking that acknowledges the complexity involved in the governance of the assessed problem, and is therefore better equipped to develop appropriate solutions.

The contributions of this module relate in particular to means for increasing the salience of indicator-based assessments, which has been identified as one of the central determinants of their potential for influence (Cash et al., 2003; Parris and Kates, 2003). The work thus responds to the calls for balancing the overwhelming focus of scholarship on developing assessment methodologies that are technically increasingly sophisticated, while their real-world relevance has been largely neglected (Sébastien et al., 2014; Hák et al., 2016). The approach, which expands the focus of assessments from indicators *per se* to their contextual embedding, builds on the work of previous authors that have acknowledged the importance of considering such contextual aspects (Astleithner et al., 2004; Lee, 2006; Holman, 2009;

Sala et al., 2015) by proposing a concrete solution for operationalizing this idea systematically into contextually-rich assessments. Such systematic focus on contextualizing the information provided by indicators is rare in existing literature (see, e.g., Binder, 2007), since typically engagement with context is limited to the stage where goals and indicators are defined for the assessment (see, e.g., Reed et al., 2006). Furthermore, the proposed approach supports the perspective that the salience of indicator-based assessments does not depend solely on the indicators themselves (see, e.g., Hák et al., 2012), but also on how they are framed (Innes, 1990; Gudmundsson et al., 2009a). It can also be noted that the proposed approach is meant to complement, not to compete with, earlier scholarship that has argued for a focus on participatory assessment procedures as a means for enhancing the salience of assessments.

Through the case study, the work of Module 3 secondarily also contributes to literature on housing sustainability (Marcuse, 1998; Pagani et al., 2020; Adamec et al., 2021) with an assessment model that makes explicit the goals that local urban governance needs to balance if its housing system is to be sustainable. As such, the model can be considered as an umbrella that collects in a single assessment the concerns of different stakeholders, all involved in the housing system, and with mutual impacts between their respective concerns (Feige et al., 2011). The model is comparable in the scope of its goals with the principles promulgated by the Geneva UN Charter on Sustainable Housing (UNECE, 2015), and can therefore be seen as an operationalization of the latter.

7.1.4 Integrating contributions

As described in Section 5.1, this thesis adopted a pragmatic stance to research, contributing from different angles and with different means to the overall objective of supporting the reflexive development of indicator-based sustainability assessments. In taking such a problem-oriented stance, the thesis follows the increasing number of authors that are calling for cities and urban sustainability to be approached with comprehensive interdisciplinary research programmes, instead of researching them from the perspectives of traditional disciplines (McPhearson et al., 2016; Groffman et al., 2017; Acuto et al., 2018).

Within the broad palette of approaches and tools that fit under the banner of sustainability assessment (Ness et al., 2007; Gasparatos and Scolobig, 2012), the contributions of this thesis relate to a particular kind of sustainability assessment. That is, the thesis concerns indicator-based assessments targeting the local governance of cities, the latter taken to include not only policymaking but also broader dialogue and social learning (van Zeijl-Rozema et al., 2008). In addition, the public policy-oriented definition of sustainability assumed for the thesis emphasizes the requirement of a comprehensive and balanced coverage of different aspects of sustainability (Patterson et al., 2017). In other words, the kind of sustainability assessments discussed in this thesis concern mostly indicator systems that aim to cover sustainability in all its dimensions, and that are used for identifying the strengths and weaknesses of the entire city or one its main sub-systems (e.g., housing, transport, etc.), thus performing an agenda-setting function at the broad strategic level of urban governance (EEA, 2005; Hezri, 2005; Loorbach, 2010). This kind of sustainability assessments can be seen to form a part of a broad ‘urban transformative capacity’ towards sustainability (Wolfram, 2016).

More specifically, the challenge that motivated the research conducted within this thesis was the design of assessments that operationalize urban sustainability in a comprehensive and reflexive

manner in order to meet the set of quality criteria laid out in Table 4-1. The research was divided into three research modules that proceeded in parallel, but linked conceptually according to the idea that operationalizing urban sustainability into assessments draws from three interpretative levels – visions, conceptual frameworks and indicators (see Fig. 4-1). The contributions of the three research modules are summarized in Fig. 7-1, which refers to the three levels of interpretation presented earlier as part of the thesis' conceptual approach (see Fig. 4-1). In brief, the contributions of Module 1 aim to make discussions about fundamental visions of cities and their aspired futures more explicit and productive. The contributions of Module 2 at the level of conceptual frameworks aim to support choices related to these frameworks. Module 3 builds on this by proposing a particular kind of conceptual framework expressly designed for enhanced salience. And finally, Module 2 also contributes to understanding current practice at the level of indicators, thus providing lessons for future practice.

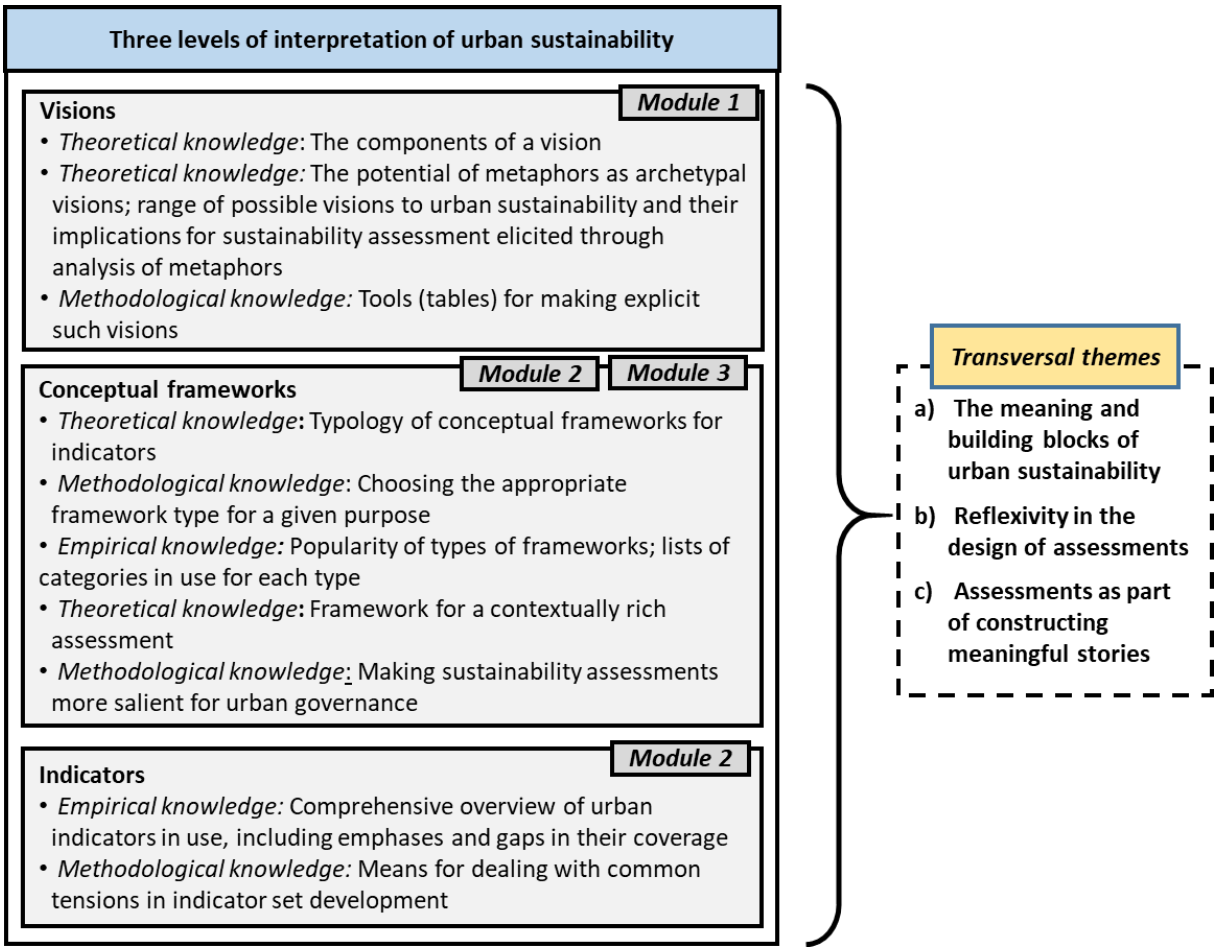

Fig. 7-1. Summarized contributions and transversal themes of the thesis.

Although the contributions of the three modules reside at three different conceptual levels, as shown in Fig. 7-1, they are tied together by, and contribute to, three important transversal themes:

a) The meaning and building blocks of urban sustainability

The first transversal theme pertains to the meaning of urban sustainability (Finco and Nijkamp, 2001; Mori and Christodoulou, 2012; Zhang and Li, 2018). The idea put forward in this thesis is that this concept gains its meaning across three interrelated levels, beginning from more abstract (and often implicit) visions, via conceptual frameworks, to more concrete indicators and metrics. Engaging with

all three levels can therefore serve to construct comprehensive definitions of urban sustainability, characterized by a coherence of meaning from the fundamental aspirational images conveyed by different visions of urban sustainability to the more concrete levels of conceptual frameworks and indicators.

b) Reflexivity in the design of assessments

The second transversal theme of the thesis concerns the requirement of reflexivity in the design of sustainability assessments (Kemp and Martens, 2007; Pintér et al., 2012; Popa et al., 2015). Again, the argument made in this thesis is that such reflexivity must extend across the three interpretative levels of urban sustainability, and may entail iteration to ensure a coherence across the levels, and in order to perform well against the quality criteria described in Table 4-1. To that end, the thesis contributes theoretical, methodological and empirical knowledge for making explicit and discussing different options when it comes to the choices in the design of indicator-based urban sustainability assessments (see the following Section 7.2 for more details).

c) Assessments as part of constructing meaningful stories

The third important transversal theme of the thesis concerns the idea that assessments can contribute to the construction of broader 'stories' around urban sustainability, as opposed to being purely technical and managerial exercises revolving around data and metrics. Aligned with this theme is the perspective taken that sees indicators and conceptual frameworks as carriers of meaning (Astleithner and Hamedinger, 2003; Lehtonen et al., 2016). This meaning can be further enriched and related to the lived experiences of local stakeholders by connecting these indicators and frameworks, on the one hand, to deeper visions, and on the other hand, to contextual elements in the manner proposed by the work of Module 3. This can help sustainability assessments to realize their potential as a bridge between facts, social meanings, and governance towards sustainability.

7.2 Recommendations for policy and practice

Based on the results and insights produced throughout the three research modules, a number of recommendations can be put forward for future sustainability assessments. These recommendations are directed in particular for the kind of assessments that have been the primary focus of this thesis, i.e., indicator-based assessments that aim to cover sustainability in its broad meaning, that are used for agenda-setting at a strategic level of local urban governance, and that involve a broad set of urban stakeholders as either participants or target audience. However, with reservations, the recommendations also apply to sustainability assessments in general.

The recommendations pertain to different tasks in the process of constructing an assessment, as illustrated in Fig. 7-2[30]. The intention is that following these recommendations can lead to an assessment design that is more appropriate for the local context and more insightful in its outputs (i.e., meeting the quality criteria of Table 4-1), and, hence, more effective in integrating sustainability concerns into local urban governance. It should be noted that these tasks are expected to be fulfilled

[30] Note that the covered tasks are not meant to represent a complete set of steps required in an assessment procedure, only those tasks for which the work of this thesis can provide recommendations. For more thorough discussions of the procedural steps in sustainability assessments, see, e.g., Reed et al. (2006), , Reed (2008), Binder et al. (2010).

through an iterative process that can see updates being made to different choices to ensure overall coherence as the design of the assessment takes shape.

The first task considered here concerns the discussion and clarification of a guiding vision for the assessment. As discussed in Section 7.1.1, such visions consist not only of particular aspirations and goals for the future (i.e., '*How do we want our city to look like in the future?*'), but even prior to that, they entail a particular way of looking at a city to begin with (i.e., *'What is a city?'*) and an understanding of the meaning of the concept of 'urban sustainability' (i.e., '*What does the sustainability of a city entail?*). Clarifying a vision for the assessment is important because, as Meadows puts it, the "indicator set must be able to speak to the hopes and aspirations of the people it is meant to serve" (1998, p. 26). In other words, engaging with such visions can imbue the assessment with a positive outlook, whereby the quest for sustainability is not seen merely as a question of problems and limitations, thereby increasing the motivation of the participants to stay involved in the assessment.

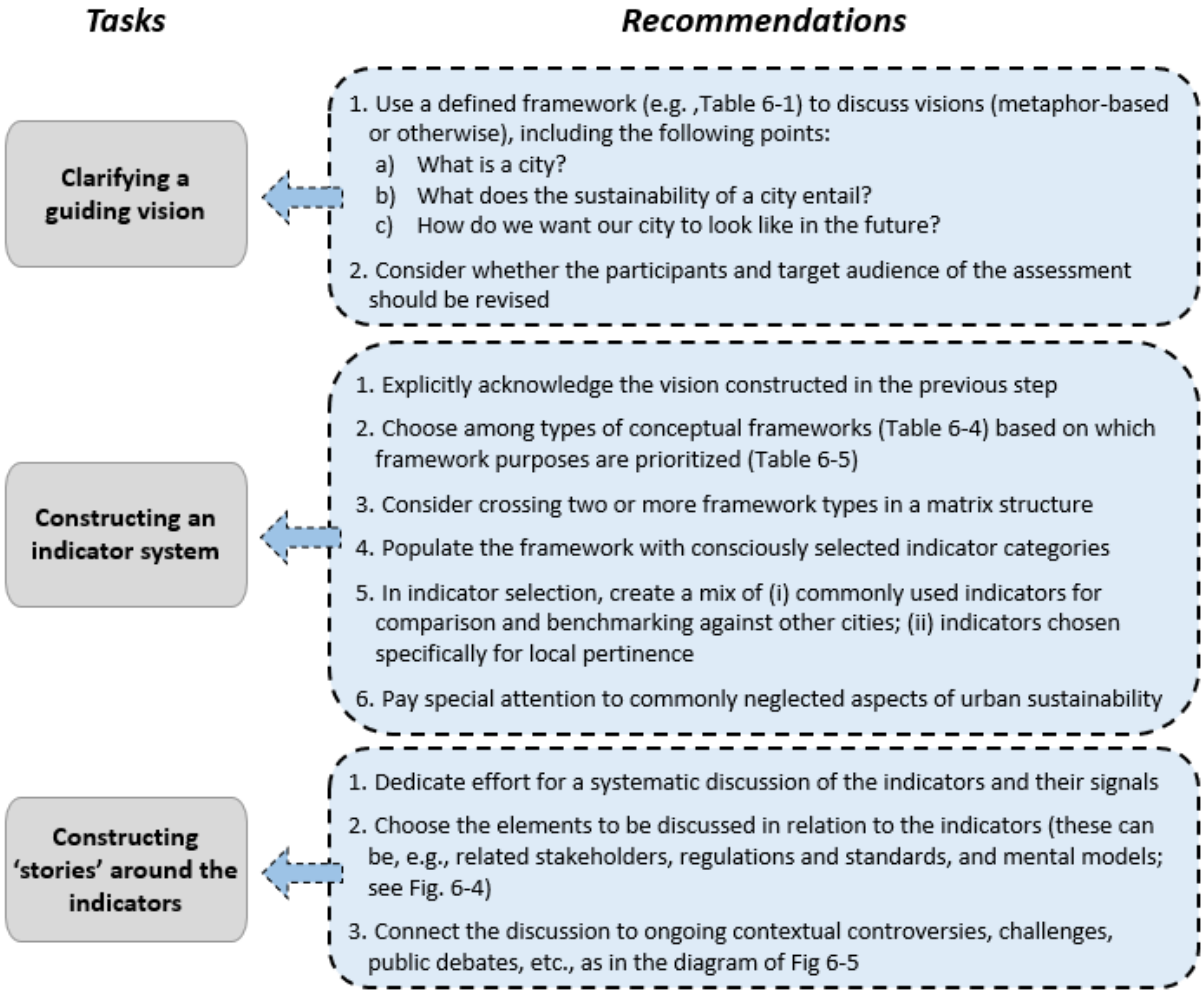

Fig. 7-2. The recommendations for different tasks in sustainability assessment practice drawn from the results and insights of this thesis.

For discussing the above questions systematically, the use of a dedicated framework, like the one provided in Table 6-1, is recommended. Different strategies can be imagined for this task. For example, the discussion can either construct a single vision by filling in the categories (i.e., the rows) of the table, or multiple parallel visions can be constructed concurrently with the aim of creating a comprehensive view that acknowledges different perspectives to cities and their sustainability.

This systematic discussion can be undertaken also by employing metaphors as archetypal visions of cities. The value of such metaphors is in their ability to provide easily relatable images for actors from different backgrounds, thereby facilitating a dialogue between different stakeholders, including citizens, policymakers, and topical experts, with each group contributing a particular perspective and type of knowledge to the discussion. At the same time, metaphors should be understood as a heuristic device and not taken literally, in order to avoid simplistic or caricatural representations. In addition, the discussion and characterization of metaphors is not expected to lead to definitive and unequivocal definitions of each metaphor, but the process should rather serve to facilitate dialogue, leading to a more reasoned and comprehensive consideration of different visions in the design of an assessment.

The first consequence of explicitly discussing the guiding vision of the assessment may be a re-thinking or refinement of the participants, purposes and target audience of the assessment (see Table 6-2). For example, if the vision sees a sustainable city as a harmonious melting pot, the equal participation of different groups of residents in the assessment is a logical choice, in order to achieve a representative view when selecting the indicators for that aspirational vision.

The outcomes of the discussion on guiding visions should also be carried over to the second task of Fig. 7-2, in which the assessment is made more concrete using a conceptual framework and a set of indicators. The link can be achieved in different ways. An illustrative imaginary example is given in Table 7-1, where particular visions provide rubrics for thematic categories of indicators, via specified sustainability principles and objectives. The anchoring of indicators to visions better elucidates and communicates their meaning and purpose in the assessment.

Table 7-1. Example of a possible conceptual framework for indicators incorporating visions of the city.

Vision of the city	Related sustainability principles	Theme: Energy	Theme: Transport	Theme: Housing
Machine	Efficiency	• **Objective:** Low per capita energy consumption • **Indicators**: …	• **Objective**: Transport system with high carrying capacity • **Indicators**: …	• **Objective**: Efficient housing markets • **Indicators**: …
Organism	Health and resilience	• **Objective:** Energy provision from multiple and renewable sources • **Indicators**: …	• **Objective:** Transport system with high reliability • **Indicators**: …	• **Objective**: Housing with low environmental footprint • **Indicators**: …
Network	Connectivity	• **Objective:** Universal access to energy • **Indicators**: …	• **Objective:** Proximity to transport services • **Indicators**: …	• **Objective**: Housing close to services and public transport • **Indicators**: …
Melting pot	Harmony and equity	• **Objective:** Equal access to affordable energy • **Indicators**: …	• **Objective:** Affordable public transport system • **Indicators**: …	• **Objective**: Accessible housing and convivial and diverse neighborhoods • **Indicators**: …

In general, a strong recommendation can be put forward to grant adequate attention to the development of the conceptual framework of an assessment, given the multiple important purposes that they can ideally serve. This task entails considering different types of indicator categorization logics (Table 6-4) and choosing among them based on which of the framework purposes (Table 6-5) are given priority. For example, while a simple domain-based framework may serve well the purpose of communicating to a broad audience, a systemic framework may find higher resonance in scientific contexts. It is also possible to combine the strengths of different framework types in a hybrid framework. Furthermore, if the general intention is to construct the assessment through an inclusive participatory procedure, this participation should also extend to the development of the conceptual framework. This can ensure that the ensuing indicator set adequately captures the different stakeholder concerns, but the dialogue itself also allows for these stakeholders to learn mutually from each other and to develop a shared understanding of what sustainability entails.

A further recommendable strategy is to construct the framework by combining two or more types of logics in a matrix-like structure; for example, the framework of Table 7-1 crosses a thematic and a goal-based logic in this way (in this particular case, a goal consists of three elements: 'vision', 'principle' and 'objective'), and the framework of Fig. 6-3 crosses a goal-based logic with a systemic one. This strategy is an easy way to elaborate a more detailed representation of the problem being assessed, thereby countering the tendency of indicator initiatives to utilize simplistic conceptualizations of urban sustainability, as discussed in Section 7.1.2. The more refined categories can both lead to a more accurate selection of indicators, but also, they can better serve to communicate the meaning and importance of the indicators they contain. This strategy can also serve the parsimonious selection of indicators, as it can ensure a more complete coverage of different sustainability aspects with as few indicators as possible. With a less refined framework, indicators that are selected may be superfluous and not add much new information to the assessment, thereby wasting resources.

It should be noted that crossing several framework types also has its limits, as too convoluted frameworks easily become weak in their practical applicability and understandability. Also, not all the boxes of a matrix framework have to be necessarily filled with indicators; using the framework of Table 7-1 as an example, the vision of the city as a machine may not be appropriate for defining goals for certain themes, such as social cohesion or equality.

After choosing the manner in which the conceptual framework is constructed, the next task is to populate the framework with categories. Here, while learning from past practice is recommended, as it can provide inspiration and help reflecting on different options[31], it is also recommendable that the selection of categories is done consciously having in mind the context and the object of the assessment. For example, if a domain-based framework is developed, instead of simply using a framework based on the three pillars of sustainability (i.e., economy, society and environment), a selection of domains that better matches the urban context should be used, such as complementing the three typical pillars with the domains of built environment and governance.

When selecting the indicators for the different categories of the conceptual framework, the assessment should consider a balance between indicators that allow for comparability and

[31] To that end, Manuscript 3 and the related Appendix C provide comprehensive lists of potential urban sustainability indicator categories for all types of frameworks.

benchmarking against other cities, while also making sure that particular local challenges and stakeholder concerns are adequately represented. In fact, a recommendation can be put forward for creating a specific sub-set of indicators for each two purposes.

As the analysis of Module 2 of this thesis revealed, certain key aspects of urban sustainability are commonly neglected in current practice of indicator-based assessment. Therefore, future indicator set developers are recommended to pay particular attention to these aspects, both at the stage of framework construction and the stage of indicator selection. These currently underrepresented aspects include distributional concerns, gender equality, food, climate action and governance. Future practice could also benefit from explicitly including certain currently neglected areas at the level of conceptual framings; in particular, paying attention to spatial aspects, such as the relationship of cities towards their environment or the differences between scales, and to temporal aspects, such as contrasting future-oriented indicators with indicators focusing in the present-day, could elevate the quality of information that assessments produce.

Finally, it is important that the assessment procedure does not finish after the indicators have been selected and data for them has been found. Instead, as shown in the third task of Fig. 7-2, it is recommended that a systematic elaboration of the indicators, especially the challenges that they reveal, is undertaken. For this purpose, making use of ongoing controversies (e.g., debates about particular policies, regulations or developments) can be recommended, as they can provide lenses through which tradeoffs between different goals and concerns can be revealed and brought to deliberation. This can be done, for example, in the diagrammatic manner shown in Fig. 6-5. More specifically, the recommendation is to enrich the output of the assessment by embedding the indicators into their context. In the example provided in this thesis, the contextual elements considered included related stakeholders, regulations and norms, as well as deeper mental models, although other elements can also be considered.

The value of this systematic contextualization of the indicators is to transform them from abstract measurement devices to real-world relevant stories. This is important in particular when it comes to approaching the problems revealed by the indicators, since prior to embarking on solving such a problem it needs to be properly defined and understood. Otherwise the solutions (e.g., policies) that are developed will at best be partial, and at worst only lead to exacerbating the situation.

Taken together, the recommendations discussed in this section increase the potential of the resulting assessments to meet the quality criteria enumerated in Table 4-1. More specifically, the recommendations concerning the first two tasks (clarifying a guiding vision and constructing an indicator system) support the reflexive development of assessments that incorporate an adequately broad range of stakeholder concerns and goals; that reflect particular characteristics of cities; that reflect contextual specificities; and that are tailored for particular purposes and target audiences. The recommendations concerning the third task (constructing ‘stories’ around the indicators) support in particular the construction of assessments that are salient in their output to the needs of their stakeholders.

The three transversal themes of the thesis (see Fig. 7-1) can be also seen carrying through the recommendations to practice discussed in this section. First of all, throughout the tasks covered, the participants engage in discussions about the building blocks of a sustainable city across the three levels

of interpretation (visions, conceptual frameworks, indicators). The lack of an exact definition for this term should not be taken as a hindrance for commencing such discussions, nor should the fact that a commonly agreed definition rarely emerges be taken as a sign of failure, since having these discussions is already an achievement that contributes to moving a step further towards sustainability. Second, the completion of the tasks should be characterized by reflexivity, i.e., using the range of options available for the design of the assessment in a way that is appropriate for its context and purposes. In other words, drawing from previous practice for inspiration is recommendable, but simply using carbon copies of past designs is not, since they may contain important omissions or elements that are not appropriate for the needs of the new assessment. Third, the procedure should not be conceived as a technical fact-finding exercise, but as an opportunity for constructing meaningful stories around those facts that can create an impact by connecting to the everyday experiences and challenges of stakeholders. Here, a coherent and explicit thread from indicators, through conceptual framings, to aspirational visions is crucial for giving the assessment deeper meaning.

7.3 Reflections on limitations and avenues for future work

The thesis work began motivated by the overarching objective to support the reflexive development of indicator-based sustainability assessments that are contextually appropriate and salient for local urban governance. In approaching this objective, the research adopted a pragmatic stance in which this real-world challenge was placed in the center, and the research that was conducted used multiple methods and materials to contribute tools and insights (see Fig. 7-1) that can support developers with different tasks and challenges along the construction of such assessments (see Fig. 7-2). However, the research approach that was taken included certain limitations that should be addressed in the future for a more complete response to the overarching objective of the thesis.

Concerning the research on the topic of visions of urban sustainability, the work conducted within this thesis project had the limitation of remaining at a relatively initial, explorative stage. In particular, although the second stage of Module 1 involved a moderately large number of participants from different disciplinary backgrounds (ten academics including the doctoral candidate), involving also participants from outside of academia would yield more complete insights on the applicability of the proposed method for engaging with visions. Such a transdisciplinary participatory process could also produce more knowledge in particular about the value metaphors as archetypal visions. Nevertheless, given that the feedback on both occasions of applying the method was largely positive concerning the ability of the procedure to provoke reflections among the participants, the proposed method can be considered as a promising avenue for creating systematic engagement with visions of cities and urban sustainability.

Another limitation in the scope of research on visions was that explicitly connecting such visions to the more concrete levels of sustainability assessment (i.e., conceptual frameworks and indicators) was only tentatively explored (see Table 1 of Manuscript 2). Again, a participatory procedure involving different types of urban stakeholders could produce more insights concerning the value of aspirational visions of urban sustainability, for example those represented by metaphors, in framing the selection of indicators.

For the research on conceptual frameworks and indicators (Module 2), certain limitations can be mentioned related to the empirical sample that the analysis relied on. Since the sampling was

restricted to indicator initiatives whose documentation had to be available in certain languages (English, French, German, Italian or Spanish), the resulting picture on urban sustainability indicators in use may contain a geographical bias. This may be an issue especially when it comes to initiatives developed by local governments. The sampling was also restricted to initiatives published during the last decade (2010-2019), which meant that analysis of the evolution in practices over time was not possible. In other words, a different strategy for sampling could elaborate both on the temporal and geographical differences in emphases and gaps of coverage of different sustainability aspects, as well as in the use of conceptual frameworks.

When it comes to the research conducted at the level of indicators within Module 2, the method of assigning indicators to particular categories of the screening typologies (SDGs, STEEP and MONET) relied on the opinion of the four participating researchers, thus entailing certain limitations and inherent biases. However, these biases were countered through the negotiated and iterative process, which aimed to elevate the reliability of the analytical process and its results. Nevertheless, an interesting idea for the future would be to utilize large-scale crowdsourcing methods for this procedure, in order to better understand what meanings are attributed to different indicators not only by academics, but also by the general public.

Concerning the research on conceptual frameworks, since the analyzed sample was limited to applied initiatives dedicated to *indicators* of *urban* sustainability, certain possible framework types may have been missed. Therefore, to complete the palette of possible frameworks that future urban assessment developers can draw from, additional research could be directed to investigating a broader sample, including also non-urban initiatives as well as frameworks not originally developed for indicators.

The research of Module 3, which aimed to develop an approach for enhancing the salience of indicator-based sustainability assessments, relied on a single-case study, which means that its contributions may have limitations in their generalizability. However, when it comes to the kind of applied research of a complex real-world phenomenon that the work of Module 3 entailed, traditional representational generalizability (i.e., generalizing the findings as such from the studied case to all comparable cases) is in any case less pertinent as a quality criterion. Rather, what becomes more important is inferential generalizability, i.e., the transferability of the produced insights to other contexts (Lewis and Ritchie, 2003; Korstjens and Moser, 2018). The selected case study object (housing system of the City of Geneva) represents a typical case (Patton, 1990) of the kind of complex sustainability challenges faced by local urban governance around the world. Therefore, arguably, the insights of the study can indeed be transferred to other contexts.

Perhaps a more pertinent limitation of the research of Module 3 was that its scope did not include a final feedback round with the stakeholders (e.g., in the format of a workshop) to validate the value of the final conceptual framework used (Fig. 6-4) and the manner in which it was applied for the contextual embedding of indicators (Fig. 6-5). This shortcoming should be first on the agenda of future research for building on the work of this thesis. For the moment, the validity claim of the proposed approach for addressing the challenge of salience relies on the demonstrated argument that the output from using the approach indeed increases “the relevance of the assessment to the needs of decision makers” (Cash et al., 2003, p. 8086) by elaborating a more contextually rich picture around the assessed indicators.

Another limitation that can be mentioned in relation to the research of Module 3 concerns the proposed approach itself. That is, given the complex character of urban sustainability challenges, reaching sufficient depth in the contextual analysis to provide useful insights requires effort. In other words, the proposed method is time- and resource-consuming and may not therefore be suitable for all assessment applications.

Based on the insights produced by this thesis project, and its limitations discussed above, a proposal for a future research project can be put forward for further pursuing the objective of supporting the development of indicator-based assessments for urban governance. The idea is to build on the themes and contributions of this thesis through a case study that accompanies, throughout the different tasks involved, a participatory process of constructing an indicator-based assessment for a particular city. This comprehensive case study could address the following research avenues and questions:

1. The first research avenue concerns the integration of the three levels of interpretation – visions, frameworks and indicators – discussed in this thesis. This integration entails, first, a *vertical* component, whereby the three levels are tied together in a structure that explicitly displays how given visions (e.g., based on metaphors) connect to particular conceptual framings and categories, and on to particular indicators. In addition, the integration concerns a *horizontal* component, i.e., finding ways to relate to each other different parallel visions, parallel conceptual frameworks and categories, and (groups of) indicators. For example, such horizontal integration could use 'topic modeling' (Mohr and Bogdanov, 2013) or other network analysis methods to identify clusters of categories and/or indicators from existing assessments. The research question that captures this first research avenue for the future can be expressed as:
    - RQ: *How to integrate visions, frameworks and indicators of urban sustainability into a coherent assessment, while ensuring consistency and understandability across these three levels both vertically and horizontally?*

2. The second future research avenue relates to the level of visions of urban sustainability. In particular, the work should test using the ideas and tools produced in Module 1 of this thesis to engage a broad spectrum of urban stakeholders in discussion concerning possible visions of urban sustainability. Such broad participation could also produce more information about the value of metaphors as boundary objects in enabling stakeholders with different backgrounds to participate in such dialogue on visions. Thus, the pertinent research question to address is:
    - RQ: *How to involve a broad spectrum of urban stakeholders in discussions on guiding visions for urban sustainability assessments?*

3. The third research avenue within the proposed case study concerns analyzing further the value of enriching indicator-based assessments through the kind of controversy-based contextual analysis proposed in Module 3. In particular, the work should complete the step that was left missing in the research of this thesis, i.e., discussing the outputs of the assessment with relevant stakeholders. This would be important for the validation of the approach, and could also be used to develop more specific tools and processes for creating dialogue and learning around the challenges revealed by the indicators. In other words, the relevant research question is:

- RQ: *How can an in-depth, contextually sensitive analysis of indicators be leveraged for making assessments that facilitate both policymaking and broader learning and networking among stakeholders?*

4. The fourth possible research avenue would be to investigate the use of digital means for enhancing participation in the conduct of urban sustainability assessments. As has been discussed in this thesis, the construction of an assessment entails taking many decisions that have normative consequences. Therefore, to enhance the democratic character of the process as well as the local pertinence of the assessment, an expert-led assessment design could be complemented by inputs from crowdsourcing methods for different tasks, such as the formulation and selection of guiding visions, as well as the selection and association of particular indicators to those visions. The relevant research question could therefore be:
    - RQ: *How can digital technologies be used to enable the large-scale participation of urban citizens in the construction of pertinent sustainability assessments?*

5. The final interesting research avenue that can be put forward is to investigate methods for making indicator systems dynamic and modular, i.e., able to be periodically updated as the sustainability challenges of the city in question evolve, and as the pertinent goals, indicators and controversies evolve along with them. The point of this line of research would be to allow using the indicator system for making assessments on a regular basis, addressing the issues that are pertinent at any given time, but without having to reconstruct the indicator system anew for every assessment. For example, while the visions and goals may remain constant over longer periods of time, the indicators and metrics for expressing them may require updating. Likewise, although new visions and goals may emerge over time, it does not necessarily mean that they should supersede earlier visions, but rather be added to complement them. Based on this, an interesting research question for the future can be formulated as:
    - RQ: *How can urban sustainability indicator systems be made dynamic and modular, so that they can be used for making governance-relevant assessments continuously over time?*

8 Conclusion

This thesis was in the whole motivated by the need to find workable methodologies for integrating sustainability as a strategic principle into the governance of cities. In particular, the type of methodology at the center of attention for this thesis concerns indicator-based sustainability assessments, and the overarching objective was to contribute tools and insights for the reflexive design of such assessments in order to ensure that they are contextually appropriate and salient for local urban governance. The need for knowledge in this area is urgent, as operationalizing urban sustainability in all its complexity into assessments is not a trivial matter, and guidelines for assisting their development are lacking in important respects. In fact, the validity of this concern was supported by the analysis of current practice performed within this thesis, as the results showed that the indicator initiatives often contained omissions of important aspects of urban sustainability.

The first contribution of this thesis is to elaborate on the idea of visions, which can provide both aspirational images for formulating goals and targets for the assessment, but also provide clues for how different stakeholders see the city to begin with. Therefore, engaging with such visions in the context of sustainability assessments is important for creating dialogue and for infusing the assessment with meaning, and the work of this thesis provides tools and ideas for doing it in practice. Secondly, drawing from a critical review of the indicators and conceptual frameworks used in indicator-based urban assessments, the thesis elaborated both on the options available for the design of such assessments, as well as on the critical areas where future initiatives can improve compared to current practice. In other words, the work contributes to reflexive practices in the construction of these assessments. Furthermore, the thesis contributes to knowledge concerning means for increasing the salience of indicator-based assessments for governance, a requirement that has been largely neglected in scholarship. To that end, the thesis proposes as a solution to systematically embed the assessed indicators into their contexts, thereby closing the gap between the knowledge provided by the assessment and the complex real-world challenges faced by the stakeholders of the assessed problem. To build on these contributions and insights of this thesis, an important potential future research avenue would be to investigate putting these ideas into practice in a comprehensive participatory case study that follows the construction of an indicator-based assessment for a given city.

Three transversal themes provide the backbone of this thesis. First, the construction of urban sustainability assessments concerns also the construction of the meaning of urban sustainability. Therefore, the structured and deliberative design of assessments, engaging with the three levels of interpretation considered in this thesis, is an opportunity to create explicit and shared understanding about the meaning of the concept, even if that meaning is essentially evolving over time. Second, the thesis underlines the requirement of reflexivity in the choices made along the design process of an assessment. This is imperative not only for the coherence of the resulting design, but also so that the assessment appropriately addresses the complex and contextually specific character of urban sustainability. Finally, the thesis promotes the point of view to sustainability assessments that sees them not merely as technical and managerial exercises concerned primarily with data and metrics, but as occasions for constructing meaningful stories around the challenge of sustainability that, on the one hand, anchor concrete indicators and facts to deeper visions, and on the other hand, connect these indicators to the everyday challenges of the relevant stakeholders.

To conclude, in general this thesis champions the perspective that for our societies to move forward towards some form of sustainability, more meaning and more motivating aspirations need to be attached to the concept. As Jasanoff states, “environmental knowledge achieves robustness through continual interaction, or conversation, between fact-finding and meaning-making” (2010, p. 248). The (currently underused) potential of sustainability assessment methodologies lies precisely in facilitating a connection between hard facts and the meanings and contextual lived experiences of people, thereby inspiring learning, networking and action towards sustainability. In addition, sustainability assessment procedures can contribute to a positive framing of sustainability that expresses it not only in terms of restrictions and limitations, but as an opportunity for achieving long-term improvements in our quality of life. Specifically in the case of urban sustainability, they can also help to see cities not only as problems to be solved, but as possible contributors to the global sustainability efforts ahead.

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Part II : Manuscripts

Manuscript 1

Reference:

Halla, P., Wyss, R., Binder, C.R., 2020. Conceptualizing Urban Systems for Sustainability Assessment: Four Powerful Metaphors, in: Binder, C.R., Wyss, R., Massaro, E. (Eds.), Sustainability Assessment of Urban Systems. Cambridge University Press, Cambridge, pp. 241–260. https://doi.org/10.1017/9781108574334.012

Contributions of the doctoral candidate:

The doctoral candidate designed and conceptualized the research, performed the analysis with the two co-authors, and was responsible for the preparation of the manuscript.

10 Conceptualising urban systems for sustainability assessment – four powerful metaphors

10.1 Introduction

Urban systems are assuming an increasingly central significance in the global sustainability challenge. As hubs of social, scientific, and economic activities, cities possess the potential for facilitating transitions towards sustainable ways of living. Therefore, tools like sustainability assessment are needed to help decision-makers unleash this positive potential of cities, while also limiting the negative impacts on their residents and environments. A major challenge, with implications across different aspects of sustainability assessment, concerns the conceptualisation of the objects relevant for the assessment. Specifically, in the case of assessing the sustainability of urban systems, the problem of conceptualisation involves identifying the constituent parts of the urban system and the necessary aspects of its sustainability. Conceptualisation constitutes a crucial step in the assessment process, since it is directly related to the selection of appropriate measurement tools and indicators, and to the definition of the goals and criteria for the evaluation. Conceptualisation also influences procedural choices by defining who should be involved in the assessment process.

Grounding sustainability assessments in explicit and structured conceptual frameworks or models is an important requirement for these to be comprehensive and transparent. Given the multitude of possible conceptualisations of urban systems, however, it also becomes necessary to develop procedures for analysing and comparing different approaches in terms of their relative emphases, strengths, and weaknesses. The idea put forward in this chapter is to base such analysis on a number of descriptive metaphors for cities (machine, organism, network, and melting pot), each conjuring up an intuitive mental image, and each accentuating different aspects of the urban system. The purpose of this exercise is to enhance reflexivity with regard to the underlying implicit visions of what an urban system is (or what it is supposed to be), and thereby, to cast light on the fundamental contrasts and contradictions present in conceptualising, measuring, and assessing cities.

The chapter is structured as follows. First, Section 10.2 elaborates on the challenge of conceptualising urban systems and introduces the idea of different metaphors for cities. Section 10.3 then proceeds to characterise the metaphors across different system-theory concepts with the purpose of making explicit the distinct meanings of each metaphor. Section 10.4 consolidates the analysis of the metaphors into a discussion of their implications for sustainability assessment. Section 10.5 finishes the chapter with condensed conclusions.

10.2 Conceptualising Urban Systems

10.2.1 Conceptualisation Frameworks

The use of conceptual frameworks is a central principle of sustainability assessment (Pintér, Hardi, Martinuzzi, & Hall, 2012). Perhaps the most famous conceptual framework used in sustainability assessments builds on the idea of the three pillars of sustainability (Pope, Bond, Hugé, & Morrison-Saunders, 2017) – economy, society, environment – sometimes augmented by a fourth domain of sustainability covering institutional and governance aspects (James, 2015; Shen, Jorge Ochoa, Shah, & Zhang, 2011; Turcu, 2013). Despite the ostensible ubiquity of the ‘three pillars’ thinking, a great number of frameworks exist that itemise in different – and often more refined – manners the different

objects, structures, and dimensions of sustainability to be considered in assessments. Examples of such frameworks can be found in both academic literature (e.g. Bossel, 1999; Meadows, 1998) and in the stated approaches of different institutional actors (e.g. ISO, 2014; World Bank, 2018). Maclaren's (1996) typology of frameworks, illustrated in Figure 1, captures the variety of frameworks used in the assessment of urban systems. In the typology, domain-based frameworks (e.g., the three pillars model) are joined by four other types of frameworks that each deconstruct urban systems along different categorisations (sectors, issues, goals, or causally related categories). In practice, few frameworks in use fall strictly within any of the first five types. Rather, most frameworks are of the sixth, combined type.

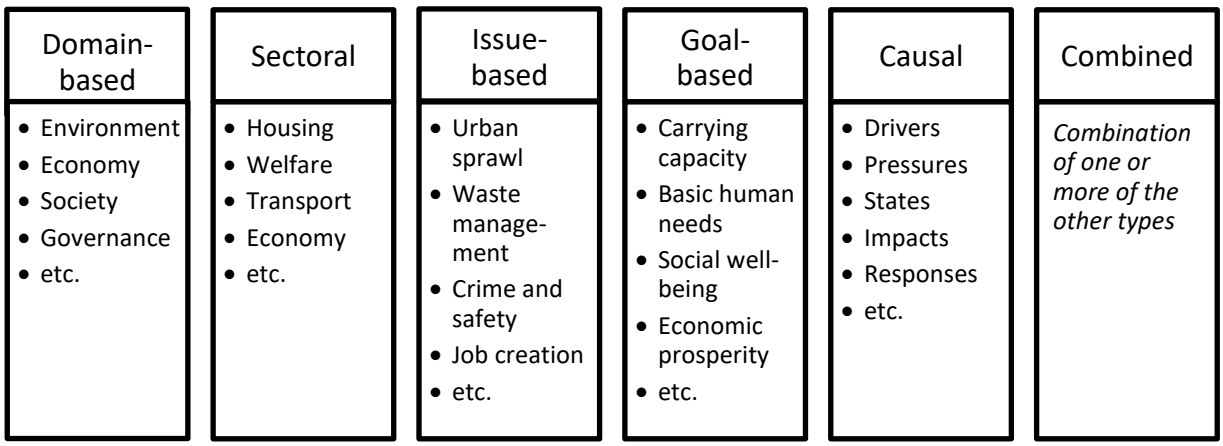

Figure 10.1: A typology of frameworks for sustainability assessment, adapted from (Maclaren, 1996).

Proceeding from an explicit conceptualisation of the assessment problem helps to enhance comprehensiveness with regard to covering the necessary aspects of sustainability when selecting the pertinent assessment tools and indicators (Griggs et al., 2013; Hák, Janoušková, & Moldan, 2016). If this conceptual framing is absent, there is a danger that important choices in the sustainability assessment process will end up being made in an arbitrary fashion, or will be biased by the simple availability of measurement tools or data. Indeed, one of the benefits of the conscious development of a framework is that it can point to areas and aspects of sustainability that have been hitherto under-appreciated, and thereby reveal the need for the development of new indicators or other measurement tools. In terms of participation, the use of a conceptual framework assists in the identification of stakeholders whose input to the assessment should be considered. The benefits of using a clear framework extend also beyond the assessment itself by better enabling the clear communication and interpretation of the assessment results.

10.2.2. The Requirement for Reflexivity and Transparency

As illustrated by the typology in Figure 1, when it comes to conceptualising urban systems, several potentially legitimate descriptions of the system exist in parallel, with each description dissecting the system along a different set of axes and categories (Cilliers, 2008; Wells, 2012). At the same time, each of these descriptions unavoidably also represents a simplification of the true extent of the complexity involved. Here, it is important to acknowledge that the simplification, by virtue of emphasising different aspects of the system as more or less important, also establishes a normative position that privileges certain values and interests over others (Gasparatos, 2010). To paraphrase Meadows (1998), these choices are a reflection of what we care about the most, but also, inversely, what is included in

our conceptual descriptions (and what is not included) ends up shaping our sense of what is important. These normative implications bring forth the requirement for reflexivity and transparency with regard to the relative emphases, strengths, and weaknesses of different conceptualisations of cities, as well as the ensuing implications for different aspects of sustainability assessment.

The use of a structured conceptual framework, like those proposed in the typology in Figure 1, is a necessary first step for addressing this requirement. It allows for the comparison of different approaches in terms of their relative emphases across different aspects and categories of the urban system. However, conceptualisation entails more than merely selecting a type of conceptual framework (such as one of the types described in Figure 1) and then populating the framework with a list of categories. Rather, it extends to deeper visions about the nature of urban systems and their sustainability. Therefore, to more fully address the challenge of reflexivity and transparency in assessing urban systems, it is necessary to develop analytical tools that can render visible and make comparable these deeper visions. Essentially, the relevant question is: What is it that we think cities are when we assess them?

Our proposal for an analytical tool that can answer the above question is based on the idea of cities as quintessential complex systems (Bettencourt, 2015; de Roo, Hillier, & van Wezemael, 2012; Portugali, 2016). As de Roo et al. argue, when it comes to complex systems the traditional 'analysis-synthesis' approach to creating knowledge needs to be complemented with a mechanism of 'association-creativity'. This mechanism refers to looking beyond the individual elements of a complex system to its interconnections and processes, and thereby, to the purposes and meanings of the system as a whole. In this task, the use of associative metaphors provides an indispensable source of creativity and inspiration for recognising themes and patterns in complex systems (Hodgson, 1997; Pickett, Cadenasso, & Grove, 2004). Indeed, the creative use of metaphors also permeates our language of cities, and various metaphorical images of cities with contrasting connotations have attained prominence at different points in history (Bettencourt, 2015; Lynch, 1984). Today, as Nientied's (2016) review shows, the number of city metaphors has proliferated, each drawing attention to specific aspects of the city. As Bettencourt puts it, 'the city is all of these things, of course, but none of them in particular' (2015, p. 219).

The idea of contrasting metaphorical images of cities presents an interesting access point into how the challenge of reflexivity and transparency in conceptualising and assessing urban systems can be addressed. In particular, considering and comparing common metaphors of cities can clarify different points of view with regard to what it is that we assume cities fundamentally are – as well as what they should be. Following this line of reasoning, the goal of the rest of this chapter is to single out a number of parallel metaphors of cities and to systematically clarify what each of them suggests about the nature of urban systems, their sustainability, and the processes by which they should be assessed.

10.2.3 Scientific Perspectives on Cities – The Three Cultures

In order to identify an adequately broad and representative selection of metaphors of cities for our analysis, it is necessary to create an overview of different scientific perspectives to cities. The idea is that underlying these perspectives are different metaphorical images which inspire their particular foci and methods for researching and making sense of the complexity of cities. The history of studying cities reaches back at least to Georg Simmel's The Metropolis and Mental Life from 1903, where he discussed

the effects of urban life on social organisation and human psychology. During the twentieth century, several scientific disciplines developed an interest in cities, some treating them as special settings of social life and others as intriguing objects of analysis in their own right. To map this varied body of research, Portugali (2011) evokes C.P. Snow's (1964) famous observation of the two opposing cultures in science, and correspondingly divides perspectives on cities into two contrasting cultures. Albeit fairly rough, this dual distinction is a good point of departure for creating an overview of the existing scholarship on cities to date.

The 'first culture of cities', according to Portugali, is inspired by the hard sciences, thus tending towards positivist and quantitative research. This culture was particularly dominant in urban research in the 1950s and 1960s. Famous early theories within this general approach include location theory, whose roots go all the way back to von Thünen's 1826 work The Isolated State (1826/1966), Auerbach's (1913) rank-size distribution theory of cities, and Christaller's (1933/1966) and Lösch's (1954) central place theories. Furthermore, Portugali assigns the Chicago school of urban sociology (e.g. Park, Burgess, & McKenzie, 1925) to the first culture of cities. Scholars associated with the Chicago school adopted the idea of cities as ecological systems comparable to natural systems, and although they originally approached the subject matter from a different perspective from that of the other scholars mentioned above, they also ended up describing cities by means of morphological models with specialised sectors or concentric zones. Overall, then, the conceptualisation of cities advanced by the first culture implies that ‘the number of their parts is relatively small, they are connected (or rather assumed to be connected) by well-defined rules and causal relations and as such these cities are assumed to be fully predictable’ (Portugali, 2011, p. 38).

The 'second culture of cities', as Portugali defines it, consists of approaches inspired by social theory and philosophy. This culture became particularly prominent in the 1970s and directly criticised the earlier positivistic and quantitative approaches to cities as simplistic and socially problematic. Early examples based on structuralist and Marxist theories include works such as Lefebvre's Right to the City (1968), Castells' The Urban Question (1972), and Harvey's Social Justice and the City (1973). As the titles of these works suggest, a central theme of the second culture of cities has always been an ideological critique of the modern capitalist mode of social organisation. Heading into 1980s, a strand of the second culture of cities became influenced by postmodern social theory, and began to emphasise the ever-evolving, relational, and contingent nature of cities, as in Soja's Postmodern Geographies (1989) and Castells' The Rise of the Network Society (1996).

In addition to these two paradigmatic cultures, Portugali argues, a possible third culture of cities has been brewing. Forerunners of this perspective, such as Jane Jacobs (1961) and Christopher Alexander (1965), echoed the second culture of cities in terms of the criticism of the relatively simple models and methods of the first culture. However, instead of social or ideological reasons, their criticism was rooted in a conceptualisation of cities as fundamentally complex systems with emergent properties and dynamics of self-organisation. Since then, a field of complexity science focusing on cities has emerged, applying formal complexity theories that originated in physics and biology, resulting in conceptualisations of cities as, for example, dissipative (Allen & Sanglier, 1981), fractal (Batty & Longley, 1994), and self-organising (Portugali, 1997) systems. Parallel to these formalised approaches to complexity, social science theories of cities have also picked up the vocabulary of complexity science, but applyied them in a qualitative sense. In this context, for example, theories of cities based on the concept of an 'assemblage' have gained traction (Blok & Farias, 2016; de Roo et al., 2012).

As Portugali argues, these complexity-science-based approaches to cities have the potential to form a third culture of cities that acts as a bridge between the two earlier cultures. This is due to the nature of complexity as a paradigm that, on the one hand, lends itself to quantification and computational methods, but that also has an affinity with strands of the postmodernism-influenced social science theory in the second culture of cities (Cilliers, 1998). To act in this bridging function, however, the field would need to acknowledge the nature of cities as particular kinds of (socially) complex systems. Therefore, instead of merely transferring the theories and quantitative methods used for studying natural complex entities to the domain of urban studies, there is a need to explicitly engage with qualitative questions related to cities and complexity. Otherwise, the complexity science approach to cities risks being merely an updated version of the first culture of cities.

10.2.4. Four Selected Metaphors for Cities

As is obvious from the brief review above, the city as an object of research can be approached from a broad variety of scientific perspectives that can be decidedly contrasting or even antagonistic towards each other. However, rather than being a problem, this is merely a reflection of the complex nature of cities. What is more, although the presentation above of the three cultures of cities places them in chronological order, this should not be taken to mean that one culture has been supplanted or made obsolete by the appearance of another one. Instead, each culture adds depth to our understanding of cities and to the vocabulary we use to describe them. Indeed, all three cultures, as well as the metaphorical images influencing them, are very much alive today both in science and in practice. Therefore, our selection of a set of metaphors for describing cities needs to be representative of the breadth of all the three cultures.

A challenge stemming from this breadth of scientific perspectives on cities is that the number of related metaphors is equally large (Nientied, 2016). For practical reasons, however, only a limited number of metaphors could be selected for our analysis. Therefore, instead of discussing every potential city metaphor, we decided to try to identify a small number of 'proto-metaphors' that could represent to an adequate degree the variety of existing approaches to cities. In the selection of the most pertinent metaphors, three criteria in particular were employed. First, the metaphors had to be clearly distinguishable from each other. Second, the selected metaphors had to be complementary to each other in providing different vantage points on cities. Third, the selected metaphorical concepts had to be intuitively familiar and simple. The last criterion was followed in order to enable the analysis of the metaphors (see description of the analytical process in the following section) and in order to allow the reader to follow the logic of the discussion without a deeper knowledge of the origin of the related concepts.

These considerations led us to ultimately select four metaphors: machine, organism, network, and melting pot. To be clear, these four ‘proto-metaphors’ are to be considered as 'ideal types', in the sense introduced by Max Weber (Månson, 2000). Here, 'ideal' does not imply any normative ranking (as in 'better' or 'worse'). Instead, it refers to the deliberately exaggerated accentuation of chosen aspects of complex phenomena in order to create prototypes against which real instances of the phenomena can be compared.

Definitions for the four terms, as found in the Oxford Dictionary (2019), are presented in Table 10.1. Two definitions are presented for each term, one representing a literal meaning and another

representing a metaphorical meaning. In addition, the associations between the three cultures of cities and the four metaphorical perspectives are depicted in Figure 10.2. The four approaches to cities are introduced below in more detail.

Table 10.1: Oxford Dictionary (2019) definitions of the metaphorical concepts.

Metaphor	Definition
Machine	An apparatus using mechanical power and having several parts, each with a definite function and together performing a particular task; An efficient and well-organized group of powerful people.
Organism	An individual animal, plant, or single-celled life form; A system or organization consisting of interdependent parts, compared to a living being.
Network	An arrangement of intersecting horizontal and vertical lines; A group or system of interconnected people or things.
Melting pot	A pot in which metals or other materials are melted and mixed; A place where different peoples, styles, theories, etc. are mixed together.

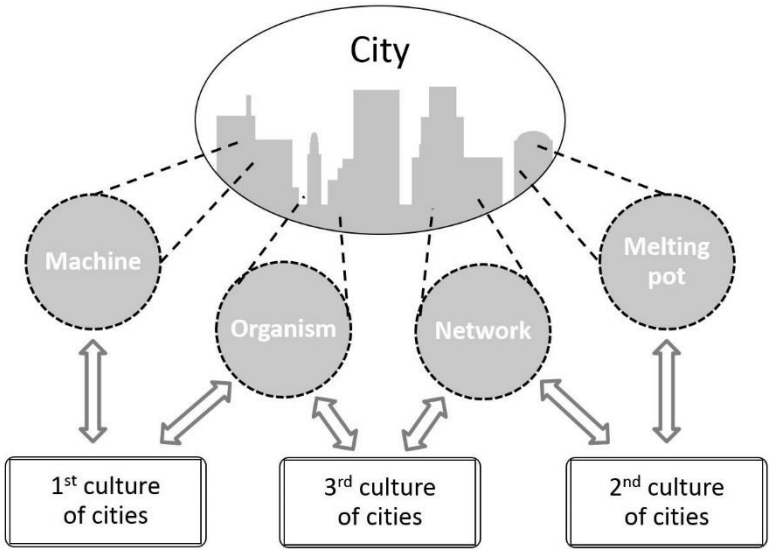

Figure 10.2: The three cultures of cities connected to the four metaphorical perspectives.

It must be noted that, strictly speaking, a network, instead of being a *metaphor*,[32] should be considered as a *metonym*[33] for the city. Depending on the source, metonymy is considered to be either a type of metaphor, or an altogether different concept (Fass, 1988). While acknowledging the difference between the terms, for the sake of fluency in the following discussion, the term metaphor is also used to designate the network approach to cities.

[32] Metaphor is defined as a 'figure of speech in which a word or phrase literally denoting one kind of object or idea is used in place of another to suggest a likeness or analogy between them' (Merriam-Webster, 2019).
[33] Metonymy is defined as a 'figure of speech consisting of the use of the name of one thing for that of another of which it is an attribute or with which it is associated' (Merriam-Webster, 2019).

The *machine* metaphor is associated with the first culture of cities. It represents the modernist ideal of solving the challenges associated with cities through rational and centralised urban planning (Lynch, 1984). A prominent example of this approach to cities is Le Corbusier's planned city *Ville Radieuse*, which sought to achieve optimisation through strict functional zoning. In *Good City Form,* Kevin Lynch argues that 'the machine model lies at the root of most of our current ways of dealing with cities: our practices of land subdivision, traffic engineering, utilities, health and building codes, zoning' (Lynch, 1984, p. 86). Lynch made his argument more than 30 years ago, and indeed, since then, the dominance of the machine view has been challenged by perspectives derived from the second and third cultures of cities. However, the image of cities as machines continues to wield influence both in science and in practice. For example, contemporary (perhaps subtler) embodiments of the machine metaphor can be detected in the popular ideas of 'smart' or 'computable' cities (Angelidou, 2015; Batty, 1997).

Another metaphorical view with a long history is that of the city as an *organism*, which underlines the living character of cities (Lynch, 1984). This metaphor can be associated with both the first and third cultures of cities, because, on the one hand, it implies that cities can be studied with the methods of natural science, but on the other hand, also acknowledges that cities are more complex than mere machines. This perspective gained popularity originally as a reaction to the heavy industrialisation of the nineteenth Century. A classic example of the organic view of cities is the Garden City movement of Ebenezer Howard. Today, the organic metaphor is prominent in, for example, initiatives for 'greening' cities, as well as in several scientific fields studying cities, including industrial ecology (Lifset & Graedel, 2002), urban ecology (McDonnell, 2011), and parts of complexity science (Bettencourt, Lobo, Helbing, Kühnert, & West, 2007).

The *network* view of cities has gained popularity more recently, and is associated with both the second and third cultures of cities. Alexander's (1965) thesis stating that a city is not a tree, but a semi-lattice structure, was a predecessor to this viewpoint. A couple of decades later, the network metaphor was forced into the centre of public imagination by the advance of globalisation and especially by the astonishing expansion of telecommunication networks in the 1980s and 1990s. Now, it is commonplace to conceptualise cities in terms of agglomerations of social, economic, and infrastructural connections that link places into networks that span both local and global scales. Scientific fields utilising the network metaphor include complexity science (Batty, 2013; Bettencourt, 2015) and several strands of social science (Blok & Farias, 2016; Castells, 1996; Granovetter, 1973).

Finally, the metaphor of a city as a *melting pot* corresponds to the second culture of cities. The idea owes its origin to American cities that, especially in earlier times, were recipients of waves of immigration, and thereby hotbeds of multiculturalism. Although the metaphor is still commonly used, to some it is problematic as it connotes a more or less forced conformity with the dominant culture. Due to this, the melting pot metaphor is sometimes replaced with metaphors of the city as a kaleidoscope, a mosaic, or a salad bowl, which explicitly refer to a continuous co-existence of heterogeneous social groups and cultures (Fuchs, 1995; Hirschman, 1983; Kolb, 2009). Nevertheless, the issues that the melting pot metaphor raises, especially seeing the city as a site of intermingling and sometimes conflicting cultures and social groups, continue to be at the centre of much of urban studies, including critical urban studies (Harvey, 2003) and urban political ecology (Heynen, Kaika, & Swyngedouw, 2006).

Table 2 presents a summary of the scientific fields, theories, and concepts that have been mentioned in the discussion, categorised under the umbrellas of the four metaphors. This list is by no means exhaustive, but represents an illustrative sample. In addition, as the four metaphorical perspectives represent ideal types, the categorisation of the scientific fields and theories under a single metaphor is a simplification of their real nature. Nevertheless, the examples listed in the table are chosen because they are the ones that we perceive as being the closest representatives of the corresponding metaphorical perspectives.

Table 10.2: Illustrative examples of scientific fields and theories for the four metaphors.

Metaphor	**Machine**	**Organism**	**Network**	**Melting pot**
Related culture of cities	1st	1st + 3rd	2nd + 3rd	2nd
Related scientific fields	• Physics • Economics	• Urban ecology • Industrial ecology	• Complex systems science • Economic sociology • Postmodern social science	• Critical social science • Urban political ecology
Related theories and concepts	• Location theory • Scaling laws	• Socioecological systems • Socio-technical systems • Urban metabolism	• (Social) network theory • Complexity theory • Assemblage theory	• Marxist theory • Feminist theory

10.3 Analysing the Selected Metaphors

10.3.1 Analytical Procedure

To facilitate a deeper understanding of the four approaches to cities, we devised an analytical framework consisting of system theory concepts that describe different aspects of a system (Bossel, 1999; Hester & Adams, 2017; see also Chapter 2 of this book). Table 3 lists these aspects and presents their definitions as they were understood within the context of this chapter. Eleven system aspects were considered in total, and grouped under four themes. Then, we characterised each metaphor across these eleven aspects. The analysis was performed through a collective discussion among the authors, with the ambition of capturing the characteristics of each metaphorical system in as few words as possible, and as clearly distinct from the other metaphors as possible. The results of this analysis are presented in Table 4 and discussed separately for each metaphor below. After the characterisation of the metaphorical systems, our analysis proceeded to derive the implications that each approach has for assessing the sustainability of urban systems. These implications cover four dimensions of sustainability assessment: (i) the purpose of sustainability assessment; (ii) the participants and their roles; (iii) the underlying principles of sustainability; (iv) the conceptual system model guiding indicator selection.

To repeat a point made above, the purpose of this analytical strategy is to consider the four metaphorical perspectives as 'ideal types' that facilitate the analysis and comparison of real-life cases. As such, these ideal types are not expected to have perfectly matching counterparts in real-life cases, and therefore, are not meant as a typology for a strict classification of these cases. Rather, the four ideal-typical approaches to urban systems, and the corresponding four ideal-typical sustainability assessment designs that are discussed below, act as an analytical framework for detecting tendencies, similarities, and differences in real-life cases of approaches to urban systems and their assessment.

Table 10.3: The system aspects and their definitions used in characterising the metaphors.

System aspects	Definition	Theme
Boundary	Describes the delimiting of the system in space and time, thus marking what is inside and what is outside.	Delimiting the system
Environment	Describes the system's relationship to its surroundings.	
Inputs/outputs	Describes what enters and exits the system across the system boundary.	
Purposes	Describes the overarching goal(s) towards which the behaviour of the system is oriented.	Understanding the system
Functions	Describes the activities performed by the system in serving its purpose.	
Elements	Describes the constitutive parts of the system.	Analysing the system
Organisation	Describes the patterns and interrelations of the system's constituent elements.	
Dynamics	Describes the typical modes of changes in and of the system.	
Monitoring	Describes the typical objects and variables to be monitored for the governance of the system.	Governing the system
Information	Describes the types of data to be collected and knowledge to be produced (epistemology) about the system.	
Decision-making	Describes the typical character and goals of the steering processes of the system.	

Table 10.4: The proposed characteristics of the four metaphors.

System aspects	Machine	Organism	Network	Melting pot
Boundary	Administrative	Functional	Arbitrary	Spatial and cultural
Environment	Decoupled	Rooted	Inseparable	Receptive
Inputs/outputs	In: materials and energy; Out: products	In: materials and energy; Out: secondary resources	In and out: everything	In: people, ideas, cultures; Out: innovation
Purposes	Satisfaction of practical needs	Survival and reproduction	Creating and maintaining associations	Coalescence and creation
Functions	Production	Metabolism	Transmission and movement	Assembly and mixing
Elements	Artificial and tangible materials and components	Natural and artificial; tangible materials and organs	Connections and nodes – artificial and natural; tangible and intangible	Intangible and tangible human constructs and processes
Organisation	Hierarchical, designed, static, and clear units	Hierarchical structures; spontaneously but slowly evolving units	Ad hoc hierarchies; emerging and dynamic units	Formal and informal hierarchies; dynamic units
Dynamics	Linear and predictable	Evolutionary and homeostatic	Non-linear and non-causal	Unpredictable and discontinuous
Monitoring	Objects: inputs and outputs; Criteria: efficiency	Objects: organ functions; Criteria: health and resilience	Objects: networks; Criteria: connectivity and distances	Objects: social interactions; Criteria: harmony, equity, and innovation
Information	Objective quantitative data; general laws	Objective quantitative and qualitative data; general principles	Statistics, big data; correlations, predictions	Qualitative and quantitative data; heuristics, theory
Decision-making	Mode: top-down control; Aim: process optimisation	Mode: top-down influence; Aim: learning, adaptation and remediation	Mode: modular and experimental governance; Aim: reactive self-organisation	Mode: top-down rules and bottom-up norms; Aim: conflict resolution and harmonious self-organisation

10.3.2 The City as a Machine

Interpretation of the metaphor – Likening an urban system to a machine portrays it as a clearly delineated unit, discrete from its surroundings. The inputs fed into the system are transformed into outputs through internal processes that can be expressed in mathematical production functions. In fact, the very meaning of the system can be expressed in clear instrumental terms: it is the satisfaction of well-defined needs by the deliberate use of the aforementioned production functions. The machine metaphor also emphasises the tangible and human-made elements of the system and expects that they are organised into relatively clear-cut, static, and hierarchical structures. This suggests that the system behaves in a linear and predictable manner. Thus, taking this perspective represents the ambition to tame complexity into manageable problems to be tackled in a top-down manner and with the tools and theories of natural sciences and economics.

Strengths and weaknesses of the metaphor – The merit of this perspective is that it urges us to systematically search for regularities in the behaviour of the system as well as for rational explanations for these behaviours. In this way, the knowledge that is produced is more palatable to decision-makers, as it translates complex information about the system into more actionable generalisations. The weakness of the perspective derives from its tendency to drastically simplify the system. In this simplification, elements of the system (including human beings) are placed in strict categories that may be inappropriate. Also, the focus is biased towards *currently* existing (or dominant) structures and functions at the expense of ones that are yet non-existing (or subordinate). Perhaps the most serious danger with the machine metaphor is that it implicitly places power over the system in the hands of an all-knowing expert, while understating the variety of values and preferences present in urban systems.

Archetypal design for sustainability assessment – Following the logic of the machine metaphor, the *purpose of sustainability assessment* is to facilitate the optimisation of the production processes of the system. The knowledge produced by the assessment is translated directly into decisions, which are executed in a top-down fashion. *Participants* are selected and involved in the assessment process based on their utility in providing information or in implementing the decisions that are taken. The selection of participants is also limited to stakeholders within the system. The machine metaphor postulates that the predominant *principle of sustainability* is efficiency, and the goals and criteria for the assessment are interpreted accordingly in terms of the efficiency of the production processes and the satisfaction of existing practical needs. The *system model* guiding the selection of relevant indicators consists of internal production processes and the related input-output relationships. The focus is on tangible and objectively measurable elements and variables. The boundary for the system is drawn along administrative lines.

10.3.3 The City as an Organism

Interpretation of the metaphor – Contemplating the urban system through the metaphor of an organism frames it as a discrete unit, but, compared to the machine metaphor, one that is more connected to and influenced by its surroundings. The system consumes its inputs in metabolic functions and discharges leftover products into its surroundings. The metabolic functions serve the system's ultimate purpose: survival and reproduction. The organism metaphor focuses on both human-made and natural elements within the system. These elements are grouped into differentiated

but interdependent organs, which in turn are organised hierarchically and following a functional rationality. The system evolves steadily along homeostatic, self-regulating pathways. Compared to the machine metaphor, the organism metaphor thus retains a higher level of complexity. In science, these ideas are translated into the analysis of cities' metabolic flows, and into theories of cities as integrated socio-ecological-technical systems.

Strengths and weaknesses of the metaphor – The strength of the organism metaphor is that it reminds us that cities are interlinked human and natural systems. Changing the emphasis from immediate efficiency (as in the machine metaphor) to survival expands the time horizon from short-term to long-term thinking, and also brings into focus the system's impacts on its surroundings. In terms of shortcomings, although the organism metaphor does convey a more variegated and nuanced image of the city than the machine metaphor, like the latter, it also assumes a relatively small number of essential, static functions and purposes for the system. Normatively, then, aspects of the urban system that do not instrumentally contribute to these predefined functions are (at least implicitly) considered as undesirable and redundant. Again, considering the diversity of people in urban systems, such a view may have problematic practical and ethical consequences.

Archetypal design for sustainability assessment – The organism metaphor suggests that the *purpose of sustainability assessment* is to learn about the functional health of the different organs of the system, and to use the information to understand the areas where adaptations and remediation are necessary. The resulting decisions are implemented with consideration of possible systemic interdependencies and feedbacks. *Participant* selection for the assessment is based on decision-making authority and substantive expertise. This also includes representatives of stakeholders affected by the external impacts of the system. The central *principles of sustainability* promoted by the organism perspective are health and resilience, which form the criteria for evaluating the metabolic socioecological processes of the urban system. The boundary of the *system model* is drawn along functional lines (containing sources and sinks), and the model consists of distinct but interrelated functions and organs. The focus is thus particularly on indicators that represent tangible elements and variables.

10.3.4 The City as a Network

Interpretation of the metaphor – The network perspective integrates the urban system into its surroundings to such an extent that delineating the boundary of the system becomes a matter of arbitrary, ad hoc choice. The system is fully open to receiving any inputs, and indeed, the creation and maintenance of connections both locally and globally forms the central purpose of the system. The functions of the system deal primarily with the transmission and transport of all types of things (people, information, materials, etc.). That is, the focus covers human-made and natural, and tangible and intangible elements of the system. In terms of structural units of the system, the network image depicts the system as consisting of connected nodes, where the connections between nodes sometimes take on a greater importance than the nodes themselves. In its default state, the system displays an extremely flat hierarchy, from which more organised units may emerge on an ad hoc basis. The dynamics of the system are therefore more driven by self-organisation than top-down planning. Predicting the behaviour of the system depends on statistical analyses, while attributing causality becomes nearly impossible due to the presence of many feedbacks. Scientific theories and methods proceeding from the network metaphor deliberately embrace the complexity of the system and resist the urge to present it in neatly organised static models.

Strengths and weaknesses of the metaphor – Of the four perspectives under comparison here, the network perspective has the most dynamic image of systems. Consequently, the strength of this perspective is that it pushes for the development of theories and methods that are sophisticated enough to take on the full extent of the complexity of real-world urban systems. The metaphor can also be seen as beneficial from a democratic point of view, as it promotes a non-hierarchical, self-organising form of social organisation over top-down command. At the same time, the image can be criticised as naive, as it turns a blind eye to the inevitable existence of structural power differences and hierarchies within societies. In this way, analyses based on the network perspective sometimes remain superficial in their focus on overt data and their neglect of the causes of the observed phenomena.

Archetypal design for sustainability assessment – Taking the network approach, the *purpose of sustainability assessment* is to provide information for the self-organising processes of the system. Therefore, the results of the assessment are disseminated to the system without decisions being implemented in any centralised fashion. The process is open to *participants*, who are determined based on voluntary interest and social connections. The *principles of sustainability* that inform the goals and criteria of the assessment relate to the connectivity of the system and the quality of the connections. The *system model* consists of a wide range of interconnected processes. The indicator list which is drawn from this model is built up of statistical measures of connections and flows. Because of the characteristic ad hoc nature of the system's boundary, the system model has to be tailored for each assessment according to the particular needs and mandate of the assessment in question.

10.3.5 The City as a Melting Pot

Interpretation of the metaphor – The metaphor of the melting pot stresses the social complexity that is present in urban systems. In this case, the system boundary is determined by the reach of social interactions, which are confined culturally and spatially. The functions of the melting pot bring together and mix different people, ideas, and cultures, and they constantly receive fresh inputs from the outside. The purpose of the system is to facilitate the co-existence and cross-pollination of these varied elements, thereby also enabling the creation of innovations and transformations of varying degrees. The metaphor pays most attention to elements related to the human world, with these elements organised into formal and informal hierarchies that change with varying speeds. The dynamics implied by the melting pot metaphor are unpredictable and discontinuous, as competing tendencies towards homogeneity and heterogeneity, as well as towards harmony and disharmony, exist simultaneously. These aspects of the urban system are typically researched with the help of theories and methods belonging to the fields of social, economic, and political sciences.

Strengths and weaknesses of the metaphor – The strength of the melting pot metaphor over the previous metaphors derives from its close attention to phenomena that are distinct to the social world. These include processes of innovation and social renewal, but also cultural and economic conflict. This sensitivity towards social complexity causes the perspective to tend towards inclusiveness and openness to pluralistic viewpoints. A weakness of the perspective relates to its anthropocentrism, as, arguably, the pure focus on social issues and interactions within urban systems tends towards a disregard of the material realities beyond the social sphere, such as the environmental effects of urban lifestyles. Also, as discussed above, depending on the specific interpretation given to the metaphor, it may be taken in some cases to gloss over the potential difficulties faced by marginalised groups when

'melted' together with more hegemonic cultures and social groups. Therefore, when deploying the melting pot metaphor, an awareness of issues related to power is essential.

Archetypal design for sustainability assessment – From the point of view of the melting pot metaphor, the *purpose of sustainability assessment* is facilitating the detection and resolution of social conflict, as well as the promotion of mutual understanding and interaction among the inhabitants of a city. Accordingly, the process aims for broad *participation*, with stakeholders engaged from both the local government and from various community groups. The implementation of the findings of the assessment consists simultaneously of policymaking and community-based action. The melting pot metaphor implies the need to maximise the positive effects and limit the negative effects of social interactions. In other words, the central *principles of sustainability* for the metaphor are social harmony, equity, and innovation. These principles are applied to the evaluation of different social and political processes, which constitute the *system model* underpinning the assessment, and which can be both negative (e.g., crime) and positive (e.g., mutual learning). As already mentioned, the boundary of the system model is defined by the reach of social interactions.

10.3.6 Summary of Implications for Sustainability Assessment

The above analysis began from four intuitive metaphorical images of cities, each with a legitimate claim to describe important aspects of urban systems. By elucidating their implications in more depth, our subsequent analysis then demonstrated how dramatically divergent these images indeed are. Table 5 summarises the contrasts between the four perspectives when it comes to the implications that they have for different dimensions of sustainability assessment. The table demonstrates where the power of the metaphors lies; it is in their ability to create normative expectations about what is important in urban systems, what are the desired directions of development, how are they to be assessed, and by whom.

Table 10.5: Dimensions of sustainability assessment interpreted for the four metaphors.

Metaphor	Purpose of assessment	Participation	Sustainability principles	Model of the system
Machine	*Optimisation*	*Based on utility*	*Efficiency*	*Practical functions within an administrative boundary*
Organism	*Learning and adaptation*	*Based on decision-making authority and substantive expertise*	*Health and resilience*	*Metabolic functions within a functional boundary*
Network	*Provision of information*	*Based on voluntary interest and social connections*	*Connectivity*	*Connections and flows within an ad hoc boundary*
Melting pot	*Conflict resolution*	*Broad participation of government and community representatives*	*Harmony, equity, innovation*	*Social and political processes within a boundary defined by social interactions*

The framework provided by Table 5 can serve at least two distinct functions. First, it can be used as a framework for the analysis and comparison of past and present applications of sustainability assessment. Second, the framework can be taken as a guideline for designing future applications of

sustainability assessment. In both cases, the framework can serve to enhance the reflexivity and transparency of sustainability assessment practice.

10.4 Discussion and Conclusion

The premise of this chapter is the insight that cities as complex systems can be conceptualised in different, equally legitimate ways. At the same time, different perspectives are not identical in their normative implications. Therefore, to appreciate these value-laden consequences, there is a need for reflexivity and transparency with regard to the emphases, strengths, and weaknesses of different conceptual approaches in analysing and assessing the sustainability of urban systems. The argument made here is that this requirement can be addressed by identifying a typology of ideal-typical approaches derived from commonly used metaphors of cities. This typology can then be deployed to understand in more depth differences in conceptualisations of cities and in practical applications of sustainability assessment. To this end, our analysis teased out two frameworks, one for discussing differences and similarities between approaches to conceptualising urban systems in general (Table 4), and one directed more specifically at analysing approaches to the assessment of urban systems (Table 10.5).

In the assessment of urban systems, it is possible to envision at least three different strategies for using the different metaphorical perspectives. First, the different metaphors may all be applied concurrently with the aim of creating a conceptualisation that is as comprehensive and balanced as possible. The second and third strategies take a more qualified approach. The second strategy makes a distinction between different parts of the urban system, and applies the most appropriate metaphor for each part (e.g., efficient economy, equitable society, resilient ecology). The third strategy suggests a temporal distinction. For example, it may be that during different phases in the historical trajectory of a city, different metaphors become more apt for guiding the development and assessment of the urban system.

The use of metaphors is not merely a literary exercise, but in fact an indispensable tool for dealing with complex reality. Whether employed explicitly or implicitly, such mental models can be detected as underpinning conceptualisations and assessments of urban systems. However, the use of descriptive metaphors entails juxtaposing things that are not perfectly identical. Hence, the obfuscated or one-sided use of metaphors can also have adverse consequences if the extent of their applicability is not understood properly. In particular, while several metaphors exist that can provide valuable additions to our library of mental models, no metaphor alone can capture the urban system completely. Therefore, frames of analysis like those provided by this chapter are required to provide the language that enables communication and collaboration across the boundaries of different approaches and scientific disciplines. In particular, parallel to advances in machine learning and big data analysis, there is a need for equal advances in interdisciplinary conceptual frameworks that can help to give meaning to the vast amounts of information that is produced by these methods.

As our presentation shows, the city as a problem transcends disciplinary boundaries. Therefore, for a comprehensive conceptualisation of urban systems that covers all four metaphorical perspectives, it is necessary to draw insights from several scientific fields. For example, the socioecological systems (Ostrom, 2009) and socio-technical systems (Geels, 2004) approaches can provide insights into and concepts for the natural and technological aspects of urban systems respectively. However, in order

to address the self-organising and emerging characteristics of urban systems, one has to turn to approaches more aligned with the concept of complexity, whether in its 'hard' (Batty, 2013) or 'soft' form (Blok & Farias, 2016; Morin, 2007). The more functionalist approaches to systems also have to be complemented with approaches sensitive to questions of power and conflict (Smith & Stirling, 2010). Finally, it is worthwhile to heed the warnings of those critical of even using the term 'system' to begin with, as it may portray cities as static and definitively definable wholes, in contrast to seeing them as ever-evolving and intrinsically contested (Gillard, Gouldson, Paavola, & Van Alstine, 2016).

Some interesting directions of research can be mentioned that would build on the work presented in this chapter. First, a comparative analysis of existing applications of sustainability assessment can be carried out with the analytical framework of Table 5. Second, the dimensions of sustainability assessment described in Table 5 can be augmented by identifying a set of indicators considered as typical for each of the four metaphors. This will concretise the metaphorical perspectives further, and thus enhance the potential of the metaphor typology as a scheme for designing assessments of urban systems. Furthermore, to add to the depth of consideration of different aspects of urban systems, the typology of the four metaphors can be refined further. For example, in the case of geographical and cultural contexts beyond those represented by the authors, additional metaphors to those considered in this chapter can prove to be fruitful and appropriate.

To conclude, we consider that the different metaphors do not merely accentuate different aspects of the reality of cities, but when used as blueprints for guiding the analysis and assessment of urban systems, they also represent different aspirational images of what the city should be. In other words, then, what is at stake in the rivalry between different metaphorical perspectives is the negotiation of a mutually liveable city for both its residents and those affected by it.

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Manuscript 2

Reference:

Halla, P., Wyss, R., Athanassiadis, A., Drevon, G., Hensel, M.U., Kaufmann, V., Koseki, S.A., Turcu, C., Vilsmaier, U., Binder, C.R., *forthcoming*. Using metaphors for addressing urban sustainability. Publication pending.

This is a preprint version of the manuscript, published in the open archive SocArXiv: https://doi.org/10.31235/osf.io/kdzxt.

Contributions of the doctoral candidate:

The doctoral candidate was principally responsible for the conceptualization of the article, for planning and leading the series of participatory workshops, for collecting and editing the inputs of the participants, and for writing the manuscript.

Using metaphors for addressing urban sustainability

Abstract

Enhancing the sustainability of cities is a timely, complex task. It involves the challenge of identifying the concerns and goals of different stakeholders in an inclusive manner and bringing into dialogue the various forms of knowledge and know-how that can address these concerns. At the moment, the lack of suitable concepts and methods for taking on this challenge limits our ability to conceive appropriate measures for promoting the sustainable development of cities. We propose three theses outlining the value of metaphors in tackling the challenge, demonstrated through the analysis of three prominent urban metaphors, and as an outcome, suggest three avenues for future work. With our contribution, we wish to encourage the construction of new approaches to urban sustainability based on transdisciplinary knowledge creation and the inclusive acknowledgement of different sustainability requirements.

1. Introduction

Currently, the majority of people live in urban areas (UN-Habitat, 2020), and cities represent centers of socio-economic activity, innovation and change (Sassen, 2005; Balland et al., 2020). As a result, cities dominate global resource use, with correspondingly high environmental impacts on surrounding land and the planet more broadly (IPCC, 2014). Therefore, the organization and development of urban areas constitutes a crucial determinant of all dimensions of sustainable development. This has placed the notion of urban sustainability in an increasingly central position of interest in both political and scientific domains (UN, 2017; Lobo et al., 2020).

Tackling urban sustainability remains a formidable task, with at least three distinct challenges for research and policymaking. Firstly, moving towards urban sustainability involves satisfying a complex set of parallel requirements (Finco and Nijkamp, 2001; Dempsey et al., 2011). Therefore, the first challenge is in identifying and acknowledging these requirements in a manner that is adequately comprehensive and representative of the different stakeholder priorities in city development (Turcu, 2013). Secondly, successfully addressing the multitude of requirements in urban sustainability entails incorporating a broad spectrum of knowledge and know-how (Ramaswami et al., 2012; Acuto et al., 2018). This, however, is not a trivial task, since the manner in which cities and their sustainability are conceptualized varies greatly across different fields and scientific disciplines (Portugali, 2011). Thirdly, urban sustainability is not a universal concept, but rather reflects contextually specific key issues and priorities (Kates et al., 2005; Hartmuth et al., 2008). This necessitates the tailoring of approaches to specific geographical and historical settings.

Given these challenges, a need exists for concepts and methods that can aid in identifying and bringing into dialogue a broad variety of ontological, epistemic and normative perspectives (Vilsmaier et al., 2017; Elmqvist et al., 2019; Norström et al., 2020; Zhou et al., 2021). Currently, work in this direction is only nascent, and significant conceptual and methodological advances remain to be achieved (Lobo et al., 2020). In response, this paper puts forward the idea of engaging with *metaphors* as a means of facilitating the creation of more comprehensive understanding of perspectives to urban sustainability. In particular, we put forward three theses:

- *Thesis 1: Metaphors can clarify and represent different aspects of urban sustainability*
- *Thesis 2: Metaphors can facilitate transdisciplinary approaches to urban sustainability by clarifying focuses and boundaries of forms of knowledge and know-how*
- *Thesis 3: Metaphors can convey visions of urban sustainability that are appropriate for particular contexts*

Our argument draws upon a dialogue between academics from different disciplinary backgrounds and a set of eight workshops through which an initial idea (Halla et al., 2020) was critically reviewed, discussed and elaborated into the three previously mentioned theses. With this contribution, we aim to encourage the construction of new approaches to urban sustainability based on transdisciplinary collaborative knowledge creation and the inclusive acknowledgement of different aspects of sustainability. We believe this line of work is crucial for finding more effective ways to conceive and apply urban sustainability measures and strategies in the 21st century.

2. Metaphors - from everyday language to science

As George Lakoff and Mark Johnson argued in their 1980 work *Metaphors We Live By*, metaphors provide a fundamental cognitive mechanism that structures our interpretation of things we observe and experience (Lakoff and Johnson, 2003). They do so by invoking the imagery of familiar and well-understood phenomena to describe other phenomena that are more opaque, either because they are more complex or because a proper conceptual repertoire for describing them is not yet at hand (Barnes and Duncan, 1992).

The use of metaphors is not limited to informal language but also extends to the scientific domain in disciplines as diverse as physics, economics and anthropology (Barnes and Duncan, 1992). Metaphors help scientists chart the unknown by tentatively assigning sameness and difference, and subsequently by stimulating the creation of technical concepts and models to be used for the scientific analysis of the phenomena in question (Pickett et al., 2004). This is particularly the case when analyzing complex phenomena, where creativity and inspiration are needed for recognizing patterns and processes beyond the individual elements involved (de Roo et al., 2012).

Metaphors are also ubiquitous in our vocabulary of cities (Nientied, 2016). During the last 100 years terms such as ‘machine’ (Le Corbusier, 1997), ‘neo-liberal’ (Harvey, 2007), ‘global’ (Sassen, 2005), and ‘networked’ (Castells, 1996) were applied to metaphorically describing cities, each offering a specific reading of the city, and each focusing on a specific aspect of urban reality. The value of such terms is in providing a heuristic conceptual foundation that helps to unravel the complexity of urban phenomena. The use of city metaphors also has a temporal dimension, in that at different points in history different metaphors have served as aspirational images for the organization and development of cities (Lynch, 1984).

The use of metaphors, however, involves juxtaposing objects that are not identical, which means that certain aspects of the target object are highlighted while others are effaced (Newell and Cousins, 2015). The use of metaphors thereby implies the taking of a normative position on which aspects of the target object are important to consider (Lakoff and Johnson, 2003). Especially, when metaphors

serve as inspirational building blocks for scientific theories and models, awareness of this limitation of metaphors, as well as of the translation process from metaphor to theory and/or model is crucial (Henle, 1996), as it can help to clarify the focal points and limits of knowing inherent to the respective scientific disciplines.

3. Comparing urban phenomena metaphors

The awareness of the perennial influence of metaphors on our thinking about cities triggered the organizing of a series of workshops to discuss among an interdisciplinary group of researchers the idea of employing these metaphors in support of efforts towards urban sustainability. During the workshops, consisting of collaborative and iterative conceptual analysis (Cornwall and Jewkes, 1995; Kerssens-van Drongelen, 2001), the participating group explored both the potentials and the limitations of metaphors in such a task (see supplementary material for notes on methodology). Our group also discussed and jointly completed a comparative table to support the argumentation (see Table 1). The table concretizes the meaning of selected metaphors across a number of aspects: (1) the key sustainability requirements implied by each metaphor; (2) their principal focuses and fields of application; (3) the contexts in which they are most appropriate for describing urban sustainability. The comparative table allows us to illustrate our three theses on the possible role of metaphors in facilitating the kind of integrative work and dialogue across fields of knowledge and know-how needed for successfully moving forward on urban sustainability.

Our example includes three metaphorical terms prominently used to describe urban phenomena: *metabolism*, *rhythm*, and *smart*. These three metaphors do not, of course, represent the full picture of urban sustainability; they were chosen for demonstrative purposes, covering a variety of distinct epistemological and historical perspectives. For example, while the rhythm metaphor has been employed by authors from Aristotle to Sharon Zukin (Smith and Hetherington, 2013), the metabolism metaphor entered wider use during the 20th Century as cities' environmental impacts became more critical (Kennedy et al., 2011), and the smart city metaphor gained prominence only as recently as the 1990s (Angelidou, 2015). The three metaphors also vary in their field of societal application (e.g., the notion of smart city being popular with policymakers and technology companies, while metabolism is mostly used in academia).

4. Thesis 1: Metaphors can clarify and represent different aspects of urban sustainability

As mentioned in the introduction, urban sustainability is a multidimensional challenge, which entails the balanced satisfaction of parallel social, economic and environmental requirements (Finco and Nijkamp, 2001; Dempsey et al., 2011). Despite an extensive amount of literature addressing the topic, a degree of fuzziness persists around the concept of urban sustainability, and its definitions typically remain at the level of abstract principles (Huang et al., 2015). This renders the concrete operationalization of the concept a particularly challenging task. In particular, the operationalization must consider different aspects and requirements of sustainability in an adequately comprehensive and balanced manner. However, observations of current practice often reveal an imbalance in the attention accorded to different dimensions of urban sustainability (Opp, 2017; Merino-Saum et al., 2020), which can at least be partially attributed to a lack of solid conceptual foundations to guide the operationalization processes (Turcu, 2013).

Metaphor	*Metabolism*	*Rhythm*	*Smart*
Working definition	*"The chemical and physical processes by which a living thing uses food for energy and growth"* (Cambridge Dictionary)	*"A strong pattern of sounds, words, or musical notes that is used in music, poetry, and dancing"* (Cambridge Dictionary)	*"Intelligent, or able to think quickly or intelligently in difficult situations"* (Cambridge Dictionary)
Clarifying and representing different aspects of urban sustainability (Thesis 1)			
Implied requirements for a sustainable city	• Use of resources adapted to carrying capacity of supporting ecosystems • Minimal waste production • Accessibility and fair distribution of resources	• Energy consumption adapted to natural rhythm (production of renewable energies) • Deceleration of lifestyles (consumption, mobility, etc.) for improved human well-being • Harmonious orchestration of urban activities	• Efficient and productive use of infrastructures • Enhanced measurability and controllability that allows optimization • Convenient urban life
Characteristic sustainability indicators	• Carbon footprint per capita • Material unit per unit of service (MIPS) • Waste production per capita • Percent of population with access to potable water	• Modal split of transportation • Peak hour capacity of the public transport system • Time use satisfaction (survey) • Changes in the balance of renewable/fossil energy use	• Energy consumption per GDP • Number of hours spent in traffic jams • Number of households with smart meters • Existence of online government platforms
Clarifying focuses and boundaries of forms of knowledge and know-how (Thesis 2)			
Examples of use in science and practice	• End of 19thC. Marx: "the appropriation of nature by the capitalist extractivist economy" • Industrial ecology (Wolman, 1965) • Urban political ecology (Heynen et al., 2006) • Related to, e.g., the circular economy movement	• 4th-century B.C. Plato "Order of the movement" • Rhythmanalysis (Lefebvre, 1992) • Critique of social acceleration (Rosa, 2010) • Related to, e.g., the degrowth movement	• Early 20th Century futurists (Angelidou, 2015) • Innovation studies (Komninos, 2009) • Related to public policies aiming to improve functionality of cities; energy efficiency; etc. (e.g. EU Partnership for Smart Cities and Communities)
Urban issues in focus	• Resource use • Urban services provision • Processes of composition and decomposition; pollution/emission control	• Temporal regulation of flows of energy, materials • Everyday movements (traffic, commute, etc.) • Time pressure and human well-being	• Infrastructure management (transport, energy, waste) • Information/digital traces • Technological development
Conveying contextually appropriate visions of urban sustainability (Thesis 3)			
Context when most appropriate	• Historically: from mid-20th Century with increasing consumption load on the environment • Today: Cities with high environmental footprint; rapidly urbanizing areas	• Historically: Industrial revolution in Europe (19th century); Functional revolution during 1960s; Digital revolution (e.g., 21st century Asian cities) • Today: Large, dense, rapidly growing cities	• Historically: Since the emergence of ICT • Today: Larger cities with resources to invest in technologies

Table 1. Comparing three metaphors used to describe cities and urban phenomena.

We argue that engaging with metaphors describing urban phenomena can help to tackle this challenge. In particular, by providing an effective shorthand for expressing different aspects and requirements of urban sustainability, discussing such metaphors can support ensuring that related efforts are constructed based on a clear and comprehensive understanding of the concept. The example of Table 1 demonstrates our point.

When applied to cities, the metabolism metaphor draws attention to the use of physical resources in support of urban activities, and to the associated environmental and social impacts. It suggests that to be sustainable, a city must reconcile resource use with the carrying capacity of the source ecosystems, and that within the city said resources must be distributed adequately to sustain different groups and functions. Common indicators relatable to this perspective on urban sustainability include statistics on energy consumption, waste production, recycling rates, and accessibility to basic services.

In contrast, the rhythm metaphor focuses on the temporal orchestration of urban life. As such, the metaphor suggests that to enhance urban sustainability is to improve the temporal patterns of resource use, movements of people and goods, and urban lifestyles in general. In addition, it implies a concern for the balancing of these temporal patterns in view of increasing human well-being and social cohesion, as well as emancipating people from the pressures of social acceleration. Possible indicators for expressing this point of view on urban sustainability include the capacity of the public transport system (in response to peak hours), the temporal variation in renewable energy use, and surveys of time use satisfaction.

The smart city metaphor evokes a city whose operations and development are rendered more controllable through technology. The metaphor suggests that the sustainability of cities depends on the efficient organization and continuous optimization of its functions. Characteristic indicators for this perspective to urban sustainability include metrics such as energy consumption per unit of GDP, the fluency of traffic (e.g., number of hours lost in traffic jams), and the existence of digital platforms for citizens to interact with authorities.

As these three examples show, metaphors can powerfully act as orientational terms that capture different aspects of urban sustainability, including particular urban processes (metabolism), attributes (rhythm) or qualities (smart). Therefore, they can support the creation of understanding and agreement on the meaning of the concept, as well as allow for moderation between its various operationalizations. Especially when it comes to the use of indicators in the sustainability assessment of cities, anchoring these indicators on specific metaphors may elevate them from loose metrics to meaningful messages.

The comparison of the three metaphor-based perspectives, each with their unique angles on cities, underlines the need to engage simultaneously with multiple perspectives, as no single perspective can capture all required aspects of the multidimensional concept of urban sustainability. As in our example, metaphors can act as catalyzers in attempts to acknowledge a more comprehensive range of sustainability aspects.

Summary:

- Metaphors have the potential to help imagining and expressing different aspects of urban sustainability.

- Engaging with metaphors could help to facilitate the simultaneous inclusion of a multitude of sustainability aspects, thus enhancing the comprehensiveness of efforts and assessments targeting urban sustainability.

5. Thesis 2: Metaphors can facilitate transdisciplinary approaches to urban sustainability by clarifying focuses and boundaries of forms of knowledge and know-how

The multidimensional nature of urban sustainability also implies that it cannot be adequately addressed by monodisciplinary approaches. Instead, the construction of successful policies and solutions for tackling urban sustainability must involve knowledge co-production both across scientific disciplines and between academic and other societal actors (Turcu, 2013; Acuto et al., 2018; Norström et al., 2020; Zhou et al., 2021). This calls for tools that allow for the inclusive integration of a wide variety of existing knowledge and know-how on cities (Bammer et al., 2020).

To illustrate this variety, Portugali (2011) presents three distinct 'cultures' among approaches to cities. The first of these cultures consists of approaches inspired by natural, engineering and economic sciences (e.g., Auerbach, 1913; Lösch, 1954) and essentially views cities as comparable to natural systems and subject to analysis through formal theory and quantitative methods. The second culture, often explicitly critical of the first culture, is rooted in qualitative social sciences and humanities (e.g., Lefebvre, 1968; Harvey, 1973), and views cities primarily as settings of social and political processes. Finally, the third culture is more recent, based on the vision of cities as complex systems of networks and flows, with emerging properties and dynamics of self-organization (e.g., Batty, 2017)**.** The third culture is also related to the strong emergence of big data-based computational methods for studying cities (Creutzig et al., 2019).

As Portugali's presentation exemplifies, fundamental paradigmatic differences exist between different approaches in terms of how they imagine, conceptualize and analyze cities and urban sustainability. The first step towards bringing them into dialogue and collaboration consists of clarifying their basic assumptions, focuses and positions vis-à-vis each other. On one hand, this entails 'boundary critique' (Ulrich, 1994), i.e., critical reflection on which issues and values are included or excluded in a given approach to urban sustainability (Achterkamp and Vos, 2007), and on the other hand, 'boundary work' (Gieryn, 1983), i.e., efforts to understand the meanings of and differences between different forms of knowledge in view of their eventual integration (Mollinga, 2010). For these purposes, so-called 'boundary objects' are needed to allow communication across knowledge fields without necessarily having mutual in-depth understanding or consensus (Star and Griesemer, 1989). We argue that metaphors can serve as such boundary objects, and again demonstrate our argument briefly with the example of Table 1.

The term 'metabolism' was originally coined by the physiologist Theodor Schwann in 1832 to describe cellular and organism phenomena. Shortly after, Karl Marx used the term metaphorically in his description of the appropriation of materials by the capitalist mode of production. Today the use of the metabolism metaphor in urban contexts is associated with three separate fields (namely, industrial ecology, urban ecology and urban political ecology), each of which is interested in a systemic understanding on how urban activities impact the environment, but each also considering the matter from different angles. The use of the urban metabolism originally focused predominantly on the

economic and environmental pillars of sustainability (and their connection), while struggling to understand the broader societal implications of resource use and pollution emission flows. However, the use of the metaphor has evolved considerably over time, and now also covers such sociopolitical implications. In particular, researchers that fall within the industrial ecology realm might focus solely on the environmental impacts of anthropogenic activities, while the ones falling within the urban political ecology realm would examine the power relations of who accesses, uses and dictates some of these resource and waste flows (Newell and Cousins, 2015).

The use of the rhythm metaphor dates back to Plato, and it is associated with several domains of philosophy, sociology and psychology. For example, the 'rhythmanalysis' approach developed by Henri Lefebvre (1992) analyses the intensity and periodicity of territories and social interactions. In psychology, scholars have more broadly focused their research on time pressures and their deleterious effects on the well-being of individuals. The analysis of urban rhythms has also raised the prospect of formulating dedicated rhythm policies (Antonioli et al., 2021) to address such issues as the temporal distribution of mobility, production, (energy) consumption, and overall time pressure on everyday life.

During the last two decades, the use of the smart city metaphor has featured prominently in the vocabulary of policymakers and technology companies to describe and inspire the use of digital technologies in the organization and development of urban areas. The metaphor is related to terms such as digital city, information city, etc., that preceded it during the 20th Century (Angelidou, 2015). Smart city initiatives often involve close collaborations between public authorities and private technology companies. The primary focus of these initiatives is evidently on the enhanced and more efficient delivery of urban services, including energy, transport, etc., with the help of new technologies. As such, the use of the metaphor has been criticized for excessive optimism in technological solutions at the expense of more fundamental societal changes, as well as for lack of attention to questions of equality and access (Vanolo, 2014; Angelidou, 2015).

As these examples show, metaphors can serve as powerful reference points for making visible and for reflecting on the basic assumptions, focuses and boundaries of different approaches to urban sustainability ('boundary critique'). In addition, metaphors can serve as boundary objects, facilitating communication and collaboration between these approaches ('boundary work'), as they are "both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" (Star and Griesemer, 1989, p. 393). In other words, metaphors can provide a starting point for a transdisciplinary dialogue in view of transdisciplinary co-production of more comprehensive forms of knowledge.

Our discussion also implies that the meaning of particular metaphors is not absolute, but rather evolves over time, both as the fields that are associated with them develop and respond to criticism directed at them, and also as the source objects of the metaphors evolve. It is a reminder that to avoid obsolete or caricaturistic representations, it is necessary to periodically update boundary judgments on what is included or excluded in a given metaphor and the knowledge fields related to it.

Summary:

- Metaphors could be used in boundary critique and boundary work to clarify the focal points, limits and relative positions of different approaches to cities and urban sustainability.

- Metaphors could support transdisciplinary research and construction of integrated forms of knowledge and know-how, both across scientific disciplines and between academic and other societal actors, in order to better address the current challenges related to urban sustainability.

6. Thesis 3: Metaphors can convey visions of urban sustainability that are appropriate for particular contexts

As is commonly accepted, the concept of sustainability always acquires a meaning that is context-specific (Kates et al., 2005; Hartmuth et al., 2008). When it comes to urban sustainability, this context-specificity has at least three dimensions. Firstly, the definition of the concept reflects local circumstances (such as geography and climate) and community preferences (Turcu, 2013). Secondly, the meaning of sustainability varies depending on the particular stage in the evolution of a city. For example, Bai and Imura (2000) show how the most pressing urban challenges evolve from poverty to production-related and then to consumption-related issues in the economic development of a city. Thirdly, the variability in the interpretation of urban sustainability also reflects changes in broader cultural expectations, worldviews and thought styles. Indeed, such changes across different historical epochs have also been reflected in popular and scientific conceptions of what makes a city 'good' (Lynch, 1984).

Again, we argue that metaphors could provide a powerful means of expressing these contextually variable understandings of urban sustainability. Our argument is demonstrated by the comparison of Table 1. The metabolism metaphor is most relevant in the context of cities whose environmental footprints are high to the point of starting to reach the carrying capacity of supporting ecosystems. The prominent use of the metaphor therefore coincides with an increasing awareness and concern for the need to moderate these footprints, which began in the 1960s, and which today is expressed e.g., in the call for more circular economies.

The rhythm metaphor, historically, is interesting when considering important epochal changes (e.g., the Industrial Revolution), and how they have affected the everyday life of urban dwellers. Today, rhythm metaphor is particularly relevant in large and densely populated cities where mass transportation and communication has increased the speed of everyday life, and where commerce and services are in constant operation.

The metaphor of the smart city, then, is most relevant when describing present day cities facing the challenge of efficient organization of their functions (e.g., energy and transport) and that have the capacity and willingness to invest in technologies for solving these challenges. In fact, the smart city metaphor has become a global symbol of the quest for urban modernity (Glasmeier and Christopherson, 2015), prevalent in urban policy discourses on all levels of government (Datta, 2019).

As these examples show, metaphors provide a language through which to describe contextually specific and evolving interpretations of urban sustainability. Associating such interpretations with specific metaphors makes it possible to better appraise the results of sustainability assessments in different contexts as well as compare different assessment practices and approaches. Discussing contextual interpretations through evocative metaphors can also make the concept of urban sustainability more broadly accessible and subject to public deliberation.

Furthermore, the use of metaphors is in a co-constructive relationship with evolving reality (Jasanoff and Kim, 2015). The promotion of new, imaginative metaphors for envisioning cities has therefore the potential to not only deepen and refine our understanding of urban sustainability, but provoke the kind of cultural and social change needed for the creation of more sustainable cities.

Summary:

- Metaphors could help cities illustrate particular characteristics and sustainability needs given their historical and geographical contexts (and our evolving understanding of them).
- Metaphors could be a constitutive element when it comes to forging the imagination and conceptualization of what a (sustainable) city is throughout time.

7. Looking ahead - implications for research and practice

The use of metaphors is a cognitive tool that permeates both informal everyday life and more formal intellectual activities. Instead of dismissing metaphors, we argue, the more productive choice is to make their use more explicit and reflective. For efforts targeting urban sustainability, metaphors could be of particular use in clarifying the different required aspects for a sustainable city (Thesis 1), facilitating transdisciplinary work and dialogue across fields of knowledge and know-how (Thesis 2), and conveying contextually relevant interpretations of sustainability (Thesis 3). Based on our theses, we suggest three possible paths forward while also issuing a warning about the pitfalls related to metaphors. Please see supplementary material for more precise suggestions for pursuing these pathways.

Pathway 1: Investigate the deliberate use of metaphors to facilitate collaboration between citizens, policymakers and scientists

As we have argued, urban metaphors could act as boundary objects in transdisciplinary knowledge co-creation. Metaphors can facilitate communication between actors with different backgrounds and with conflicting interpretations and opinions of the concept of sustainability, as well as make the respective focuses and limitations of different approaches more tangible. This is a necessary first step in bringing the various urban stakeholders into dialogue and opening the door for the integration of different viewpoints into comprehensive policies. Therefore, we suggest investigation of the deliberate use of metaphors in a participatory procedure aimed at the development of new urban development policies.

Pathway 2: Construct sustainability assessment frameworks with metaphor-based indicator categories

As seen in Thesis 1, metaphors can effectively capture different aspects of urban sustainability. When constructing indicator frameworks for the assessment of urban sustainability, metaphors can act as guiding labels for categories of indicators, both inspiring the selection of these indicators as well as communicating their meaning. In particular, connecting the indicators used in an assessment to particular metaphors creates transparency concerning the underlying assumptions and prescriptive ideas held by those in charge of selecting the indicators. Still, no single metaphor can capture all aspects of urban sustainability. Therefore, attempts at metaphor-based sustainability assessments must simultaneously consider sets of metaphors, with each metaphor drawing attention to particular sustainability aspects and calling for a certain group of indicators.

Pathway 3: Investigate the dynamic interplay between metaphors and the urban phenomena they describe

Urban metaphors not only change as a response to the evolving reality that they describe, but by inspiring urban development they play a performative role in changing that reality. For example, certain metaphors can remain influential for a long time even when the metaphor has already lost its pertinence in describing current urban challenges. Awareness of this evolving bi-directional relationship between cities and metaphors over time can provide valuable critical perspective into the analysis of current practices in urban development. Moreover, analyzing the emergence of new metaphors can provide a means of anticipating urban challenges and our evolving understanding of them. In the future we may be confronted with challenges requiring entirely new approaches and knowledge forms related to cities – and the metaphors for anticipating them might already be at hand.

Be mindful of pitfalls when working with metaphors in the context of urban sustainability

The value of metaphors has limits, and their expediency in describing complex phenomena is accompanied by certain potential pitfalls (Newell and Cousins, 2015). Firstly, metaphors should not be taken literally. For example, a city is not a machine, nor an organism, etc., even though some aspects may be similar. Therefore, the requirements that apply to evaluating whether a machine or an organism is sustainable only partially cover the requirements for a sustainable city. In other words, care should be exercised in considering the extent of a metaphor's applicability. Secondly, metaphors are in constant evolution, both because the metaphorical term is interpreted in different ways in different situations, cultural contexts, historical moments, etc., but also because the reference point may change (e.g., a 'machine' today is different than in the past). Therefore, the use of metaphors requires that the characteristics implied by a particular metaphor are periodically reviewed to avoid possible misunderstandings or misrepresentations. Thirdly, sustainability priorities are not static but evolving in response to changing events and circumstances. This necessitates flexibility and precludes the existence of a definitive city metaphor to guide urban sustainability. Finally, working with metaphors can be 'messy', with terms that overlap and evolve, and with implied rather than explicit meanings. Consequently, it should be noted that our argument emphasizes the *heuristic* value of metaphors; they should not be taken as a replacement for the rigorous development of more specific concepts and models to analyze and describe urban phenomena. Awareness of these four pitfalls can help to ensure the kind of productive use of metaphors that we have argued for throughout this article, and thereby spur comprehensive, transdisciplinary efforts to strengthen global urban sustainability.

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Manuscript 3

Reference:

Merino-Saum, A., **Halla, P**., Superti, V., Boesch, A., Binder, C.R., 2020. Indicators for urban sustainability: Key lessons from a systematic analysis of 67 measurement initiatives. Ecological Indicators, 119, 106879. https://doi.org/10.1016/j.ecolind.2020.106879

This is a postprint version of the manuscript.

Contributions of the doctoral candidate:

The doctoral candidate contributed to the design and conceptualization of the research, was one of the four equal participants in the sampling and data generation phase, wrote the Python code used for analyzing the data, and participated in the writing and reviewing of the manuscript.

Indicators for Urban Sustainability: key lessons from a systematic analysis of 67 measurement initiatives

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 draw instructive lessons to support the development of future indicator sets by elucidating the emphases and gaps in how urban sustainability is currently translated into metrics. 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.

Keywords: Urban systems; sustainability; indicators; SDGs; MONET; STEEP.

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.

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*[34] (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).

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

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	N° applications; focus on urban aspects.	Frequency of use	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**

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

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) 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.

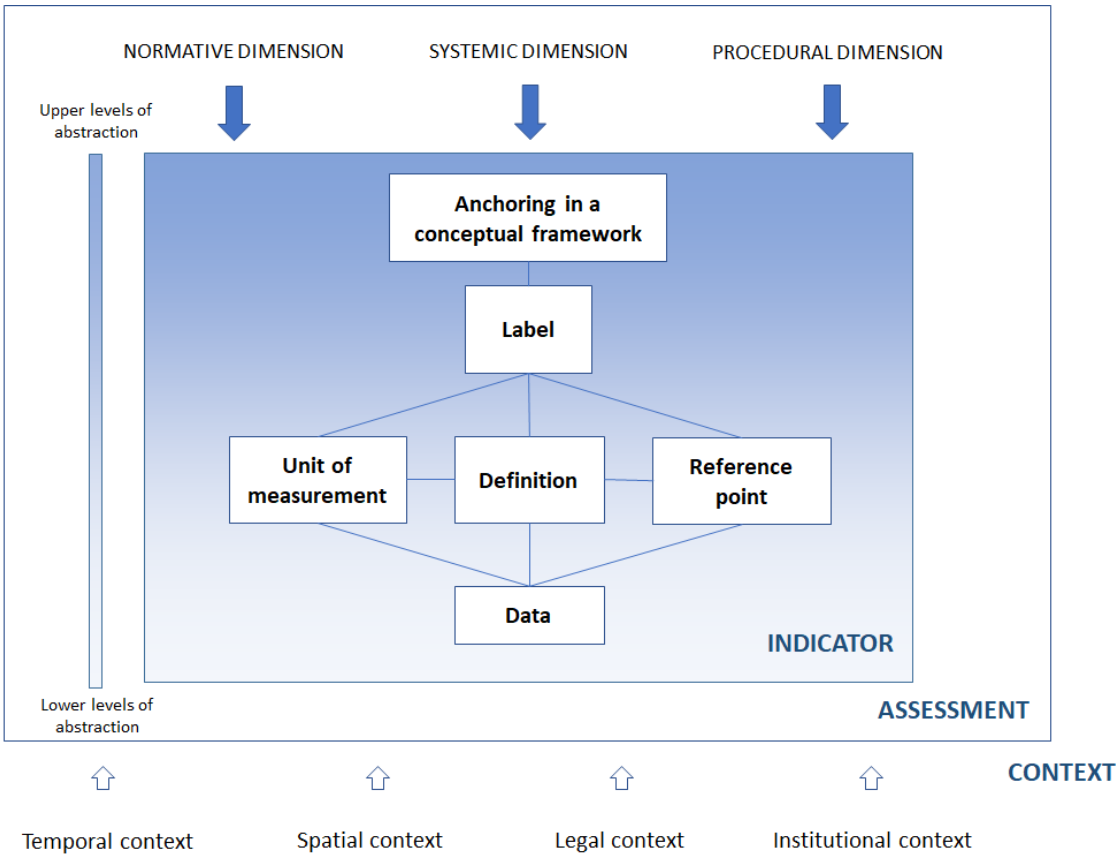


Fig. 1: Core elements of an ideal indicator and potential influencing factors.

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 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.

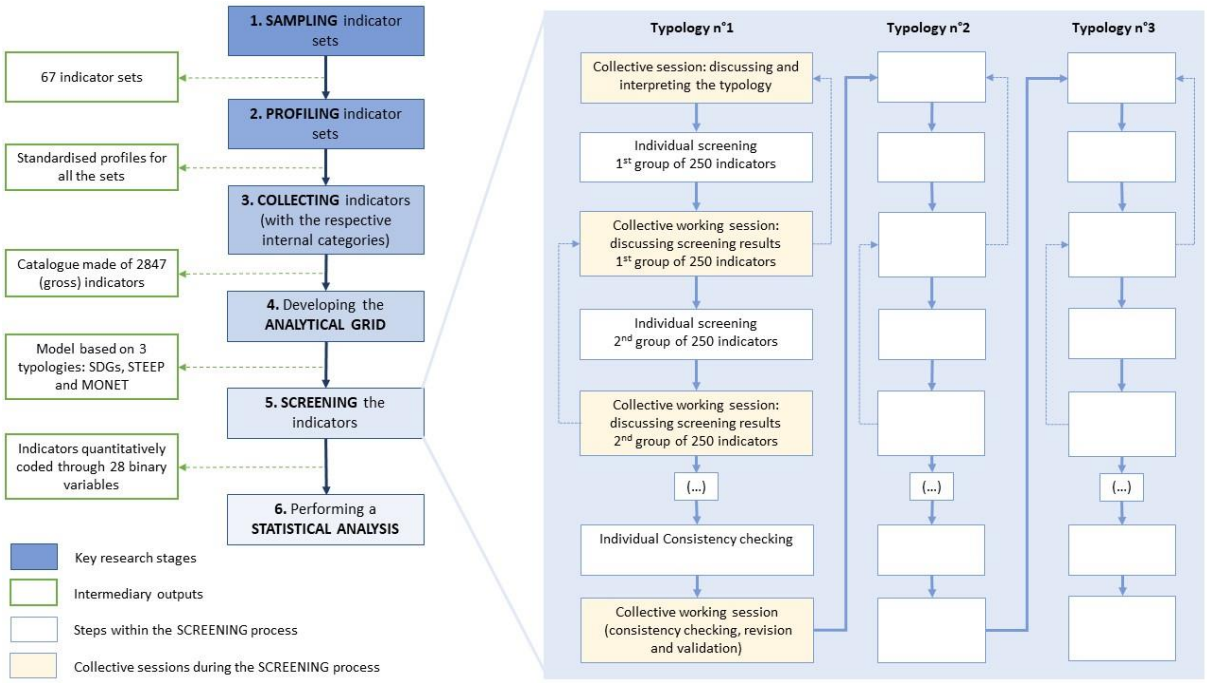


Fig. 2: Key steps followed in the present study.

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[35]. 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[36] 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 scales and sizes (n° of indicators) were retrieved and stored for all 67 indicator sets.

[35] 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")).

[36] 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).

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 & CAG Consultants 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	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 Malaga 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
Kotharkar 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 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.

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 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.

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

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

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.

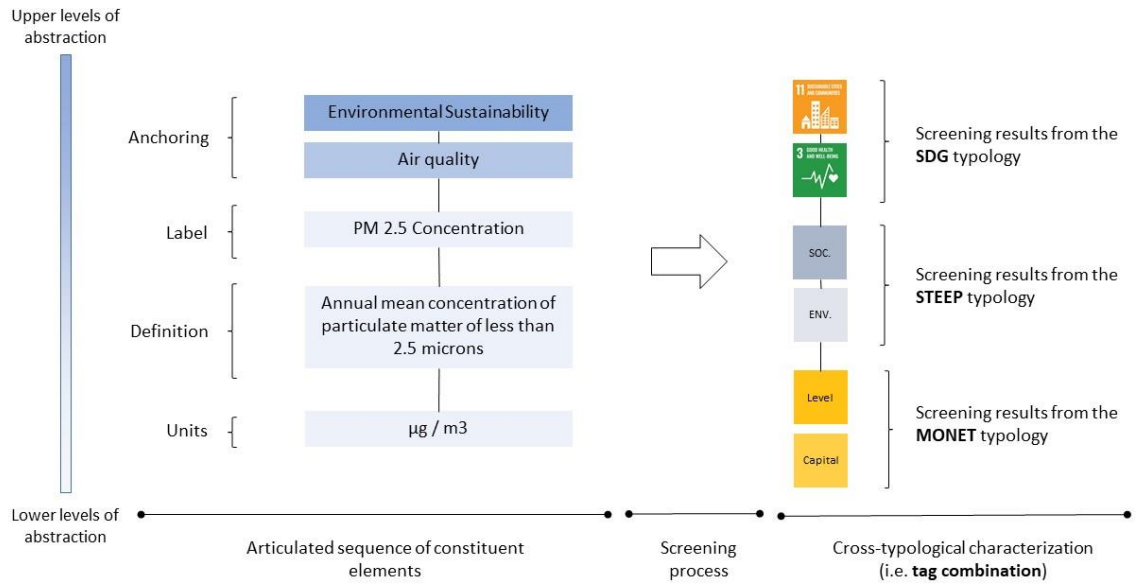


Fig. 3: Illustration of the screening process; example of the *PM2.5 Concentration* indicator.

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 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.

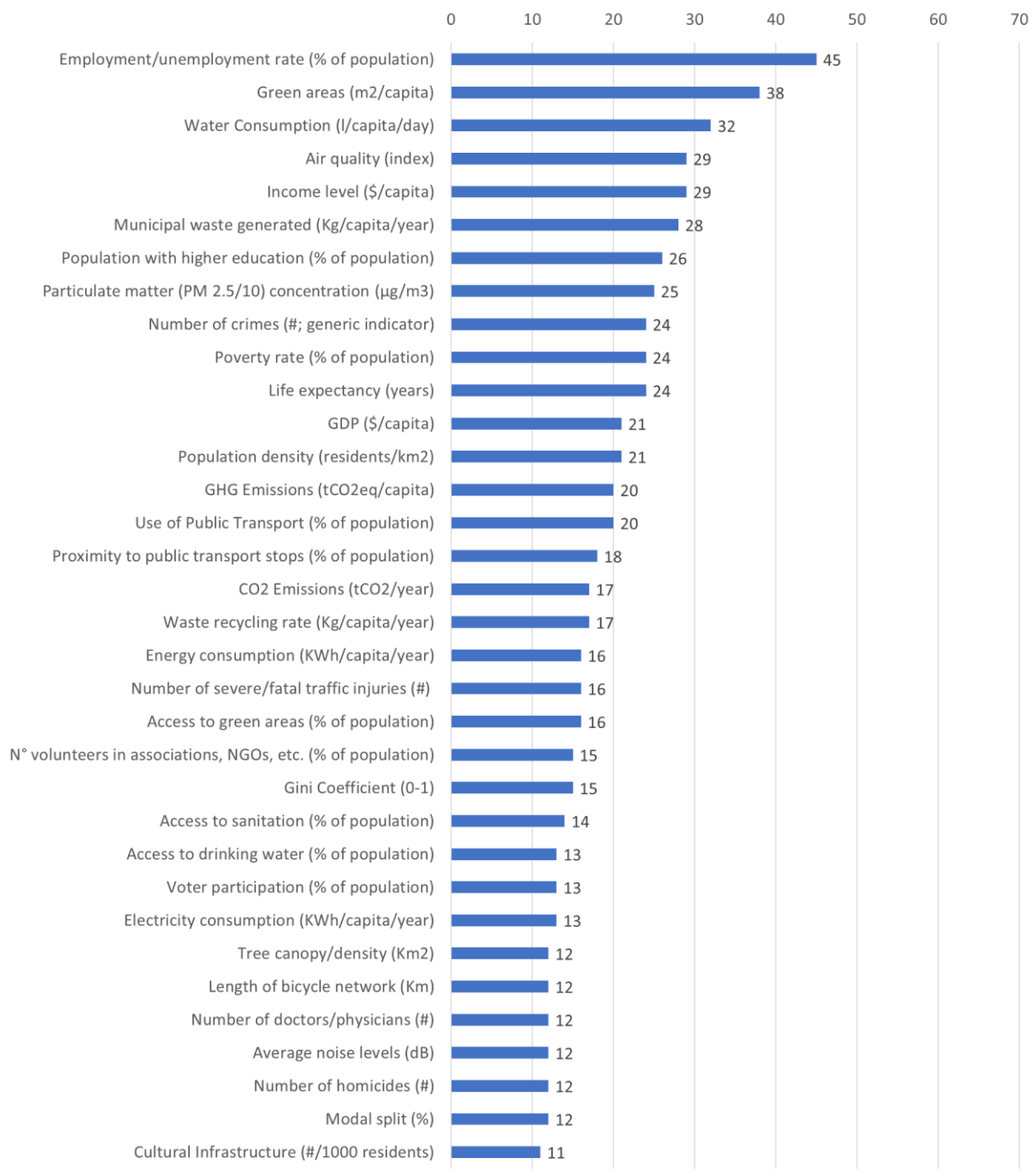


Fig. 4: Most frequent (net) indicators ranked by the number of indicator sets in which they appear. Brackets enclose exemplified measurement units for each indicator based on the most frequent unit used in the indicator sets.

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[37] 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)[38]. As expected, SDG11 (Sustainable cities 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.

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

[38] 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 MONET) follows the same logic.

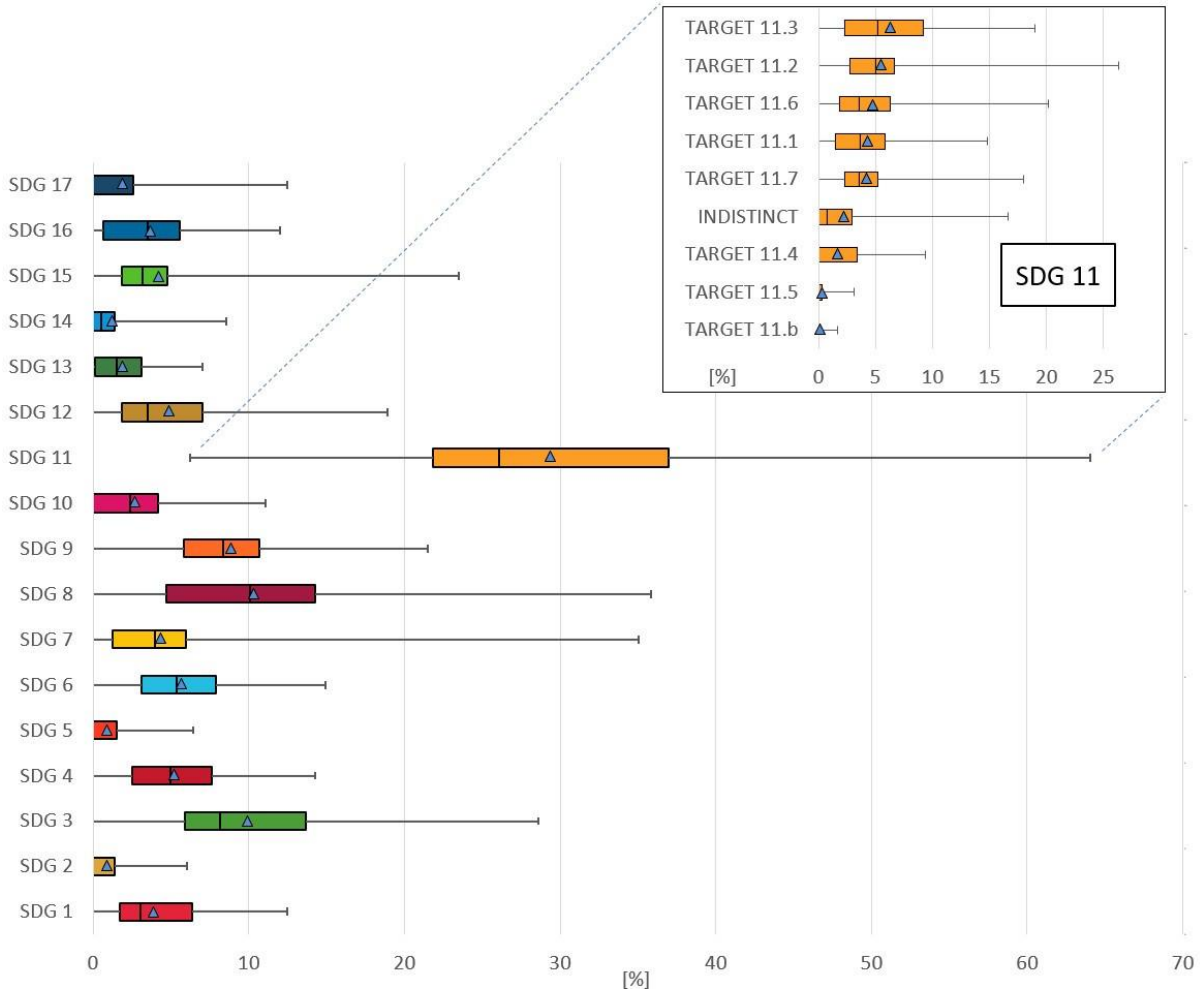


Fig. 5: Relative importance given to each SDG by the analyzed indicator sets.

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%.

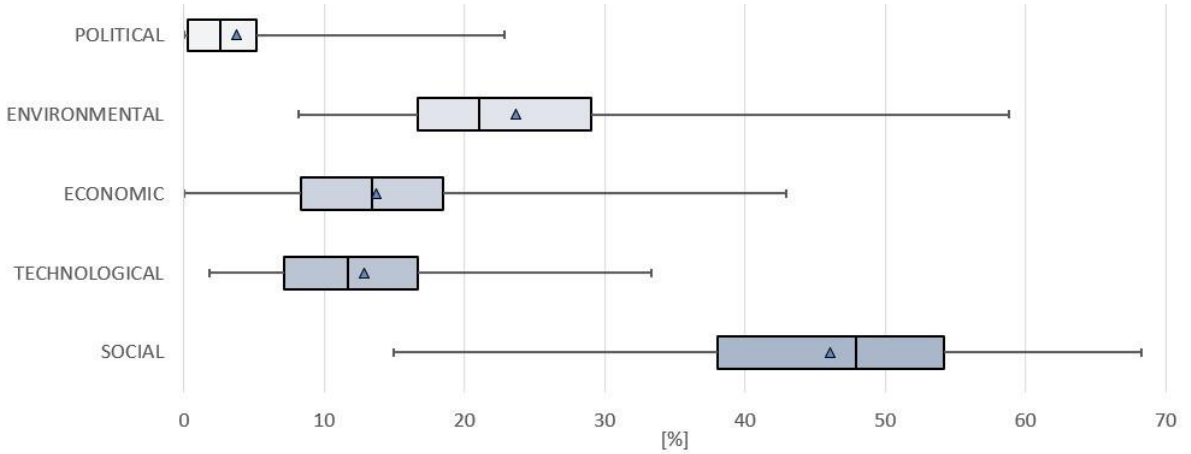


Fig. 6: Relative importance given to the STEEP categories by the analyzed indicator sets.

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%.

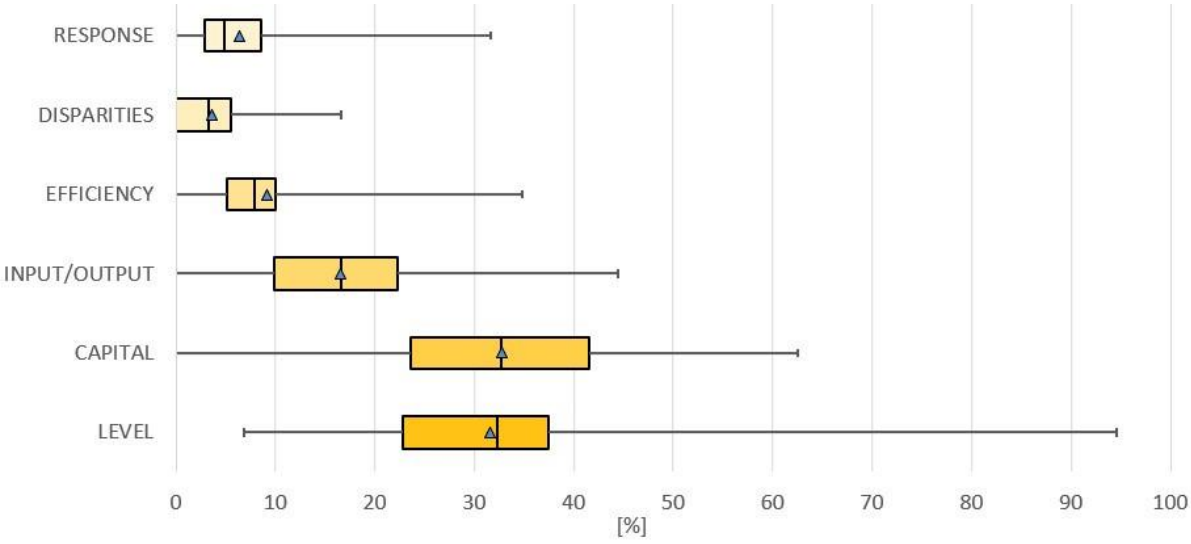


Fig. 7: Relative importance accorded to the MONET categories by the analyzed indicator sets.

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

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.

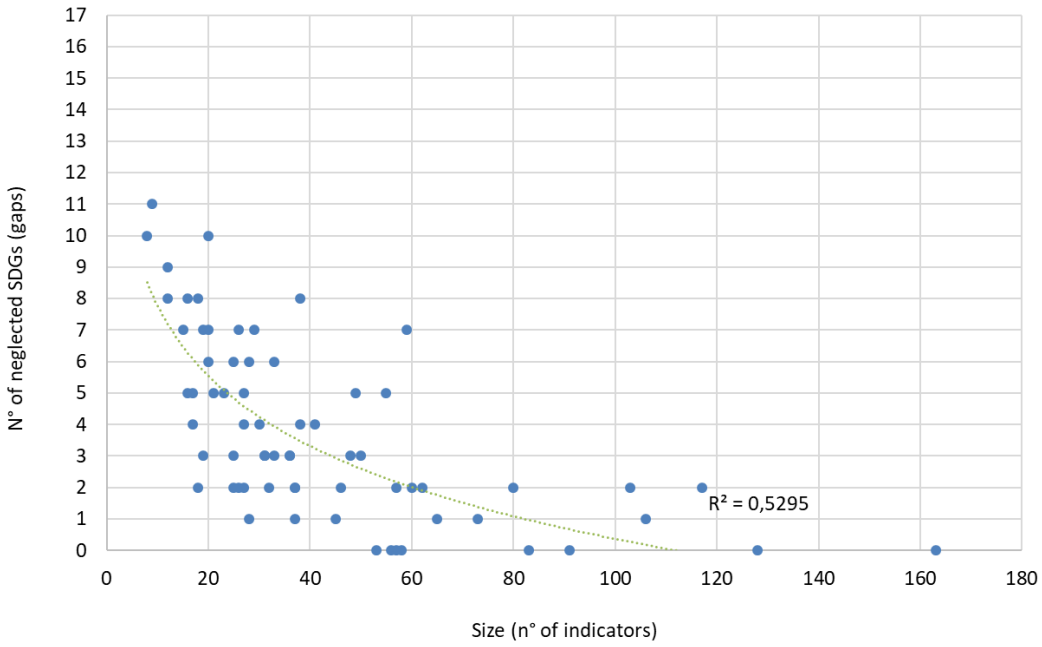


Fig. 8: Number of neglected SDGs and total number of indicators per indicator set. Each point in the figure represents a set.

- **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 (see section 4.2.1), 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)[39], 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.

[39] 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.

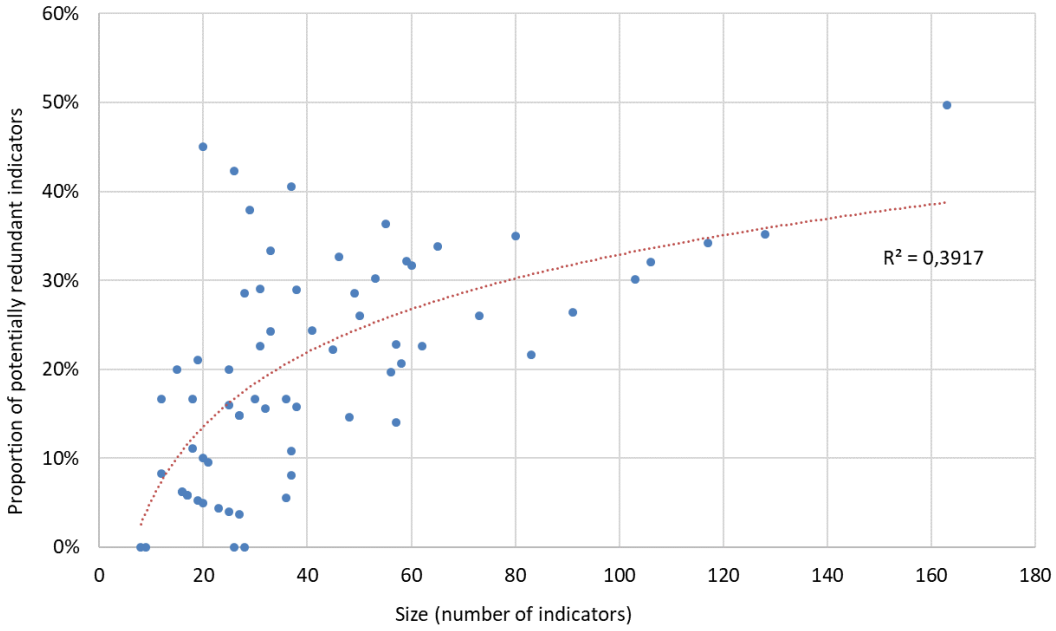


Fig. 9: Proportion of potentially redundant indicators and number of indicators per set.

- **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 be sufficient to render them visible.

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

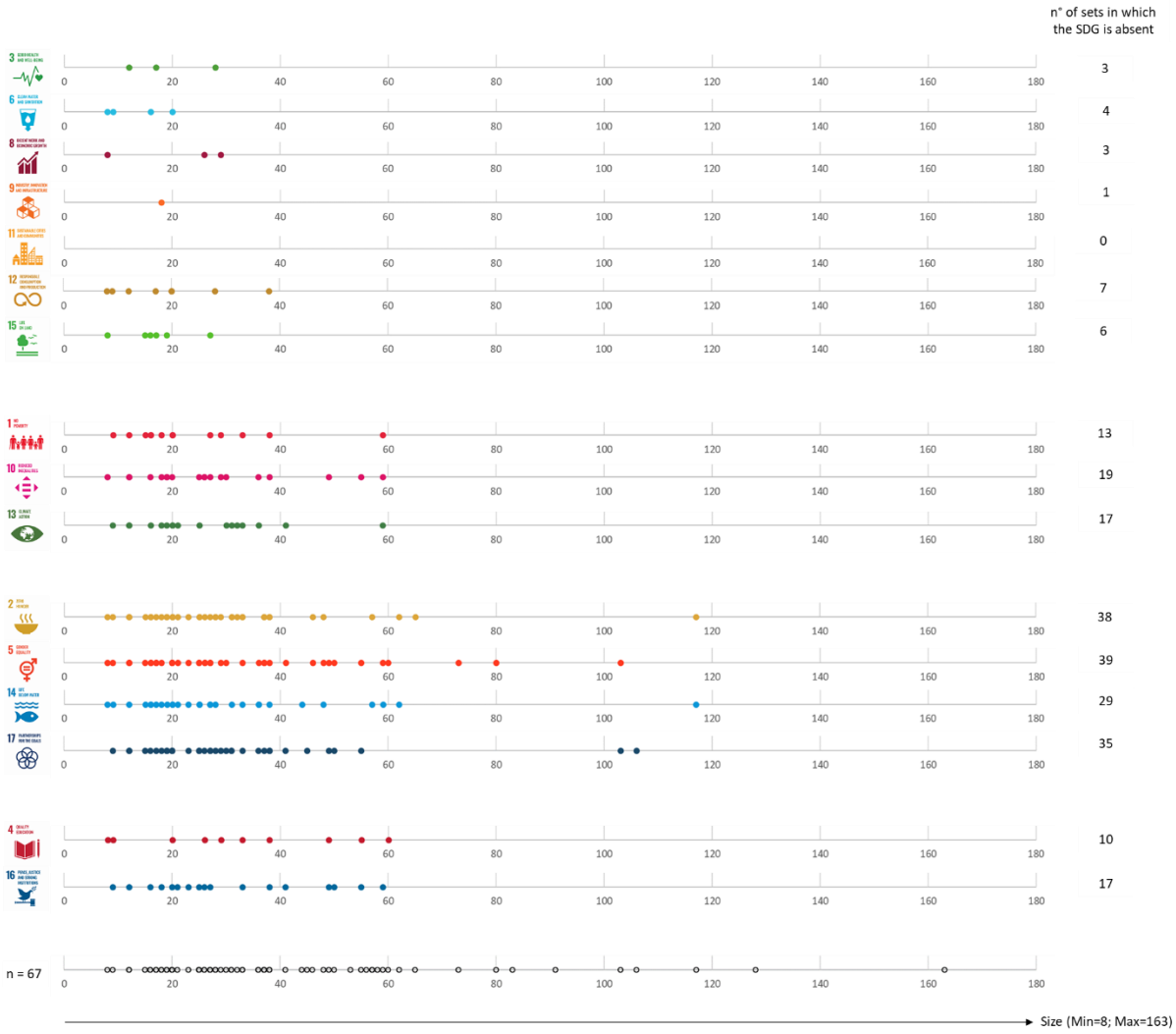


Fig. 10: Cases in which a given SDG is absent from an indicator set. Each filled circle represents an indicator set in which the SDG is neglected (hence, for instance, SDG4 has 10 filled circles, meaning that it is absent from 10 indicator sets, of which the smallest is comprised of eight indicators 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.

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).

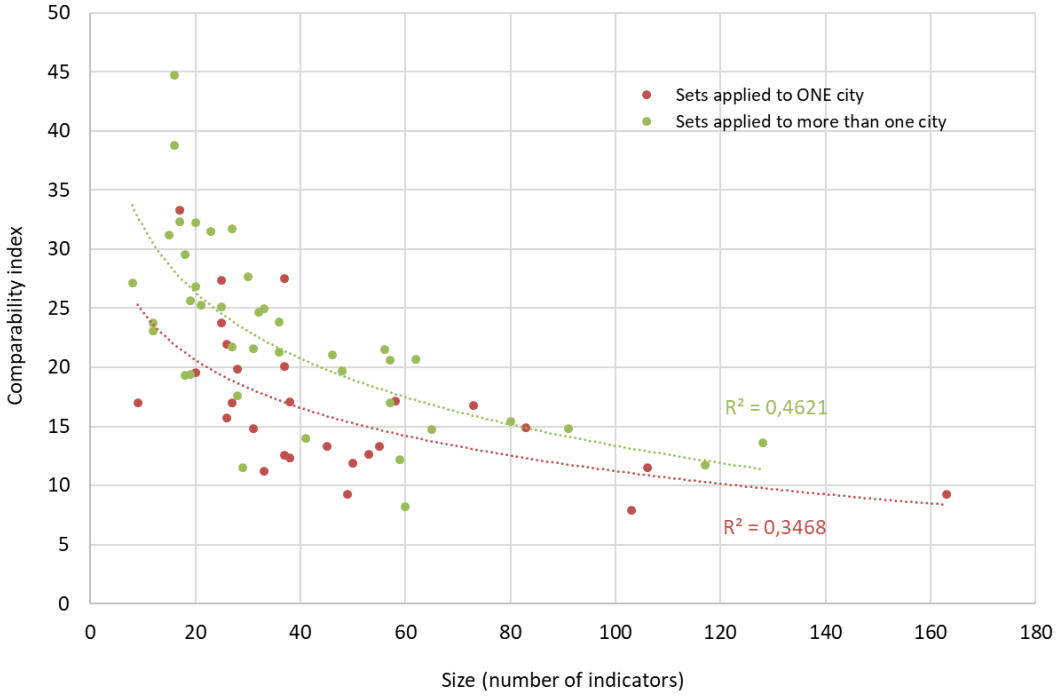


Fig. 11: Comparability level by size

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.

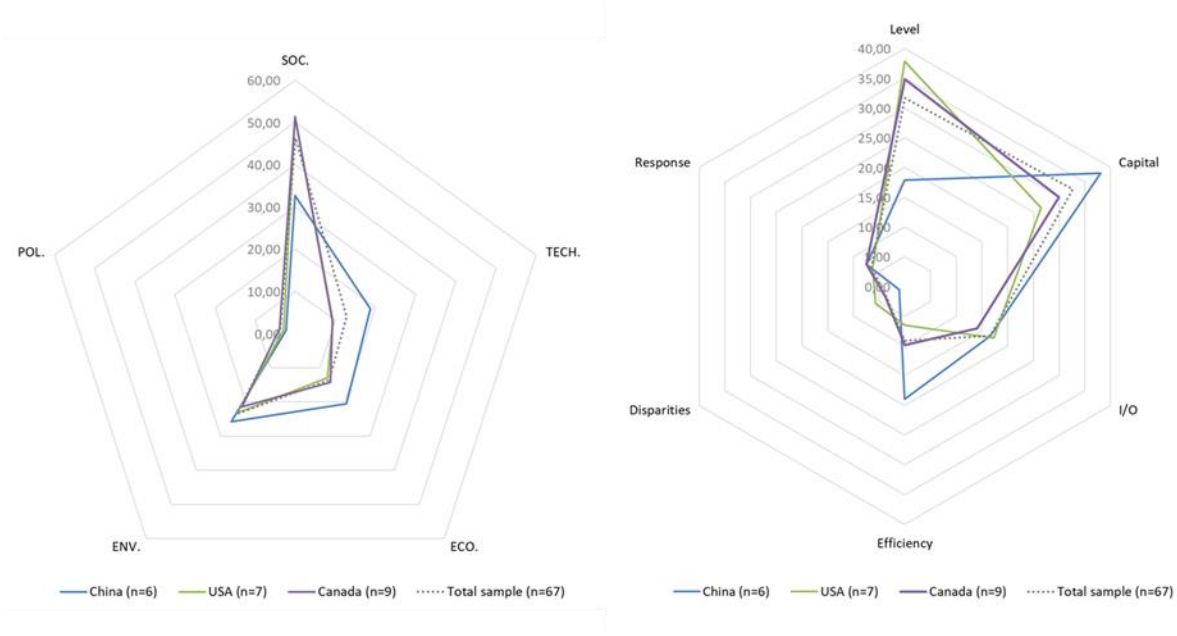


Fig. 12: Average attention paid to STEEP and MONET categories in indicator sets developed in the USA, Canada and China.

- **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

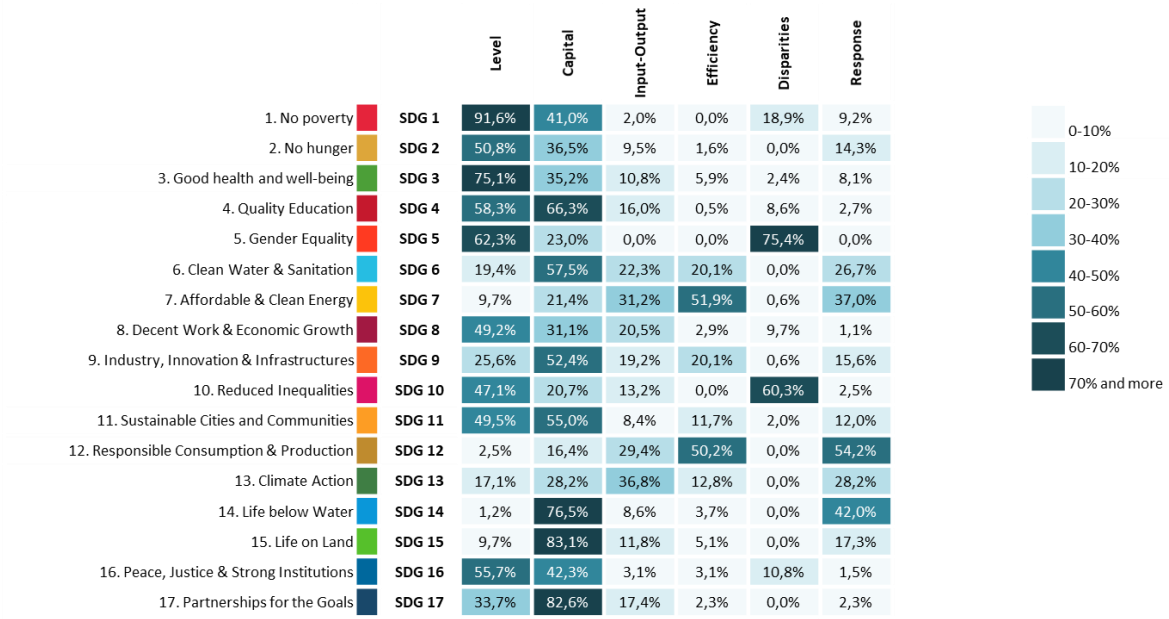
Observation #6: Indicator sets tend to prioritize frameworks based on simple logics

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, 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.



		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%

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.

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.

Acknowledgements

We gratefully acknowledge Dr. Silvia Hostettler for her comments on a previous version of this paper. Authors acknowledge support from Swiss Mobiliar and the Swiss Federal Office for the Environment (OFEV) as part of the funding of the Laboratory for Human Environment Relations in Urban Systems (HERUS) at EPFL. We are also very thankful to the anonymous reviewers for their constructive and helpful comments during the review process of the paper.

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Manuscript 4

Reference:

Halla, P., Merino-Saum, A., *forthcoming*. Conceptual frameworks for urban sustainability indicators - an empirical analysis. Publication pending.

This is a preprint version of the manuscript, published in the open archive SocArXiv: https://doi.org/10.31235/osf.io/vayq7

Contributions of the doctoral candidate:

The doctoral candidate had the main responsibility for designing the research, carrying out the analysis, as well as writing the manuscript. The second author contributed to the design of the research, was the principal author of the theoretical section, the analysis of goal-based frameworks and the comparison of framework types for different purposes, as well as contributed to revising the manuscript.

Conceptual frameworks for urban sustainability indicators - an empirical analysis

Abstract

Indicator-based assessment represents a popular means of operationalizing the concept of sustainability. A central yet often neglected aspect in the development of indicator sets concerns the elaboration of accompanying conceptual frameworks. Despite the pivotal role that such frameworks play, and the normative power they wield, little explicit guidance exists for their development. To address this issue, we analyze an extensive sample of conceptual frameworks drawn from 67 urban indicator initiatives. The results of the analysis elaborate an empirically-based typology of four principal and two emerging framework types, each based on a particular logic for creating conceptual categories for urban sustainability indicators. We also develop a comparison of the framework types in terms of their respective abilities to meet the different purposes that conceptual frameworks ideally serve in indicator set development. The results allow us to provide much-needed guidance for indicator set developers; first, by laying out the range of options available; second, by helping developers choose between types of frameworks in accordance with their particular aims. In addition, through analysis of how urban sustainability is *de facto* defined in indicator initiatives, we aim to make a conceptual contribution that advances our understanding of the meaning of this complex concept.

Keywords: Urban systems; sustainability; indicators; conceptual frameworks

1. Introduction

Over the last decades, the concept of sustainability has increasingly become more prominent in the strategies of both public and private sector actors. As part of this general concern, particular attention has been given to the sustainable development of urban areas (UN, 2017), which, due to their role as socio-economic hubs of human activity, constitute a crucial determinant of global sustainability (IPCC, 2014). To address this issue, a range of different actors from the international to the local scale have developed sets of indicators for measuring the sustainability of cities (Verma and Raghubanshi, 2018; Merino-Saum et al., 2020). Such indicator sets represent important means for the deployment of the complex concept of urban sustainability at a more concrete and operational level.

A central component in all sustainability indicator initiatives concerns the development of the accompanying conceptual frameworks (Pintér et al., 2012; Hák et al., 2016). These frameworks not only support the selection of indicators, but more fundamentally, they also contribute to the very definition of the concept (e.g. 'urban sustainability') being measured (Pintér et al., 2005; UN, 2007), which bestows them with tremendous normative power. Given the pivotal role of frameworks, it is surprising how little explicit guidance can be found in literature on how to suitably develop them (Burgass et al., 2017). Yet, each framework should be constructed with conscious consideration of the context and purposes of the indicator initiative in question (Munier, 2011), since simply copying frameworks from earlier initiatives can easily lead to the selection of indicators with poor resonance and usability for local decision-making (Nicholson et al., 2012).

Within the general lack of guidance for framework development, a more specific shortcoming concerns the vagueness around the options available when choosing between types of frameworks. To be precise, a number of authors have addressed the topic (Maclaren, 1996; Gallopín, 1997; Pintér

et al., 2005; Olalla-Tárraga, 2006; Lyytimäki and Rosenström, 2008; Nathan and Reddy, 2012), but their work lacks a firm foundation on a systematic empirical review and comparison of the range of options available. As a result, current scholarship is missing an explicitly defined and empirically-based typology of frameworks that could support indicator set developers in the task of framework construction.

The aim of this research is to address this gap in current scientific knowledge by systematically analyzing and comparing conceptual frameworks used in connection with urban sustainability indicator sets, based on a comprehensive empirical sample of 67 such indicator initiatives from the previous decade. This work allows us to make several contributions to the field of urban sustainability assessment. First, we lay out the range of options available to indicator set developers, both in terms of types of frameworks as well as their internal categories. Second, in comparing types of frameworks we aim to clarify their respective abilities to serve different purposes. Finally, by revealing what is included and excluded in the analyzed conceptual frameworks, i.e., how the indicator initiatives *de facto* define the concept of 'urban sustainability', we aim to contribute to the discussion on the meaning of this complex concept.

The organization of the article is as follows. Section 2 begins by providing a theoretical foundation for understanding the characteristics and purposes of conceptual frameworks in sustainability indicator initiatives. Section 3 presents the empirical sample and the method by which it was analyzed. Section 4 presents the results of the analysis in the form of an elaborated empirically-based typology of conceptual frameworks for urban sustainability indicators. Section 5 discusses the findings and formulates recommendations for future set developers. Section 6 concludes the article with a brief summary and a look ahead.

2. Indicator frameworks - Theoretical background

2.1. What is an indicator framework?

Although most reports and studies focusing on sustainability indicators allude to conceptual frameworks to some degree, concrete definitions are rarely provided. This reflects the general ambiguity that surrounds the term (Miles et al., 2014; Ravitch and Riggan, 2017). While for some a mere visual representation of a study's organization qualifies as a conceptual framework, for others it encompasses a broader set of elements, including a study's goals, theories and methods (Ravitch and Riggan, 2017). Therefore, there is a need to define what is meant by conceptual frameworks in the context of this article.

To that end, it is worth first making a distinction between procedural and conceptual frameworks (see Fig. 1). While procedural frameworks depict the methodology implemented to measure a particular concept (e.g. How can urban sustainability be measured?) and often consist of a sequence of stages with dedicated tools (Lyytimäki and Rosenström, 2008), conceptual frameworks are centered on the concept itself, along with its representation and subsequent translation into metrics (e.g. What is a sustainable city?).

The focus of this study is on a particular subset of conceptual frameworks used in connection with indicators (see Fig. 1)[40]. Different definitions exist in the literature for such indicator frameworks, with authors understanding them as 'models' (Becker, 2005), 'structures' (Nathan and Reddy, 2012; Burgass et al., 2017) or 'networks of interrelated concepts' (Pope et al., 2017). As we understand them in this paper, indicator frameworks are made of (i) an overarching concept; (ii) a finite number of conceptual categories to which the concept at hand can be broken down; and (iii) the interlinkages between the overarching concept, the categories and related metrics. More fundamentally, indicator frameworks may be conceived as *informational conductors* through which significance flows bi-directionally between abstract concepts and tangible metrics. Understood in this way, frameworks serve several purposes (see the following section).

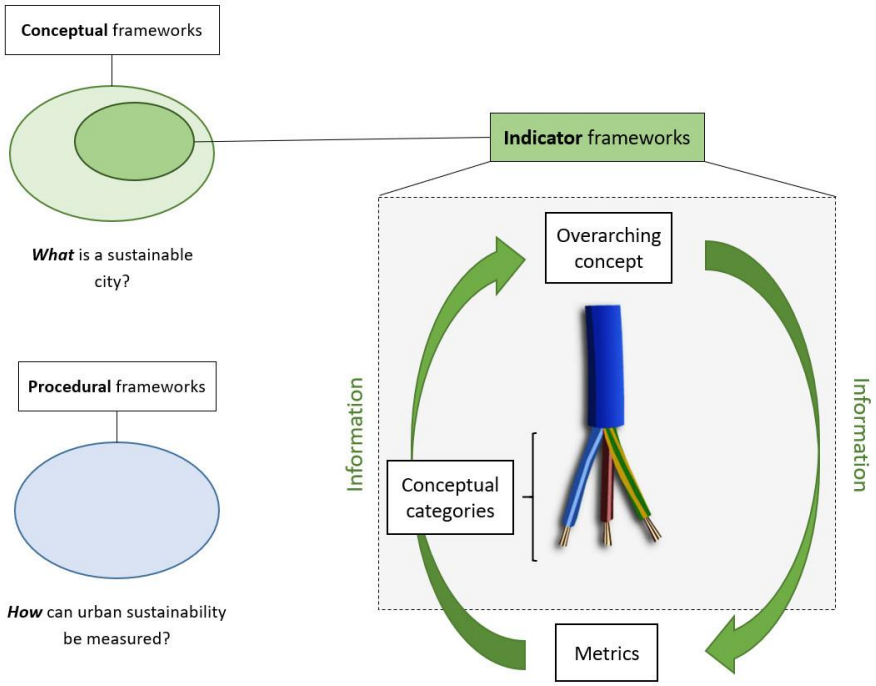

Fig. 1. Indicator frameworks as informational conductors bringing abstract concepts and tangible metrics together (source: Authors).

2.2. What are indicator frameworks for?

2.2.1. (re)Defining the overarching concept to be monitored (indicator frameworks as *mind maps*)

By depicting a finite set of constituent categories, indicator frameworks convey a particular understanding of the concept to be monitored (e.g. 'urban sustainability'). In that sense, indicator frameworks can be seen as *mind maps*, deepening the understanding of a central concept through key words and ideas. In Elgert's words, indicator frameworks crystallize *per se* a particular "sustainable city imaginary" (Elgert, 2018, p. 17), and as such, create a common 'meta-language' that can support interdisciplinary work and mutual learning (Sébastien and Bauler, 2013; Pope et al., 2017).

[40] For brevity, we will henceforth refer to these kind of conceptual frameworks simply as 'indicator frameworks' or 'frameworks'.

2.2.2. Guiding indicator selection and development (indicator frameworks as *radars*)

Indicator frameworks are used in indicator selection and development processes as *radars* through which areas that need to be covered by indicators are identified (Bossel, 1999), and as a means of spotting potential gaps and/or redundancies among the candidate indicators (Montmollin and Scheller, 2007; King, 2016). Such a scanning process allows for both the detection of possible problems of comprehensiveness and for increased parsimony (Spangenberg et al., 2002; Binder et al., 2010), thus leading towards more complete, balanced and reasonable indicator sets. The use of indicator frameworks as radars can also be done ex post, revealing degrees of coverage in existing indicator sets and allowing for comparison across several indicator initiatives (Merino-Saum et al., 2018; Feleki et al., 2018).

2.2.3. Structuring information (indicator frameworks as *skeletons*)

All sustainability indicator initiatives embed a plethora of diverse and complex information (Gallopín, 1997; Bossel, 1999). Hence, to be intelligible and meaningful, these elements need to be managed in some way. Indicator frameworks help in this task by 'organizing' (Babcicky, 2013), 'structuring' (van Oudenhoven et al., 2012), and 'classifying' (Bond et al., 2012) the information embedded in a sustainability indicator set. From this perspective, indicator frameworks can be seen as *skeletons*, in that they constitute the central supporting part of any indicator set without which the set would collapse into a mere conglomeration of disparate and disconnected items (Becker, 2005).

2.2.4. Representing how a phenomenon functions (indicator frameworks as *scale models*)

Indicator frameworks can be used to clarify interlinkages between both categories and indicators, and to elucidate their respective roles vis-à-vis the entire object under study (Wiek and Binder, 2005; Lewison et al., 2016). Frameworks as such not only depict what the overarching concept consists of, but can also promote a more detailed understanding of how the assessed object functions, thereby providing better insights as to how to move further towards sustainability. In this role, they can be compared with educational *scale models*.

2.2.5. Putting metrics into context (indicator frameworks as *anchors*)

Indicator frameworks are *anchors* that explicitly connect generic metrics to the concept they are expected to represent, in accordance with the object, context and general approach of the indicator initiative (Gudmundsson, 2003). In doing so, frameworks mutate otherwise non-specific metrics into indicators (Maggino, 2017; Merino-Saum et al., 2020) [41]. Indeed, by explaining how raw numbers and/or words are linked to a particular concept, indicator frameworks elucidate the concrete signification they carry in the ambit of a specific indicator set, thereby making them intelligible and relevant for decision-makers and stakeholders (Lyytimäki and Rosenström, 2008; Maggino, 2017).

[41] We understand indicators as multifaceted constructs ideally composed of: (i) a label; (ii) a unit of measurement; (iii) a definition; (iv) accessible data; (v) a reference point; and (vi) its anchoring in a particular conceptual framework (i.e. the categories and the concept with which it is associated) (Merino-Saum et al., 2020). This last element is what differentiates an indicator from a metric, which can be seen as a 'generic' or 'raw' indicator without any concrete meaning, thus being associable with more than one concept.

2.2.6. Communicating with the target audience (indicator frameworks as *business cards*)

Finally, indicator frameworks can also be used as communication tools, summarizing key information and providing a visual identity to the indicator initiative (Gallopín, 1997; Burgass et al., 2017). From this point of view, an indicator framework can be understood as a *business card* comprised of text and images through which an indicator initiative is communicated to its target audience as well as demarcated from other initiatives according to its particular focus and purposes. A good illustration of this is the framework of 17 Sustainable Development Goals (SDGs), which provide a strong (visual) identity for the United Nations' Agenda 2030 (UN, 2015).

2.3. How to develop an indicator framework?

Generally speaking, indicator frameworks can be built from two different starting points (van Zeijl-Rozema et al., 2011): (i) from a specific conception of urban sustainability, which is then disaggregated into several categories (concept-driven frameworks); or (ii) from a list of key indicators considered essential and which are sequentially aggregated into progressively abstract categories (indicator-driven frameworks). In either case, the steps followed should be considered carefully and documented transparently, since it is generally a normative "process of invention, not discovery" (Turnhout, 2009, p. 404), and which significantly influences the entire indicator initiative and its potential results (Merino-Saum, 2020).

A key step in the construction process of all indicator frameworks concerns the selection of a logic according to which the internal categories of the framework are defined, with each logic leading to a distinct type of framework. A number of authors have discussed these types of indicator frameworks, both for sustainability indicators in general (Gallopín, 1997; Pintér et al., 2005; Lyytimäki and Rosenström, 2008) and, in particular, for indicators dedicated to urban sustainability (Maclaren, 1996; Olalla-Tárraga, 2006; Nathan and Reddy, 2012).

However, what is lacking in the work of the above authors - and what this article aims to achieve - is (i) a systematic empirical exploration of different categorization logics from applied indicator initiatives; (ii) a mapping of how these logics are crystallized through specific categories; and, (iii) a comparative analysis of different indicator framework types considering both their key distinctive characteristics and their respective suitability to support the purposes elaborated in Section 2.2. In the absence of such analysis, indicator set developers are missing an overview of the range of options available for framework construction, as well as an understanding of why, in certain cases, one type of framework should be preferred over another, given their different intended purposes.

3. Materials and methods

The methodology applied in the research followed the steps depicted in Fig. 2. In broad terms, the methodology consisted of collecting a sample of urban sustainability indicator initiatives (Section 3.1), analyzing their respective conceptual frameworks (Sections 3.2-3.4), and creating a systematic comparison of the types of frameworks found in the sample (Section 3.5). The result is a typology of frameworks based on empirical evidence, with each type described by a definition and a list of type-specific categories.

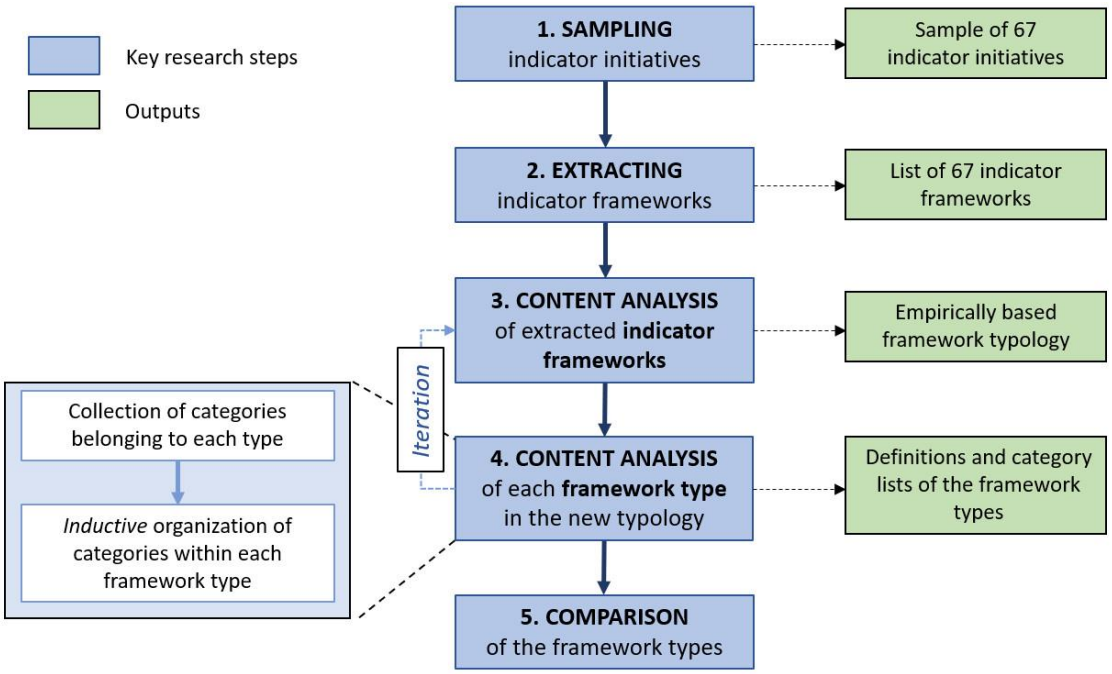

Fig. 2. The methodological steps followed in the research (source: Authors).

3.1. Indicator initiative sampling

The analyzed sample of indicator initiatives for urban sustainability, all developed between 2010 and 2019, was collected from both academic and grey literature (for complementary information, see: Merino-Saum et al., 2020). To create a first sample of potential indicator initiatives, the Scopus search engine was used as a means of systematically identifying relevant academic literature[42]. In contrast, the sampling of pertinent grey literature was more explorative: some initiatives were found through Google searches, while others were discovered by a snowball sampling method through references in related literature as well as the authors' own professional networks.

Five selection criteria were then applied to the first sample of 891 potential indicator initiatives: (i) empirical orientation; (ii) recent activity; (iii) clear and comprehensive focus on sustainability; (iv) explicit focus on the urban scale; and (v) access to indicators. The resulting final sample contains 67 indicator initiatives, of which 30 originate from academia and 37 from public, private or non-profit entities operating at the local, regional, national or international levels (for a full list of references see supplementary material or Merino-Saum et al., 2020).

3.2. Extracting indicator frameworks

The second step in the methodology was extracting the indicator frameworks from the associated material (articles, reports, websites, etc., related to the indicator initiatives). All initiatives but one were found to use some type of framework. To be consistent with our definition of an indicator

[42] The Scopus query: 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")).

framework (see Fig. 1), it was necessary at this point to clearly define the cutoff line between the metrics and the framework (see Fig. 3). As a rule, to qualify as a conceptual category and therefore as part of the framework, a term had to either (i) encompass at least two more specifically defined terms (like 'Air' in Fig. 3) or (ii) belong to a group of terms existing at an equal level of specificity that generally fulfilled criterion 1 (like 'Water' as part of a group together with 'Air', 'Health' and 'Economic welfare', in Fig. 3)[43]. In this manner, once the cutoff line between the metrics and the framework was determined, the terms considered to be metrics were omitted from the subsequent analysis.

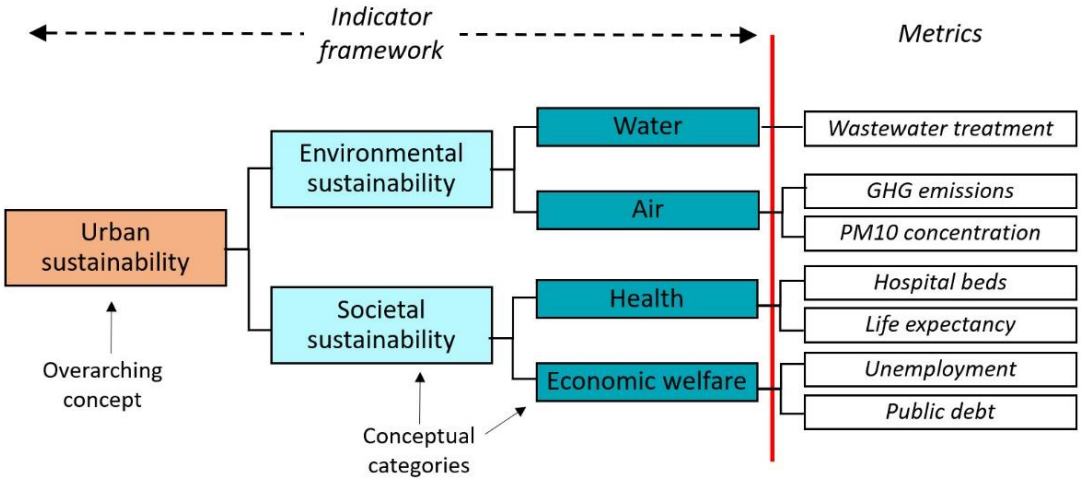

Fig. 3. An illustrative example of a distinction between conceptual categories (i.e., the indicator framework) and metrics (source: Authors).

3.3. Content analysis of indicator frameworks

The third step of the research process concerned a content analysis (Mayring, 2000) of the indicator frameworks extracted from the sample in order to develop a typology for their classification. More specifically, the analyzed content consisted of the titles of the conceptual categories included in the frameworks. The analysis followed an inductive procedure, whereby an initial coding scheme (representing types of categories) was first developed based on a rough scanning of the extracted frameworks. Then, a negotiated and iterative process among the authors followed, which involved assigning coding tags to the frameworks depending on the types of categories discovered within them and refining the original coding scheme to better represent the range of categories. Some frameworks in the sample were assigned a single tag (i.e., all categories representing a single type). However, in most cases the frameworks were 'hybrids' (see Section 4.1.6), i.e., they contained categories following more than one type of logic. The output of this step is a typology of indicator frameworks, where each type is defined by an archetypal logic for formulating categories of indicators of urban sustainability (See Table 1).

3.4. Content analysis of framework types

In the next step of the research, conceptual categories were assembled by framework type, according to the typology elaborated in the previous step. This involved the assimilation of duplicates, which

[43] The only exception to the rule was Cercle Indicateurs (2017), whose framework contains a set of items mostly encompassing one metric. However, the titles of the items are expressed in a sufficiently conceptual manner as to qualify them as *conceptual* categories.

considerably reduced the overall number of categories (see Fig. 4). The research team then analyzed the lists of categories in-depth with the aim of organizing them into logical structures. The analysis followed the logic of inductive content analysis (Mayring, 2000), and resulted in a distinct structure for each of the framework types (see Sections 4.1.1-4.1.5). The collection and organization of the indicator categories within the framework types also resulted in a deeper understanding and demarcation of said types. Consequently, this led to an iterative refinement of the definitions of the framework types. To augment the transparency of the choices made in the process, lists of indicator categories considered for each of the framework types are can be found in the supplementary material.

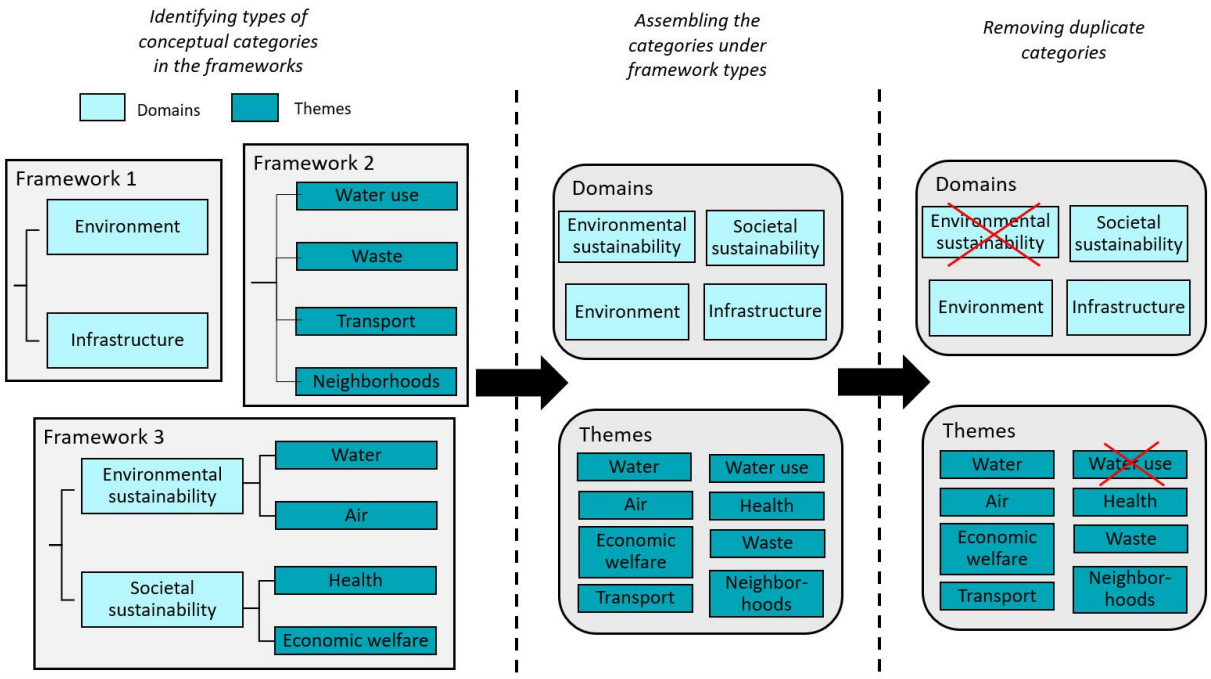

Fig. 4. An illustrative example of the collection of lists of categories for each type (source: Authors).

3.5. Comparison of framework types

Finally, the thorough definition and analysis of the framework types found in the sample allowed us to make comparisons between them. This comparative analysis first focused on the basic characteristics that make each framework type distinct from the others, and then, based on this, their respective suitability to address the purposes of indicator frameworks (see Section 2.2). The results of this two-step analysis are presented in Section 4.2.

4. Results

4.1. New indicator framework typology for urban sustainability

The analysis of the 67 frameworks allows us to propose the typology seen in Table 1. The typology consists of four principal types, each defined by an archetypal logic for categorizing indicators of urban sustainability. Also, a small number of frameworks in the sample displayed distinctive logics falling outside of the four principal types. These additional logics may be viewed as emerging logics in

indicator framework development. In addition to the types based on a single logic, our typology also acknowledges hybrid frameworks, i.e., frameworks combining multiple logics.

Type		Definition
Principal logics	***Domain***	Categorization based on the most general perspectives or sub-systems pertinent to sustainability and reducible only to the overarching concept
	Theme	Categorization based on topics and challenges pertinent to sustainability
	Goal	Categorization based on outcomes seen as desirable for sustainability
	Systemic	Categorization based on a model that explicitly defines the relationships between indicator categories
Emerging logics	**Spatial**	Categorization based on physical location or scale
	Epistemological	Categorization based on kinds of knowledge
	Hybrid	Categorization combining several of the above logics through either hierarchization, juxtaposition, assimilation or matrix-like integration

Table 1: Typology of indicator frameworks based on the analysis of 67 urban sustainability initiatives.

4.1.1. Domain-based frameworks

The use of domains was prominent in the analyzed sample, with 34 out of 67 initiatives identified as using this type of logic. From the 34 frameworks, an initial list of 119 categories was produced. After the assimilation of duplicates and the removal of categories falling under the definition of other types, the final list of domain-based categories consisted of eleven examples (see Fig. 5). Among these, 'environment' (26 instances), 'economy' (24 instances) and 'society' (22 instances) were by far the most common, both in terms of their appearances individually and in combination with each other. 'Governance', on the other hand, featured only in six cases.

In addition to these four typical domains, alternative domains were also discovered. In particular, rather than a more generic 'environment', six cases used the more specific domain of 'built environment' and four cases the domain of 'natural environment'. In addition, five cases referred to 'natural resources', one of them (Xu et al., 2016) to explicitly distinguish it from 'natural environment'. Furthermore, using 'human' or 'people' as a domain instead of or alongside 'society' was preferred by some cases in the sample (Sustainable Society Foundation, 2014; Wu et al., 2018). Finally, two examples were found to use the domain of 'external connections' (Shen and Yang, 2014; Xu et al., 2016), i.e., referring explicitly to the relationship that urban systems have to their surroundings.

Note that our definition of domain-based frameworks refers to conceptions of domains as either 'perspectives' or 'sub-systems'. Indeed, both ways of understanding domains can be observed in the analyzed sample. For example, in Phillis et al. (2017) all water-related metrics are embedded within the environmental domain, thus implying that the latter is seen as a distinct sub-system. In contrast,

in Smiciklas et al. (2017) water-related metrics can be found both within the economic (e.g. access to water supply) and environmental (e.g. water consumption) domains, which implies that the domains are viewed as perspectives that highlight different aspects of the theme in question.

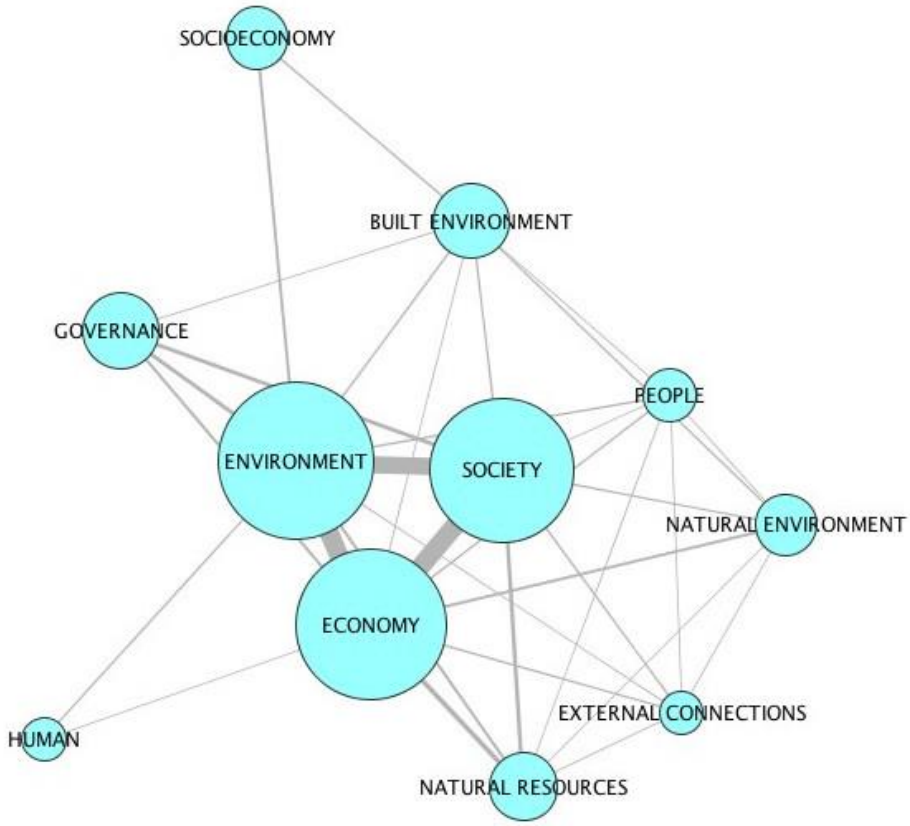

Fig. 5. The eleven domains of urban sustainability identified in the sample. The size of each node is based on the number of cases containing the respective domain. The thickness of the edges indicates the frequency with which the respective two nodes co-occur. The position of the nodes in the graph is defined using a stress minimization algorithm. The graph is drawn from data found in the supplementary material (source: Authors).

4.1.2. Theme-based frameworks

Themes represented the most common categorization logic of the analyzed sample, as 52 of the 67 analyzed frameworks were identified as containing categories of this type. In total, an initial list of 703 thematic categories (prior to the removal of duplicates) was collected from these frameworks. Analysis of these two categories saw the emergence of a two-tiered structure (see Table 2) [44], thus marking two subtypes of the theme-based logic. The difference between these two tiers is the specificity of the categories; the first level ('headline themes') consists of fairly general topics (e.g., transport), while the second level ('sub-themes') refers to more specific challenges (e.g., congestion). The final list of theme-based categories contains 38 headline themes and 140 sub- themes. Note that due to space restrictions Table 2 contains only a maximum of 2 sub-themes for each headline; a comprehensive list of sub-themes can be found in the supplementary material.

[44] Table 2 should be read as a qualitative mapping of the breadth of themes found in the sample. For quantitative information on the relative attention that the indicator sets give to different areas of sustainability, refer to Merino-Saum et al. (2020).

Well-being	**Natural resource use**	**Culture & arts**
- Social well-being	- Urban metabolism	- Cultural heritage
- Personal well-being	- Resource recovery	- Heritage conservation
- (…)	- (…)	- (…)
Basic needs	**Water**	**ICT infrastructure**
- Poverty	- Drinking water	- Connectivity
- Affordability (cost of life)	- Wastewater	
- (…)	- (…)	
Demography	**Solid waste**	**Urban planning**
- Workforce	- Waste management	- Complexity
- Immigrant population	- Waste generation	- Land use
- (…)	- (…)	- (…)
Employment	**Air**	**Neighborhoods**
- Jobs & livelihoods	- Air quality	- Local welfare
- Work-life balance		- Local management
- (…)		- (…)
Economic system	**Soil**	**Civic environment**
- Economic growth	- Soil protection	- Civil participation
- Structure of the economy	- Soil pollution	- Political participation
- (…)	- (…)	- (…)
Industry & Trade	**Externalities**	**Community**
- Creative industries	- Pollution	- Social cohesion
- Distinctive local industries	- Noise	- Cultural diversity
- (…)	- (…)	- (…)
R&D and Technology	**Energy**	**Partnerships**
- Innovation	- Energy consumption	- Exchange
- Research & Development	- Quality of energy	- Interregional solidarity
- (…)	- (…)	- (…)
Investments	**Education**	**Public system**
- Foreign investments	- Lifelong learning	- Institutional capacity
- Public investments	- Environmental education	- Participatory pub. management
- (…)	- (…)	- (…)
Environmental quality	**Health & healthcare**	**Public finance**
- Life below water	- Mental health	- Public expenditure
- Life on land	- Primary care	
- (…)	- (…)	
Urban landscape	**Housing**	**Services**
- Green & blue spaces	- Green buildings	- Public service delivery
- Open & public spaces	- Indoor environmental quality	- Digital public services
- (…)	- (…)	- (…)
Climate	**Transportation**	**Lifestyle behaviors**
- Climate protection	- Congestion	
- Low carbon society	- Transport proximity	
- (…)	- (…)	
Environmental exposure	**Security**	**Inclusion & equality**
- Disaster risk management	- Crime	- Social inclusion/exclusion
- Vulnerability to climate change	- Gender-based violence	- Gender inclusion & equality
- (…)	- (…)	- (…)
Food	**Sport & recreation**	
- Hunger & food security	- Leisure	
- Urban agriculture	- Recreational facilities	
- (…)	- (…)	

Headline theme
- Sub-theme 1
- Sub-theme 2

Table 2. Theme-based categories.

4.1.3. Goal-based frameworks

In total, 219 categories (from 18 indicator sets) were extracted with titles explicitly referring to a specific goal, i.e., an outcome seen as desirable. The analysis of these categories showed that they all

express their respective goals by referring to a particular *area of sustainability* (i.e., either a domain or a theme) combined with either an *action* (e.g., promote, prevent), an *attribute* (e.g., local, healthy), or both[45]. From the analyzed categories, the research team identified in total a list of 20 actions, 42 attributes, and 43 areas of sustainability. The Sankey diagram presented in Fig. 6 illustrates how these actions, attributes and areas of sustainability are combined among the goal-based categories (the diagram only considers those combinations appearing more than once).

As seen in the figure, no clear trends are evident, and elements are used together in a multitude of different ways. Only a few combinations are repeatedly used in the sample, such as "assure-accessible-...", "promote-sustainable-...", "reduce-externalities" or "protect-natural ecosystems". Generally, goal-oriented categories are formulated in a positive manner (e.g. "promote"; "develop"; "assure"; "create"; etc.), and refer to the same domains and themes as identified in Sections 4.1.1 and 4.1.2.

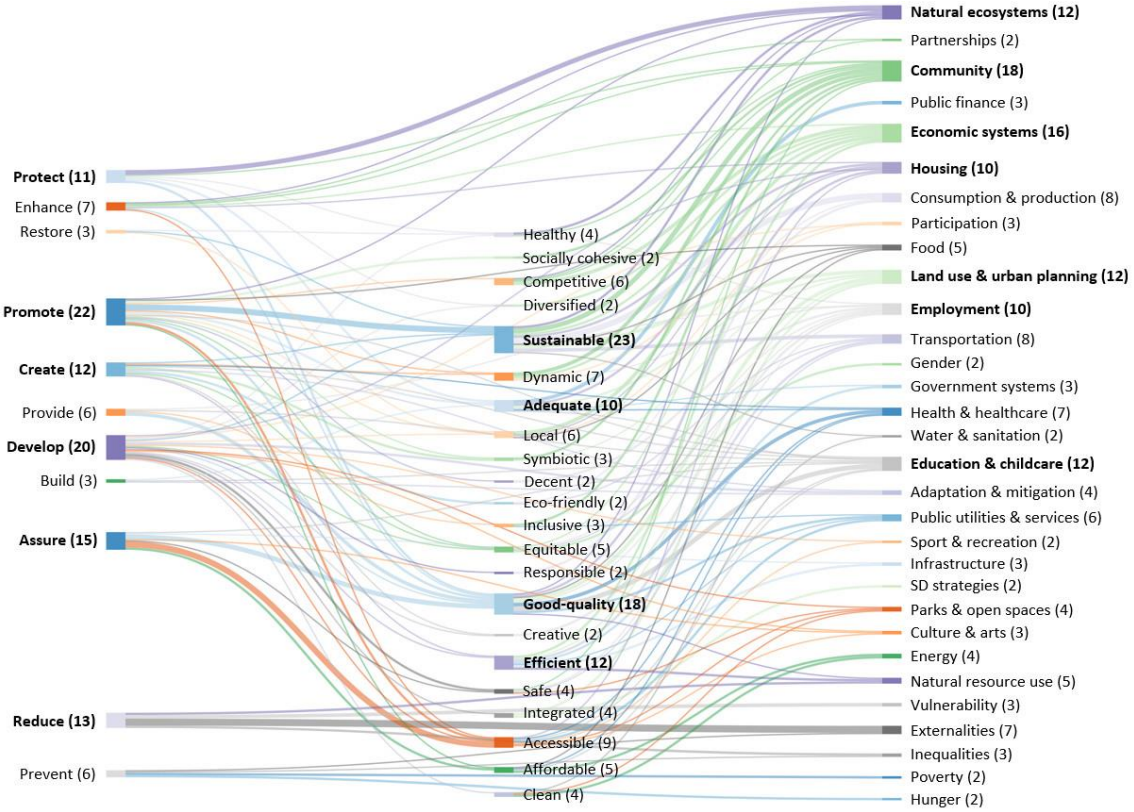

Fig. 6. Sankey diagram illustrating the diversity of goal-oriented categories found in the sample (categories are codified as combinations of actions, attributes and/or areas of sustainability). Numbers in brackets express the appearance frequency of each construct. Categories in bold appear ten times or more (source: Authors).

4.1.4. Systemic frameworks

In the analyzed sample, five cases were considered to fit the definition of the systemic type[46]. The analysis revealed that among these five cases there are two different manners of defining the

[45] A theme combined with both an attribute and an action (e.g., "Promote sustainable urban transport"; "Provide good-quality housing") was the most frequent case in the sample with 85 occurrences (i.e., 38.81%).

[46] To clarify, we consider two common framework models (1. A simple hierarchy of categories; 2. A model where all categories are portrayed as connected with all other categories in a symmetric manner) to have fallen outside of the definition as *insufficiently* specifying the relationships between the categories.

relationships between categories, as illustrated by Fig. 7. Four cases (Dubiela, 2011; Wang et al., 2013; Xu et al., 2016; Valcárcel-Aguiar et al., 2019) differentiate indicator categories in terms of the functional roles that they play vis-à-vis each other within the system (Fig. 7a). In contrast, in one case (Wu et al., 2018) the relationships are elaborated via dedicated indicator categories placed at the interfaces of primary categories (Fig. 7b).

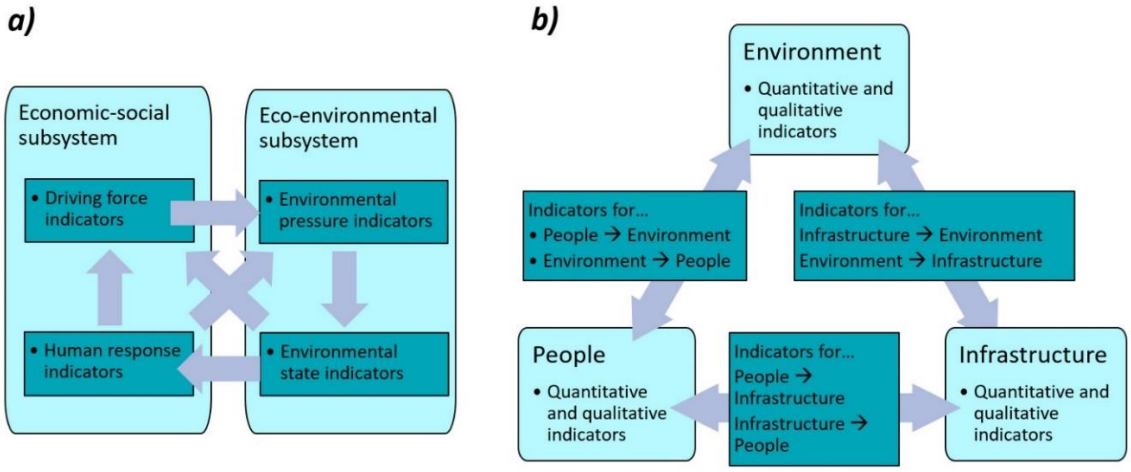

Fig. 7. Examples of systemic frameworks: a) Wang et al. (2013); b) Wu et al. (2018) (source: Authors based on said original sources).

4.1.5. Emerging framework types

As mentioned above, some cases in the sample were identified as using an indicator categorization logic other than the four principal types. Two such emerging logics were discovered in the sample, one making a spatial distinction between categories of indicators, and another making an epistemological distinction, i.e., categorizing indicators based on the kind of knowledge that they represent.

The spatial distinction between categories can appear in terms of scale, as in the case of Yigitcanlar et al. (2015) who identify indicators at both the micro and mezzo levels, or in the case of Balaras et al. (2019) who distinguish between building scale and neighborhood scale indicators. Alternatively, the spatial distinction can also be made in pure geographical terms. An example of the latter is Baca (2014) who discriminates between urban and rural indicators. It can be noted that several of the analyzed indicator initiatives provide measured data at different scalar levels (most often neighborhoods or districts); however, they do not conceptualize the scalar differences in their frameworks.

As for the epistemological distinction between categories of indicators, for three examples found in the sample (Baca, 2014; Wu et al., 2018; Association suisse pour des quartiers durables, 2018) this meant specifically differentiating between quantitative and qualitative indicators.

4.1.6. Hybrid frameworks

The framework types presented above must be understood as theoretical archetypes differentiated from each other for didactic purposes. In practice, frameworks are most often hybrids that combine several logics at once. In our sample, hybrid frameworks represent almost three quarters of the total examples (49 out of 67). Their analysis revealed four generic ways in which the hybridization occurs: (i) hierarchization; (ii) juxtaposition; (iii) assimilation; and (iv) matrix-like integration (see Fig. 8).

Hybrid frameworks most frequently rely on a *hierarchical* treelike structure through which categories from one type (e.g., themes) are systematically placed within one or several categories from another type (e.g., domains), as if the latter were broader constructs embedding the former. More than one third of the indicator sets in the sample are based upon such a hybrid framework, with a majority of them containing domains as upper-level categories and themes as lower-level ones (see for instance: Sustainable Society Foundation, 2014; Cercle Indicateurs, 2017).

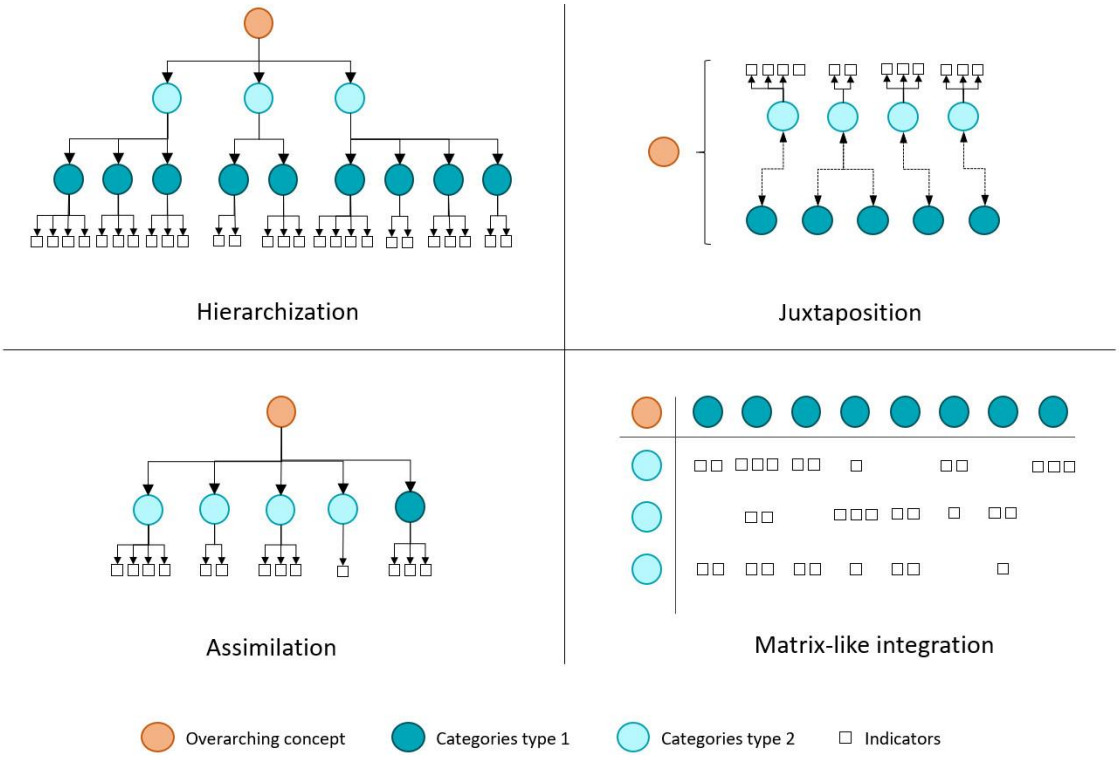

Fig. 8. A typology of hybrid frameworks observed in our sample (source: Authors).

While hierarchization involves a vertical combination of framework types, assimilation implies a horizontal one. In this manner of hybridization, categories are equated with each other without consideration of the underlying categorization logic (Keough et al., 2011; City of Minneapolis, 2012; Basque government and Udalsarea21, 2016). Assimilation most often relies on an unbalanced combination, with categories from one specific type being majoritarian and those from other types constituting isolated cases (see Fig. 8).

Hybrid frameworks can also be built by juxtaposition, where indicators are simultaneously associated with two frameworks representing two different types (generally one of them plays a central role). Most often, juxtaposition is used when co-existing frameworks fulfil different purposes within the same indicator initiative, e.g., indicator selection and communication (see Section 2.2). As an example, Smiciklas et al. (2017) connect their indicators both to a theme-based framework as well as to the framework defined by the SDGs.

Furthermore, framework types can be integrated through a matrix-like reasoning in which two different types are considered at the same descriptive level, and all categories from one type can be associated with any category from the other type. In our sample, only one indicator set relies on such a hybrid framework (Haider et al., 2018).

Finally, our analysis also demonstrates that hybrid frameworks can be built through several combinative methods. For instance, the framework of Wu et al. (2018) is framed as a tree made of two hierarchical levels: an upper one including domains and a lower one horizontally mixing themes and system components.

4.2. Comparison of principal framework types

4.2.1. Comparing the characteristics of framework types

The analysis presented above allows us to elicit the inherent characteristics of the principal framework types with regard to each other. We make this comparison along three axes (see Fig. 9) selected to provide a maximum possible contrast between the framework types. It should be noted that the comparison refers to type-specific tendencies, and not absolutes.

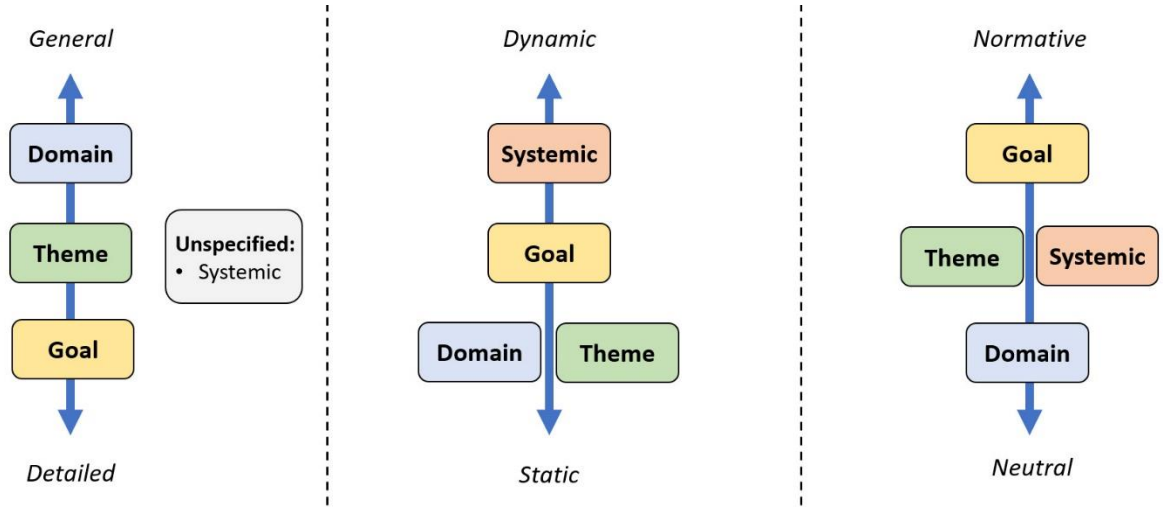

Fig. 9. Comparing the framework types (source: Authors).

The first comparative axis concerns the level of detail with which the conceptual categories are defined. Here, a progressive increase of detail can be seen proceeding first from domains (the most general type), to themes (by narrowing the focus of the categories to more specific areas of sustainability), and then to goals (by attaching actions and/or attributes to the themes). Meanwhile, the systemic type, although being more *complex* than the other types by including interrelationships between categories, does not inherently imply a particular level of detail.

Secondly, a difference can be made between the framework types in terms of whether they convey a predominantly dynamic or static image. Here, systemic frameworks, in attempting to capture the inner workings of the overarching concept being measured, display a dynamic understanding of said concept. At the same time, the goal-based logic, by expressing certain intended future outcomes also contains an element of dynamism. In contrast, the domain and theme types limit themselves to lists of areas of sustainability, and can therefore be described as more static than the two previous types.

Concerning the third axis of Fig. 9, goal-based logic, by explicitly specifying outcomes against which evaluations can be made, represents the highest level of normativity. However, the other logics also display varying levels of normativity. Namely, whether by adding detail (theme type) or complexity (systemic type), a framework implicitly also increases in normativity when becoming more specifically defined. Conversely, the domain type, by virtue of its generality, remains more neutral, and therefore

leaves a greater part of the normative task of interpreting the meaning of the overarching concept to the selection of metrics with which the framework is populated.

4.2.2. Comparing suitability of framework types for different purposes

The inherent differences between the framework types presented in the previous section render them unequal in serving the different purposes elaborated in Section 2.2. For instance, given their broad level of description, domain-based frameworks might be unsuitable for deepening understanding of the overarching concept or for attributing a clear signification to related metrics. Their simplicity, however, makes them particularly appropriate for communication purposes. In contrast, systemic frameworks generally involve more elaborated categorizations, which certainly better explain how a particular phenomenon works, but the logics of which might be difficult to grasp for lay people, thus potentially making communication more difficult.

In Table 3, we develop this comparison of the principal framework types in more detail. Goal-oriented frameworks are seen to effectively address the highest number of different purposes (4 out of 6). At the same time, the systemic framework type is the only one found not to be incompatible with any of the given purposes.

	DOMAIN-BASED	THEME-BASED	GOAL-BASED	SYSTEMIC
(re)Defining the overarching concept	▶ Remains abstract in understanding of the overarching concept	▶ By being more detailed (compared to domains), adding clarity to concept	▶ More detailed than either domains or themes; thus, clearer in understanding of concept	▶ Contributes a dynamic and holistic aspect to the concept; however, may remain abstract
Guiding indicator selection and development	▶ Helpful for easy check of balance of coverage; however, not supportive in indicator definition or selection due to being unspecific	▶ More detailed level (compared to domains) assists in identifying indicators; however, dynamic aspects are neglected	▶ Provides multiple lenses through which candidate indicators can be identified (i.e., themes, attributes & actions)	▶ By elucidating links, can point to areas otherwise not covered by indicators; however, may remain too abstract or difficult
Structuring information	▶ Not helpful due to unspecific description of categories	▶ The specificity of categories facilitates easier organization of information	▶ High potential by having highly specific categories (actions, attributes and themes)	▶ May remain too abstract or complex for this purpose
Representing how a phenomenon functions	▶ Says very little, if anything, about the functioning of a phenomenon	▶ Says very little, if anything, about the functioning of a phenomenon	▶ Despite involving a certain dynamic perspective, saying little about the functioning of a phenomenon	▶ By elucidating both links between components and their respective functions, particularly well-suited for this purpose

Putting metrics into context	► Not much support for anchoring metrics due to low level of detail	► Connecting metrics to themes generally elucidates a precise anchor	► With the presence of specific goals is able to confer a precise anchoring to any metric	► Can provide a very specific anchoring to metrics; however, may be too abstract or complex for anchoring metrics understandably
Communicating to targeted audience	► Easy to understand and resonates with all audiences; however, meaning may be ambiguous due to lack of specificity	► Generally easy to understand and relatable to a wide audience	► Generally easy to understand and relatable to a wide audience; however, normativity may make acceptance more difficult	► Limited under-standability and resonance with non-experts; some systemic frameworks known in the policy arena (e.g. PSR, DPSIR)

Table 3. Comparing principal framework types across purposes. The color scheme indicates the suitability of the type for the given purpose (red = poor; yellow = ambiguous; green = good), with the type considered best indicated by the grey background color of the cell.

5. Discussion

5.1. The new indicator framework typology

As we have argued, conceptual frameworks constitute a central component in the translation of the concept of urban sustainability into sets of indicators. This claim is supported by the observation that 66 of the analyzed 67 urban indicator initiatives employed a conceptual framework of some kind. To support the design of these frameworks, the analysis presented in the preceding results sections elucidates a typology that aims to make explicit the available options, both in terms of types of frameworks and their internal categories.

The typology, which consists of four principal and two emerging types, can be contrasted with earlier scholarly work on urban indicator frameworks, especially Maclaren (1996), Olalla-Tárraga (2006) and Nathan and Reddy (2012). When compared with these authors, our typology represents both an elaboration and a simplification. In terms of the elaboration, the work presented in this paper deepens our knowledge of the four principal framework types (domain, theme, goal and systemic) in several ways: first, by giving each type a clear definition that demarcates them from each other, thereby furnishing them with a more precise meaning; second, by elaborating on their internal structure and sub-types; third, by making explicit the features that differentiate them from each other; fourth, by illustrating a list of potential categories for each type. Furthermore, our analysis revealed two emerging framework types (spatial and epistemological) not mentioned by the above authors. Although these types of frameworks were exceptions in the analyzed sample, they nevertheless represent interesting alternatives to the more established framework types.

In terms of simplification, the typology collates three types discussed by the previous authors ('sectoral', 'issue-based' and 'thematic') into one 'theme-based' type, because any difference between the three logics is, in practice, difficult to maintain. At the same time, we illustrate that the theme-based logic is not monolithic, but can be made operational at different descriptive levels (see Table 2). In addition, our typology makes an association between several types discussed by the above authors

('causal', 'capital', 'ecosystemic', 'systems') based on the observation that all of these types share a common focus on the interrelationships between categories, thus warranting the creation of a general 'systemic' type.

The methodical analysis of the framework types also allows us to draw conclusions with regard to their relative suitability to serve different purposes (see Table 3). As we show, none of the types presented in this paper are able to perfectly address all of the potential indicator framework roles (i.e., frameworks as *mind maps*, *radars*, *skeletons*, *scale models*, *anchors* and/or *business cards*; see section 2.2). Hence, the selection of a framework type should hinge on the particular aims, context and target audience of each indicator initiative. For example, while supporting communication can be a key priority when the initiative is primarily addressed to the general public, representing how a system functions likely has greater resonance in scientific contexts.

5.2. The meaning ascribed by the indicator frameworks to 'urban sustainability'

Another aim of the present paper was to inquire into what is included and excluded in the indicator frameworks, and in doing so contribute to a discussion about the meaning of the concept of urban sustainability. The first relevant observation is the pure number of cases using a particular logic for framework construction: out of the 67 cases analyzed, 52 used theme-based logic, 34 domain-based logic, 18 goal-based logic and 5 systemic logic. This implies that, at least at the framework level, urban sustainability is mostly conceptualized as a matter of different areas (domains, themes) of concern, and less so as an explicitly value-laden concept related to specific normative goals (Wiek and Binder, 2005). The low number of frameworks utilizing a systemic framing also conveys an impression of urban sustainability mostly understood as being composed of discrete and static rather than interconnected and dynamic elements. Arguably, such framing of the concept is rather simplistic, and is only partly compensated by the added conceptual depth gained through the use of multi-tiered hybrid frameworks.

The analysis of the domain-based categories revealed that the standard three pillar model (environment, society, economy) continues to be an influential vision for urban sustainability. However, our mapping also uncovered other possible domains that project a more nuanced meaning behind urban sustainability. For example, by distinguishing the domain of built environment from natural environment, some of the analyzed frameworks highlight that the presence of human-made infrastructures is a distinct, even definitional characteristic of cities (UN, 2019). Likewise, separating the domain of natural resources from natural environment, as some of the analyzed frameworks do, emphasizes the reliance of cities on their hinterlands for resource inputs (Rees and Wackernagel, 1996), and more generally highlights two distinct conceptions of the relationship between humans and nature (ecocentric vs. anthropocentric).

The great number of thematic categories (Table 2) evidenced by our analysis paints urban sustainability as encompassing a broad variety of subjects, focuses and concerns. In fact, this multiplicity can be argued to represent a distinct feature of both urban systems and urban sustainability (Halla et al., 2020), reflecting the role of cities as hubs of people, infrastructures and socioeconomic activity (Mori and Christodoulou, 2012). Indeed, disregarding this multiplicity, and evaluating the sustainability of cities for example only on their environmental records would mean ignoring the leading role that cities play in the socioeconomic aspects of sustainability.

The important relationship between cities and their surroundings (locally or globally) is generally poorly represented in the frameworks of the sample, with only a few exceptions explicitly referring to the topic (Baca, 2014; Shen and Yang, 2014; Xu et al., 2016). This can be considered a crucial omission, as managing the leakage effects of urban systems constitutes a central challenge in urban sustainability (Kennedy et al., 2007). Another feature of urban sustainability found absent in the frameworks concerns the temporal dimension. This aspect could be taken into account, for example, by categories referring to different time horizons (e.g., 'now' and 'later' in UN (2014); 'immediate', 'medium-term' and 'long term' in Alderton et al. (2019)).

In summary, the analyzed sample displays a broad diversity of interpretations of urban sustainability, both in terms of the level of detail embedded in the frameworks (ranging from a few domains to complex systemic framings), as well as the selected categories (ranging from the standard three pillars of sustainability to categories tailored to the urban context). To some extent, the frameworks can be criticized for their simplicity (e.g., the low number of systemic frameworks) or for neglecting certain key areas of urban sustainability (e.g., spatial and temporal aspects). Of course, any criticism of the conceptual shortcomings of the indicator frameworks must be tempered given that generally they must, in contrast to those conceptual frameworks expressly developed to support scientific analysis (e.g., Ramaswami et al., 2012), reconcile accuracy with the requirement of understandability among non-expert stakeholders.

5.3. Recommendations to indicator set developers

Based on the analysis presented above, we put forward the following recommendations for future urban indicator set developers. The first recommendation is simply to grant adequate attention to tailoring a framework that is suitable for the context-dependent needs of the indicator initiative, since it directly influences how compelling the initiative as a whole will be. In particular, this tailoring pertains to the selection of a particular categorization logic (domain, theme, goal, systemic, etc.) based on which the indicator framework is constructed, since each type of logic has its own strengths and weaknesses in serving different purposes. In addition, populating the framework with a list of categories should reflect the specific characteristics of the object being measured (e.g., a particular city with specific challenges), and not merely follow the blueprints of earlier initiatives.

The second recommendation relates to the level of elaboration incorporated into the indicator framework. This decision involves a tradeoff. On the one hand, a highly elaborated framework can ensure a more detailed coverage of pertinent areas and goals of sustainability, as well as provide functional information about the system being measured, thereby better enabling the design and monitoring of different intervention strategies. On the other hand, frameworks which are too convoluted can become limited in practical applicability and understandability. Therefore, we recommend that the level of elaboration of the framework is addressed explicitly at an early stage of the development of an indicator initiative. The decision should hinge on the purposes targeted by the initiative in question; in particular, whether the aims of the initiative relate more to communication or to the production of scientific knowledge. It is also perfectly possible to use two parallel frameworks, with one used for communication and another for scientific purposes.

Third, to target several purposes simultaneously, hybrid solutions combining elements from several types can be recommended. In such cases, set developers must carefully consider potential problems

of coherence. Notably, particular caution should be exercised when categories based on different logics are assimilated to each other (see Fig. 8). For example, considering categories that express a different level of detail as equivalent (e.g., assimilating the domain 'society' and the theme 'waste management') creates an imbalance in the framework whereby some aspects of urban sustainability receive disproportionate attention in comparison with others. Another form of imbalance is created if normative goal-based categories are mixed with purely descriptive ones (e.g., 'efficient economy' vs. 'society').

The fourth recommendation concerns the use of domains in indicator framework construction. Despite its ubiquity, the meaning of the concept of domain is not obvious, as it can be understood as either a sub-system or as a perspective (see Section 4.1.1 and Purvis et al., 2019). This alters the meaning of each domain category, and consequently also changes the group of metrics which should be selected for each category. Therefore, to avoid confusion and randomness in choosing which metrics are to be contained within each domain, the recommendation is to clearly define what the domains represent in each application.

Finally, as outlined throughout the analysis and discussion in this paper, urban sustainability can be expressed through a multiplicity of possible frameworks, and the decisions taken to arrive at a particular framing have normative consequences. Therefore, if the ambition is to develop an indicator set through an inclusive procedure involving both experts and non-expert stakeholders, the inclusiveness should also extend to the phase of framework development. This not only enhances the ability of the resulting indicator set to adequately capture the diversity of concerns embedded in the concept of sustainability, but it also allows for the involved actors to discursively develop a common understanding of what a sustainable city is.

6. Conclusion

Conceptual frameworks are a central but often unappreciated part of indicator initiatives, despite the many important roles that they may perform, and the normative power they wield. The work reported in this article contributes to making the development of these frameworks more reflective and transparent. We achieve this by creating a typology of frameworks based on a comprehensive empirical sample, by discussing the relative strengths and weaknesses of each framework type, and by highlighting the gaps that remain in the conceptualizations used by current indicator initiatives. Through the analysis, the presentation of available options (both in terms of types of frameworks and their internal categories), and the general recommendations that we formulate, we hope to assist indicator set developers in formulating frameworks that are appropriate for their particular purposes. In general, we hope that this contribution lends attention and encourages debates on this specific yet crucial aspect of (urban) sustainability assessment.

The analysis of a large number of indicator frameworks presented in this article also provides an interesting overview of the practical meaning of the concept of urban sustainability. Knowledge on this is crucial, given the influence that such framing exerts in the shaping of ensuing actions and policies. The analysis revealed a generally multifaceted understanding of urban sustainability in terms of breadth of areas covered. However, important omissions remain, especially related to spatial and temporal aspects of urban sustainability, and to the creation of more complex, systemic

conceptualizations of the concept. Filling these gaps in upcoming indicator initiatives constitutes a major opportunity to better orientate decision-making processes towards more sustainable cities.

Acknowledgements

We gratefully acknowledge Dr. Livia Fritz, Dr. Silvia Hostettler and Prof. Dr. Claudia R. Binder for their comments on a previous version of this paper, as well as Dr. Romano Wyss for drawing Fig. 5. Authors acknowledge support from Swiss Mobiliar (536527) as part of the funding of the Laboratory for Human Environment Relations in Urban Systems (HERUS) at EPFL. The research and preparation of the article was conducted without the involvement of the funding sources.

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Manuscript 5

Reference:

Halla, P., Merino-Saum, A., Binder, C.R., *forthcoming*. Contextually rich sustainability assessment for supporting local urban governance - connecting indicators to institutions and controversies. Publication pending.

This is a preprint version of the manuscript, published in the open archive SocArXiv: https://doi.org/10.31235/osf.io/m4vz7

Contributions of the doctoral candidate:

The doctoral candidate conceptualized and designed the research, carried out the empirical data collection and analysis, and wrote the manuscript. The co-authors supported the work with critical feedback and insights.

Contextually rich sustainability assessment for supporting local urban governance - connecting indicators to institutions and controversies

Abstract

The concept of urban sustainability is growing in urgency and salience for local urban governance, and indicator-based assessments represent a popular means for its operationalization. While much effort has been spent developing the technical aspects of these assessments, less attention has been given to research concerning their potential for influencing real-world urban governance processes. To address this issue, we put forward an assessment approach that systematically embeds the assessed indicators within their social and institutional contexts, thereby aiming to enhance the relevance of the assessment for local governance. Specifically, the contextual embedding is achieved through the analysis of ongoing controversies related to the assessed problem. We apply the approach to an assessment of the City of Geneva's (Switzerland) housing system. As the case study demonstrates, the proposed assessment approach can elucidate a richer picture of the challenges identified in the assessment than a typical quantitative-only analysis of indicators. Therefore, it offers more complete support to local governance stakeholders for learning about and acting upon the problem under assessment. Overall, the work reported in this article aims to contribute to a productive alliance between sustainability assessment methodologies and urban governance stakeholders, thereby leading to more informed steering of cities towards sustainability.

Keywords: Sustainability assessment; indicators; urban governance; housing; institutions

1. Introduction

The evolution of urban areas constitutes a crucial determinant of all dimensions of global sustainable development, which has raised the concept of urban sustainability to a central position in both the political and scientific domains (UN, 2017; Acuto et al., 2018). In response, literature on the assessment of urban sustainability has flourished (Cohen, 2017), often based on sets of sustainability indicators (Merino-Saum et al., 2020). A central purpose of these assessment methodologies is to translate the abstract concept of sustainability to a more operational form for the governance of the assessed problem at the local urban scale (Waas et al., 2014). This implies understanding the nature of sustainability assessment not only as a technical measurement method providing direct input for decision-making, but also as a possible medium for supporting broader 'deliberative governance' (van Zeijl-Rozema et al., 2008), which involves dialogue and social learning among the various local stakeholders present in urban contexts (Bond et al., 2012).

In supporting such deliberative governance of local urban sustainability, sustainability assessment methodologies face three serious challenges. First, the concerns related to sustainability always reflect context-specific values and key challenges. Therefore, to increase their relevance, assessments (e.g., in terms of indicator selection) must be tailored to local specificities (Hartmuth et al., 2008). Second, in a complex context such as a city, a wide variety of interconnected concerns and competing goals weigh upon decisions related to sustainability (Finco and Nijkamp, 2001). Thus, any assessment aiming to support governance must adequately recognize this complexity when delineating what is included in the assessment (O'Connor and Spangenberg, 2008). To address these challenges of local pertinence

and adequate comprehensiveness, many assessments employ forms of participatory and integrated methodologies (Reed et al., 2006; Weaver and Rotmans, 2006).

A third, less frequently addressed challenge, however, relates to whether these assessments have any influence on their targeted audience. A key determining factor of influence is the relevance of the assessment and the indicators used (Gudmundsson et al., 2009; Sébastien et al., 2014). We propose that the relevance of assessments can be increased by *systematically embedding the analyzed indicators within the sociopolitical governance context of the assessment, thereby enriching their informational value* (Pahl-Wostl, 2009). With some notable exceptions (e.g., Lee, 2006; Binder, 2007), few assessment approaches suggest systematic incorporation of such contextual aspects in quantitative indicator-based assessments. As a result, the information produced by sustainability assessments risks remaining abstract and disconnected from the real-world challenges and decision-making situations faced by the relevant stakeholders. This hinders the effectiveness of assessments in supporting the governance of cities towards sustainability.

The present article puts forward an indicator-based assessment approach that tackles not only the first two challenges presented above (by utilizing a participatory methodology) but also, centrally, the third challenge related to the influence of the assessment. For this third challenge, the approach employs a conceptual framework that systematically embeds the assessed indicators within their social and institutional contexts, thus enhancing the relevance of the information produced by the assessment for local urban governance. The aim is thereby to address the gap that exists in current knowledge concerning how the potential of sustainability assessments can be increased for exerting real influence in governance processes.

To demonstrate the approach, it is applied to the assessment of the City of Geneva's housing system. Housing plays a key role in achieving sustainability for cities (UNECE, 2015; UN, 2017). It also traverses all dimensions of sustainability and involves a broad set of local stakeholders (Marcuse, 1998; Lovell, 2004; Feige et al., 2011). This renders it a pertinent case study topic for illustrating the assessment approach, as the latter aims particularly to address such complex local urban governance problems. The City of Geneva presents an interesting case study setting with its growing and diverse population, densely-built urban area, and ageing building stock (FSO, 2019, 2020), factors which contribute to making housing an urgent sustainability challenge. Through the case study, the present work secondarily also contributes to literature on the governance and assessment of housing sustainability (Winston and Pareja Eastaway, 2008; Pagani et al., 2020; Adamec et al., 2021).

The article is organized as follows: Section 2 introduces the conceptual framework central to the assessment approach; Section 3 presents the research methodology applied in the case study. Section 4 presents the assessment results. Section 5 discusses the findings and elaborates on the value of the proposed approach. Section 6 summarizes the main points and concludes with a brief look ahead.

2. Conceptual framework for contextually rich sustainability assessment

As argued in the introduction, the relevance of sustainability assessments for supporting deliberative urban governance can be enhanced by systematically contextualizing the indicators analyzed in the assessments. Fig. 1 presents a conceptual framework developed for this purpose and used to guide the case study assessment of Geneva's housing system.

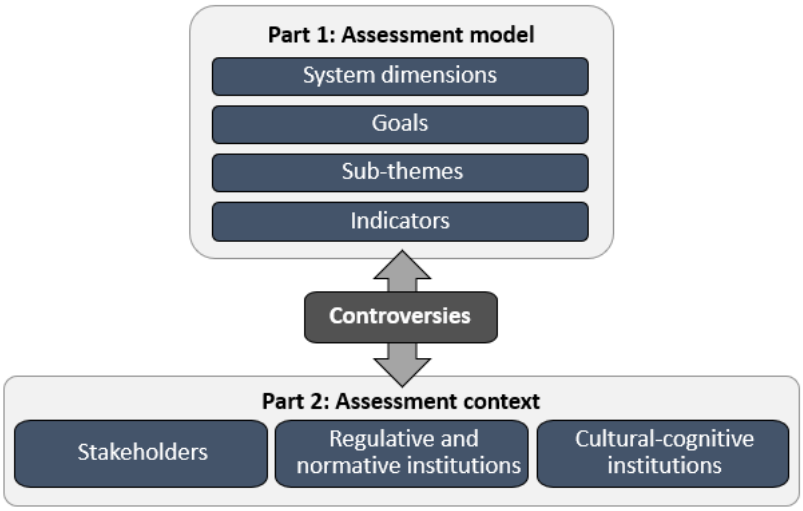

Fig. 1. The conceptual framework guiding the assessment (source: Authors).

The framework contains two parts that distinguish between the assessment model and the assessment context. The first part, the assessment model, consists of four levels that progressively concretize the assessed problem (in this case, 'sustainable housing system'). At the most abstract level, *system dimensions* list the principal categories to be covered by the assessment (e.g., 'buildings', 'neighborhoods'). The *goals* define the desired qualities of these dimensions (e.g., '*durable* buildings', '*convivial* neighborhoods'). The *sub-themes* represent constitutive factors of the goals, providing a link between the goals and their possible indicators. For example, the goal of 'convivial neighborhoods' consists of sub-themes such as 'social links', 'public spaces', etc. The model culminates in a set of *indicators* for expressing the status of the assessed problem with regard to each goal. The model is meant to establish a logical structure that ensures that the selection of indicators for the assessment is coherent and transparent (McCool and Stankey, 2004; Halla and Merino-Saum, *forthcoming*).

The second part of the framework refers to the assessment context. The first contextual element identified by the framework concerns relevant stakeholders, defined here as those affected by or affecting the governance of the problem (Reed, 2008). The second element refers to the regulative and normative institutions (i.e., respectively, the formally codified rules and regulations of the governance structure, and the standards of appropriate behavior) involved in the governance of the sustainability problem (Scott, 2014). The third contextual element considers the cultural-cognitive institutions (i.e., the conceptions and mental models through which reality is given meaning) related to the problem at hand (Scott, 2014). Cultural-cognitive institutions define the context-specific meanings and expectations associated with the problem in question ('sustainable housing system'). Together, these three categories of contextual elements represent central drivers of the assessed problem, and to a great extent they determine the opportunities and obstacles in acting upon any results gained from the assessment model (Pahl-Wostl, 2009).

The final element in our framework considers current controversies related to the assessed problem (Marres, 2007). These are contentious challenges or strategies that are the subject of ongoing public debate (e.g., the planning of a new neighborhood, a particular piece of legislation, etc.). Such controversies play a special role in that they represent entry points through which people practically engage with sustainability-related problems. They are also occasions for stakeholders to become involved and connected with each other, and in which the abovementioned social institutions are

subjected to public scrutiny and possible re-definition (Latour, 2007). Controversies can therefore presage imminent changes to the status quo.

As Fig. 1 indicates, the role of controversies is to act as connecting hubs between the assessment model and the assessment context. The value of considering such controversies in indicator-based assessments is threefold. First, their analysis can provide exceptional opportunities for revealing tradeoffs among the different goals and indicators of the assessment model, creating a more systemic understanding of the assessed problem (Wiek and Binder, 2005). Second, controversies can aid in tracing the complex interconnections and conflicts between elements of the system model and different contextual drivers in a way that would otherwise not be readily apparent. Third, especially from the point of view of local stakeholders, connecting the assessment model (and its goals and indicators) to familiar real-world controversies makes them more concrete and thereby more likely to enable social learning about different aspects of the assessed problem.

3. Methodology

The conceptual framework presented in the previous section was applied to a case study assessing the City of Geneva's housing system. The design of the case study built on two guiding principles. Firstly, *participation* of local stakeholders was emphasized, viewing them not only as informants within a predefined problem framing, but as co-constructors of the definition of the problem (Reed et al., 2006). This principle was followed to ensure that the assessment considered local specificities and included a sufficiently broad set of concerns in order to be relevant for local governance. Secondly, to increase the internal validity of the research, the case study design used *triangulation* (Meijer et al., 2002). Data was collected using multiple methods and sources of evidence, including a balancing of inputs from the aforementioned local stakeholders with those from grey and academic literature, and from topical experts (Reed et al., 2006). Fig. 2 illustrates the overall research procedure.

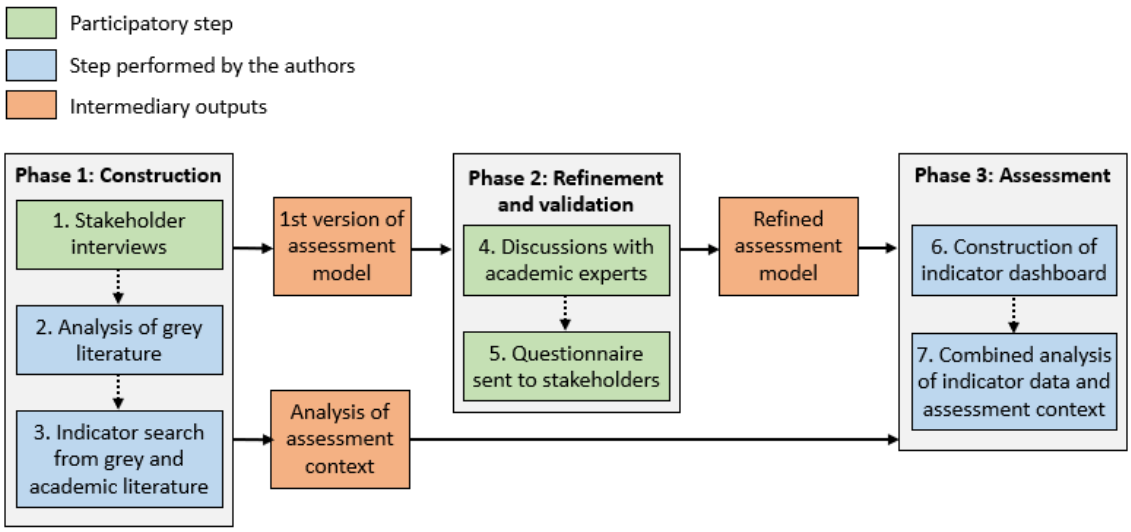

Fig. 2. The methodological steps followed (source: Authors).

To begin the first phase, qualitative, semi-structured interviews (Kvale and Brinkmann, 2009) were conducted with fourteen local stakeholders selected as representing a broad range of viewpoints on the problem. The interviewees included five persons from different departments of the municipal government, two technical professionals (an architect and an employee of a construction company), four citizen representatives (one from an owners' association, one from a tenants' association, and

two from cooperatives of owner-tenants), and three local academics. The interviews sought the interviewees' perspectives on criteria defining sustainable housing and on the current challenges facing Geneva's housing system (see interview guide in supplementary material). As a second step, analysis of relevant grey literature was performed to elaborate and triangulate the interview data (see Appendix E). The combined data from the first two steps was then subjected to qualitative content analysis (Mayring, 2000) in order to produce the first version of the assessment model, as well as to construct a picture of the assessment context and the prominent ongoing controversies. Importantly, the interview data was given primacy in determining what system dimensions should be included in the assessment model and which goals are adopted for these dimensions. In the final step of the first phase, a pool of candidate indicators was identified for expressing the goals and sub-themes of the assessment model. The indicators were collected from the same archive of grey literature, complemented by scanning the databases of federal and cantonal statistical offices, and by reviewing academic literature on indicators for housing sustainability (see Appendix F).

The second phase of the research aimed to refine and validate the assessment model. It consisted of two steps, the first of which involved discussions with eight academics whose combined expertise covered all aspects of the assessment model. This step served as a second instance of triangulation, whereby the academics were asked to review the content of the assessment model with the aim of arriving at a *reasonably* thorough set of goals and related sub-themes. In addition, through the discussion, six indicators for each goal were shortlisted from the pool of candidate indicators. The shortlisting was based on two criteria: 1. Scientific relevance (the indicator is scientifically credible and plays a central role in satisfying the goal at hand); 2. Informational value (the indicator's ability to communicate to a non-expert audience). In the next step, as a final means of triangulation, an online questionnaire with two questions was sent to the interviewed local stakeholders (see Appendix H). The first question asked the shareholders to express their opinion on the relative importance of the goals vis-à-vis each other, with the purpose of validating the presence of each goal within the set of goals. The second question asked the stakeholders to prioritize the most pertinent indicators for Geneva among the six indicators shortlisted in the previous step.

The final phase concerned the actual assessment. First, a dashboard of stakeholders' preferred indicators was constructed. This involved specifying a precise metric for each indicator, searching for data, and benchmarking the current indicator value of Geneva against its historical values, against other comparable Swiss cities (Zürich and Basel), and/or against existing policy targets. For certain selected indicators, appropriate metrics and data was difficult to find. In such cases, the indicator was kept in the dashboard to signal the need for development of appropriate metrics and data for the indicator in question. As a final step, the indicators were systematically connected to the contextual analysis in order to provide the full assessment sought with the proposed assessment approach.

4. Case study - Assessing Geneva's housing system

This section presents the results of the Geneva[47] housing system case study. Table 1 presents key numbers about the case study context. The City of Geneva is the urban center for both the eponymous canton (pop. 500,000) and the greater agglomeration (pop. 950,000). The city's housing system is

[47] For brevity, 'Geneva' is henceforth used to refer to the city; references to the Canton of Geneva are made explicit.

composed of a high number of rented apartments and an ageing housing supply. Recently, steady population growth (0.9% annually on average) has been putting pressure on the housing system of this already densely populated city.

Geneva's housing system falls under a complex governance structure of stakeholders, regulations and norms (Feige et al., 2011; Debrunner et al., 2020). Although Switzerland is known for its decentralized political system with a considerable share of regulatory power located at the cantonal level, in the case of housing, several relevant powers are held at the federal level. Swiss constitution-mandated federal authority on the topic particularly stems from Articles 108 (encouraging construction of housing and home ownership), 109 (against abuse in tenancy matters), 73 (sustainable development), 75 (spatial planning), and 89 (energy efficiency and renewable energy). The City of Geneva further complements federal and cantonal regulations through voluntary action in several relevant fields, including policies on social housing and cohesion, and land use planning (see Appendix E).

Table 1. Basic statistics for the City of Geneva (FSO, 2017, 2019, 2020).

	Geneva (city)	**Comparison**
Population (Yearly growth; 5-year average)	203,951 (0.9%)	 (Zürich 1.4%; Basel 0.5%)
Population density	12,669 per km^2	Zürich 4,724 per km^2; Basel 7,223 per km^2
Foreign resident population	48%	Zürich 32%; Basel 38%
Average taxable income per taxpayer	83,823 CHF	Zürich 79,012 CHF; Basel 76,701 CHF
Employment rate (ages 20-64)	70%	Zürich 81%; Basel 74%
Share of owner-occupied dwellings (data for cantons)	18%	Zürich 28%; Basel 16%
Share of dwellings built after 1981	19%	Zürich 24%; Basel 12%

4.1 Assessment model and indicator dashboard

Fig. 3 depicts the assessment model for Geneva's housing system, spanning five dimensions: dwellings, buildings, neighborhoods, markets and culture. Across these dimensions, the model specifies thirteen goals for the housing system to satisfy and balance. Sub-themes are defined for each of the goals (i.e., their principal constitutive factors). In Fig. 3 we present only the two top-ranked indicators from the stakeholder questionnaire (see Appendix G), which subsequently serve as the basis of the assessment. The questionnaire also validated the goals included in the assessment model, as even the worst-rated among the thirteen goals (Goal 6; see Appendix H) was seen as having below-average importance by only 30% of the respondents, strongly indicating that all of the goals included in the model are pertinent to the case in question.

System dimensions	Dwellings	Buildings		Neighborhoods					Markets			Culture
Goals	Goal 1 **Comfortable and healthy dwellings**	Goal 2 **Durable and adaptable buildings**	Goal 3 **Buildings with low energy and material footprint**	Goal 4 **Buildings and neighborhoods in harmony with their physical surroundings**	Goal 5 **Safe neighbor-hoods**	Goal 6 **Participatory neighbor-hoods**	Goal 7 **Connected neighbor-hoods**	Goal 8 **Convivial neighbor-hoods**	Goal 9 **Diverse neighbor-hoods**	Goal 10 **Economically viable markets**	Goal 11 **Accessible and fair markets**	Goal 12 **Markets with adequate supply**	Goal 13 **Cultural and aesthetic value**
Sub-themes	**1a** Quality and quantity of living space **1b** Services and equipment **1c** Thermal and aural comfort **1d** Indoor air quality **1e** Lighting and view **1f** Privacy **1g** Accessibility	**2a** Lifetime of structure, materials and technologies **2b** Quality of workmanship **2c** Mainte-nance and renovation **2d** Adaptability of space **2e** Structural modularity	**3a** Energy, climate and material footprint of structure **3b** Critical materials **3c** Energy, climate and material footprint in operation **3d** Waste management	**4a** Land use **4b** Integration with surroundings **4c** Green areas and infrastructures	**5a** Crime **5b** Traffic safety **5c** Hazards	**6a** Associative life **6b** Participatory governance	**7a** Proximity to workplaces **7b** Proximity to public transport **7c** Transport infrastructure **7d** Proximity to services	**8a** Social links **8b** Neighborhood spirit **8c** Public spaces **8d** Sharing	**9a** Social diversity **9b** Functional diversity	**10a** Investment attractiveness **10b** Operational costs **10c** Impact on local economy	**11a** Rental market affordability **11b** Ownership affordability **11c** Subsidized housing **11d** Security of tenure	**12a** New construction **12b** Quantity of supply **12c** Diversity of supply	**13a** Heritage protection **13b** Local sensitivity **13c** Aesthetic quality
Selected indicators	**1.1** Noise **1.2** Natural light	**2.1** Invest-ments in maintenance, renovation or conversion **2.2** Ease of refurbishing installations	**3.1** Energetic efficiency of buildings **3.2** Share of renewable energy	**4.1** Construction considering the natural conditions of the site **4.2** Percentage of green coverage	**5.1** Pedestrian and low speed limit zones **5.2** Existence of risk maps	**6.1** Availa-bility of community facilities **6.2** Member-ship in community associations	**7.1** Capacity of public transport system **7.2** Soft mobility infrastructure	**8.1** Architecture encouraging social links **8.2** Amount of public spaces	**9.1** Age distribution of residents **9.2** Share of residents receiving social benefits	**10.1** Cost of maintenance and retrofitting **10.2** Access to funding for investment	**11.1** Average rental price per m^2 **11.2** Subsidized housing ratio	**12.1** Construction rate relative to population growth **12.2** Vacancy rate	**13.1** Preservation of local characteristics and identity **13.2** Satisfaction with aesthetics of surroundings

Fig. 3. The assessment model for the sustainability of Geneva's housing system (source: Authors). Note that only the two most popular indicators per goal from the stakeholder questionnaire are shown and considered in the ensuing assessment. This means that not all sub-themes are covered by the selected indicators in this instance. Nevertheless, making all sub-themes transparent serves the purpose of defining the meaning of each goal more explicitly, and in a subsequent application of the model, other indicators (relating to some of the sub-themes ignored here) may be prioritized by the stakeholders.

Table 2 presents a dashboard of the selected indicators (see methodological notes and data sources in supplementary material). Unless otherwise noted, the value displayed is for the City of Geneva. As mentioned above, for some indicators finding suitable metrics and data was not possible (within the scope of this research); the presence of these indicators in the dashboard signals the need for development of appropriate operationalizations in the future.

A number of critical observations can be made from the dashboard. Firstly, Geneva's housing market is characterized by a shortage of supply, as evidenced by the low vacancy rate of 0.6%[48] (Indicator 12.2). This is exacerbated by a ratio of new dwellings to new residents (0.38; Indicator 12.1) that, despite an increase over the last decade, remains low in comparison with Basel (0.91) and Zürich (0.43). Furthermore, the strained situation in the market is accompanied by comparably high monthly rent levels (29.8 CHF/m²; Indicator 11.1). To combat this challenge with affordability, the canton has set a target of doubling the amount of subsidized housing[49]. However, as seen in Indicator 11.2, the share of subsidized dwellings has not increased in recent years (9.8% in 2019; 10.0% in 2015).

Secondly, while there are some advances in the energetic performance of the housing stock (486 MJ/m^{2}a in 2019; 507 MJ/m^{2}a in 2014; Indicator 3.1), the improvement rate is slow when benchmarked against the cantonal target of 350 MJ/m^{2}a for 2030[50]. Also, the use of renewable energy for housing purposes is low in Geneva: for example, only 10.8% of the energy for heating in 2015 came from sustainable sources, compared with 24.4% in Zürich (Indicator 3.2). At the same time, per capita investments in the existing housing stock have increased considerably in recent years (3786 CHF in 2018; 2941 CHF in 2013; Indicator 2.1), despite that, against the trend elsewhere the country, the prices of this type of work (Indicators 2.2 and 10.1) have been slightly increasing. For example, the index price of renovations and transformations in the Canton of Geneva in 2020 was 101.4 (100 in 2015) compared with 98.0 in Zürich.

Thirdly, in terms of the livability of the urban environment, several indicators display room for improvement, including: the share of population disturbed by noise (42.2% in Geneva; 15.1% in Zürich; 13.9% in Basel; Indicator 1.1); the share of moderated traffic zones (40.9% in Geneva; 55.4% in Zürich; 72.6% in Basel; Indicator 5.1); and the share of green coverage (18.6% in Geneva; 35.5% in Zürich; 12.6% in Basel; Indicator 4.2). Geneva also trails the reference cities in the area of mobility, as shown by the amount of public transport stops (0.7 per 1000 inhabitants; 1.1 in Zürich; 1.0 in Basel; Indicator 7.1) and the index score of bicycle friendliness (3 points; Zürich 2 points; Basel 8 points; Indicator 7.2). When it comes to neighborhood diversity, the city's residents represent a broad range both in terms of age distribution (the number of residents either under 20 years or over 64 years summing to half of those between 20 and 64 years; Indicator 9.1) and socioeconomic groups (11.2% of residents receive social benefits; Indicator 9.2). However, as the standard deviations between neighborhoods show, (especially the 8.7% for Indicator 9.2), this diversity varies strongly between areas of the city.

[48] According to estimates, a well-functioning housing market in Switzerland should have a vacancy rate of 1% - 1.5% (Thalmann, 2012; RTS, 2018).

[49] Cantonal Act for the Construction of Socially Beneficial Housing (LUP)

[50] Cantonal Energy Plan 2020-2030 (PDE)

Table 2. Indicator dashboard for the sustainability of the City of Geneva housing system.

Goal	Indicator	Metric [unit, year]	Value	Evolution [Year]	Benchmark
1	1.1 Noise	Share of population disturbed at night by > 55 dB(A) [%, 2015]	42.2	N/A	Zürich - 15.1 Basel - 13.9
	1.2 Natural light	*To be operationalized*			
2	2.1 Investments in maintenance, renovation or conversion	Investments in expansions, transformations and demolitions per capita [CHF, 2018]; data for cantons	3,786	2 941 [2013]	Zürich - 2,640 Basel – 4,847
	2.2 Ease of refurbishing installations	Price of renovating installations [index, 2020]; data for cantons	100.5	100 [2015]	Zürich - 92.0 National - 91.3
3	3.1 Energetic efficiency of buildings	Average heat consumption index [MJ/(m^2a), 2019]	486	507 [2014]	Cantonal target: 350 by 2030
	3.2 Share of renewable energy	Share of residential buildings with wood, electricity, heat pumps or solar collectors for heating; (if including district heating) [%, 2015]; data for cantons	10.8; (11.7)	8.8; (9.5) [2010]	Zürich - 24.4 (27.6); Basel - 1.7 (31.7)
4	4.1 Construction considering the natural conditions of the site	*To be operationalized*			
	4.2 Percentage of green coverage	Share of wooded and recreational areas [%, 2013-2018]	18.6	18.9 [2004-2009]	Zürich - 35.5 Basel - 12.6
5	5.1 Pedestrian and low speed limit zones	Share of moderated traffic zones [%, 2017]	40.9	34.9 [2013]	Zürich - 55.4 Basel - 72.6
	5.2 Existence of risk maps	Binary indicator for existence of risk maps [yes/no; 2021]	Yes	N/A	Zürich – Yes Basel - Yes
6	6.1 Availability of community facilities	Number of neighborhood centers [1/10 000 inhabitants, 2020]	0.54	N/A	Zürich - 0.43 Basel - 0.87
	6.2 Membership in community associations	Population (>15 years) involved in a communal or neighborhood association [%, 2020]; data for regions	6.2	N/A	Zürich - 4.2 National - 5.4
7	7.1 Capacity of public transport system	Amount of public transport stops [1/1000 inhabitants, 2019]	0.7	0.8 [2015]	Zürich - 1.1 Basel - 1.0
	7.2 Soft mobility infrastructure	Bicycle friendliness [index points, 2019]	3 pts	N/A	Zürich - 2 pts Basel - 8 pts
8	8.1 Architecture encouraging social links	*To be operationalized*			
	8.2 Amount of public spaces	Density of public benches [1/ha, 2020]	1.17	N/A	N/A
9	9.1 Age distribution of residents	Dependency ratio: Number of residents outside working age per those in working age; (std. dev. between neighborhoods) [%, 2020]	50.9; (9.8)	51.7; (10.1) [2011]	Zürich - 47.6 (14.3) Basel - 56.1 (11.9)
	9.2 Share of residents receiving social benefits	Share of residents receiving social subsidies; (std. dev between neighborhoods) [%, 2017]	11.2; (8.7)	10.8 [2011]	Geneva Canton - 9.7

Table 2 (Continued). Indicator dashboard for the sustainability of the City of Geneva housing system.

Goal	Indicator	Metric [unit; year]	Value	Evolution [Year]	Benchmark
10	10.1 Cost of maintenance and retrofitting	Price of renovations and transformations [index, 2020]; data for cantons	101.4	100 [2015]	Zürich - 98.0 National - 98.0
	10.2 Access to funding for investment	*To be operationalized*			
11	11.1 Average rental price per m^2	Average rent (CHF) per net floor space [CHF/(m^2month), 2017]	29.8	19.8 [2005]	Zürich - 25.7 Basel - 18.9
	11.2 Subsidized housing ratio	Share of subsidized dwellings of total number of dwellings [%, 2019]	9.8	10.0 [2015]	Geneva Canton - 8.0
12	12.1 Construction rate relative to population growth	Ratio of new dwellings to new residents [dwellings/persons, 2015-2019]	0.38	0.26 [2011-2015]	Zürich – 0.43; Basel – 0.91
	12.2 Vacancy rate	Dwelling vacancy rate [%, 2019]	0.6	0.3 [2011]	Zürich - 0.1; Basel - 1.0
13	13.1 Preservation of local characteristics and identity	*To be operationalized*			
	13.2 Satisfaction with aesthetics of surrounding architecture	*To be operationalized*			

Due to the difficulty of defining appropriate metrics and data, there is a lack of visibility with regard to certain key aspects of the housing system, including indicators for natural light (1.2), construction that considers the site's natural conditions (4.1), architecture that encourages social links (8.1), preservation of local characteristics and identity (13.1), and satisfaction with the aesthetics of surrounding architecture (13.2). The commonality among these blind spots is their relation to the architectural aspects of the housing system. To avoid being overlooked in future policymaking, this can be taken as a strong signal of a general need to develop operational indicators and generate data for this key area.

4.2 Contextualizing indicators

To summarize the indicator dashboard observations, the sustainability challenges of Geneva's housing system relate particularly to: (i) the energetic performance of the housing stock (both quantitatively and qualitatively; Indicators 3.1 and 3.2); (ii) availability (Indicators 12.1 and 12.2), especially when it comes to affordable housing (Indicators 11.1 and 11.2); (iii) selected aspects of the urban environment, including noise and traffic (Indicators 1.1 and 5.1), the amount of green areas (Indicator 4.2), and mobility (Indicators 7.1 and 7.2).

As we have argued above, this initial assessment can be enriched by connecting the indicators to different contextual elements, in particular through the analysis of ongoing controversies. The argument is illustrated with the example of two salient controversies from the Genevan context, presented diagrammatically following the conceptual framework of Fig. 1. The analysis highlights, firstly, the important trade-offs between different goals and indicators; secondly, the stakeholder groups, regulations and norms implicated in these trade-offs; thirdly, the conflicting cultural-cognitive meanings and expectations underlying different prioritizations between the goals and indicators

involved. In other words, the analysis elaborates on the drivers behind the numbers displayed by the indicators, and on the opportunities for and obstacles to affecting them.

4.2.1 Controversy 1: Regulation on demolitions, transformations and renovations

The first controversy (see Fig. 4) concerns a long-running debate in Geneva around the cantonal law on demolitions, transformations and renovations (LDTR). The law was intended to curb the loss of residential housing in the city center by restricting the ability of owners to remodel or change the use purpose of their properties. In addition, the law sets a ceiling on possible rent increases following these types of work. In other words, the law is an attempt to address both Goal 12 (sub-theme 'quantity of supply') and Goal 11 (sub-themes 'rental market affordability' and 'security of tenure') of the assessment model. As discussed above, the indicators expressing these goals display values that attest to the urgency of action to support them, especially the comparably high average rental price of 29.8 CHF/m^2 (Indicator 11.1) and the sub-optimal vacancy rate of 0.6% (Indicator 12.2).

However, the law is also often criticized, especially on two accounts: Firstly, by limiting the ability of owners to alter their properties, the law directly reduces the adaptability of dwellings (Goal 2, sub-theme 'adaptability of space') to different family sizes, preferences, etc., thereby further adding to the rigidity of the housing market in responding to changing demand (Goal 12, sub-theme 'diversity of supply'). Secondly, by reducing the ability of owners to recuperate investment costs through rent increases, the law also disincentivizes improvement of the housing stock (Goal 2, sub-theme 'maintenance and renovation'; Goal 3, sub-theme 'energy and climate footprint'). The critical value of Indicator 3.1 concerning the energetic efficiency of buildings (486 MJ/m^2a vs. the target of 350 MJ/m^2a) emphasizes the need to address this line of argumentation in order to better promote the renovation of the city's housing stock.

The controversy directly sets two groups of local stakeholders, i.e., tenants and owners, in opposition, and involves regulations and norms from the local to national scale. Interestingly, the central cantonal law (LDTR) in this debate exceeds the federal tenancy regulations on rent protection, making the Canton of Geneva a special case in the Swiss context. The new cantonal energy plan for 2030, which sets ambitious targets for the renovation rate of the housing stock, will most likely further fuel the controversy and increase calls for reconsidering the level of rent protection offered by the current regulations.

At the cultural-cognitive level, the controversy touches upon two fundamental questions. First, it contrasts two conflicting ideas about the nature of housing, i.e., whether housing should be considered a market commodity best regulated by the open market, or whether it is a public good that should be guaranteed for everyone at affordable prices through public policies and regulations. Second, the controversy highlights a dilemma between social objectives (maintaining affordability, tenure security, etc.) and environmental ones (incentivizing renovation of the housing stock). Unless solutions are found that support both of these dimensions of sustainability, the dilemma suggests that gaining public support for improving the environmental performance of housing may require efforts for reconfiguring deeper conceptions about the objectives that housing is supposed to serve.

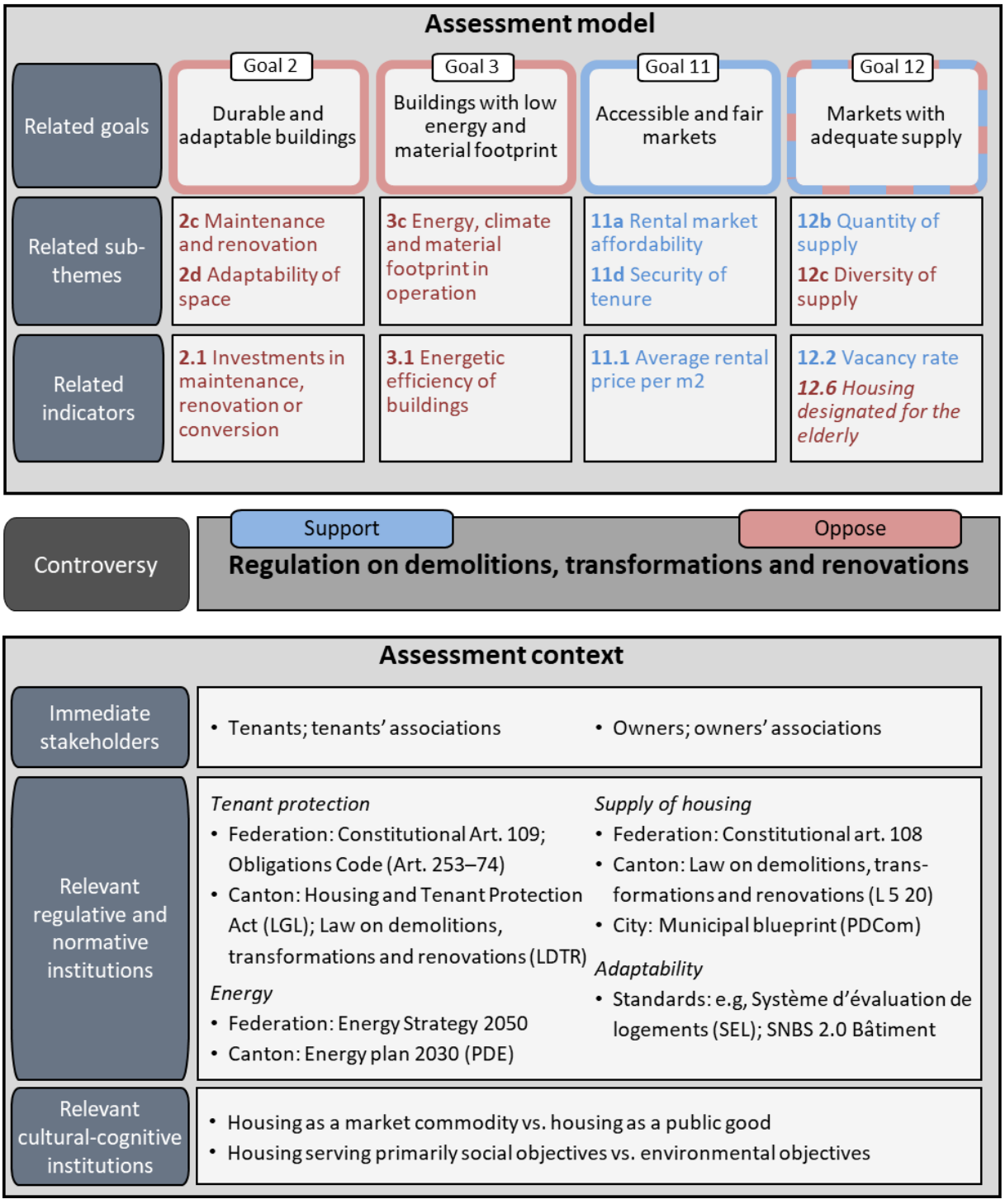

Fig. 4. Diagram of the regulation on demolitions, transformations and renovations controversy (source: Authors). The blue-and-red color-coding signals a supporting link between the goals, sub-themes and indicators, and the two positions on the controversy (blue for 'support' and red for 'oppose'). The indicators marked in *italics* were not among those selected for the dashboard (Table 2), but which would, however, be pertinent for the controversy in question.

4.2.2 Controversy 2: Densification of the built environment

The second controversy (see Fig. 5) concerns efforts to densify already built areas in the city. Densification is aimed at meeting the housing demand in the city while also limiting the encroachment on natural and agricultural land by urban sprawl. As such, these efforts relate to Goal 4 (sub-theme

'land use'), Goal 7 (sub-themes 'proximity to workplaces', 'proximity to public transport' and 'proximity to services') and Goal 12 (sub-themes 'new construction' and 'quantity of supply') of the assessment model. Densification is a particularly pertinent topic for Geneva, because, as shown by the indicator dashboard, the city is behind the reference cities in constructing new housing (Indicator 12.1), a crucial challenge given the low vacancy rate prevailing in the market (Indicator 12.2).

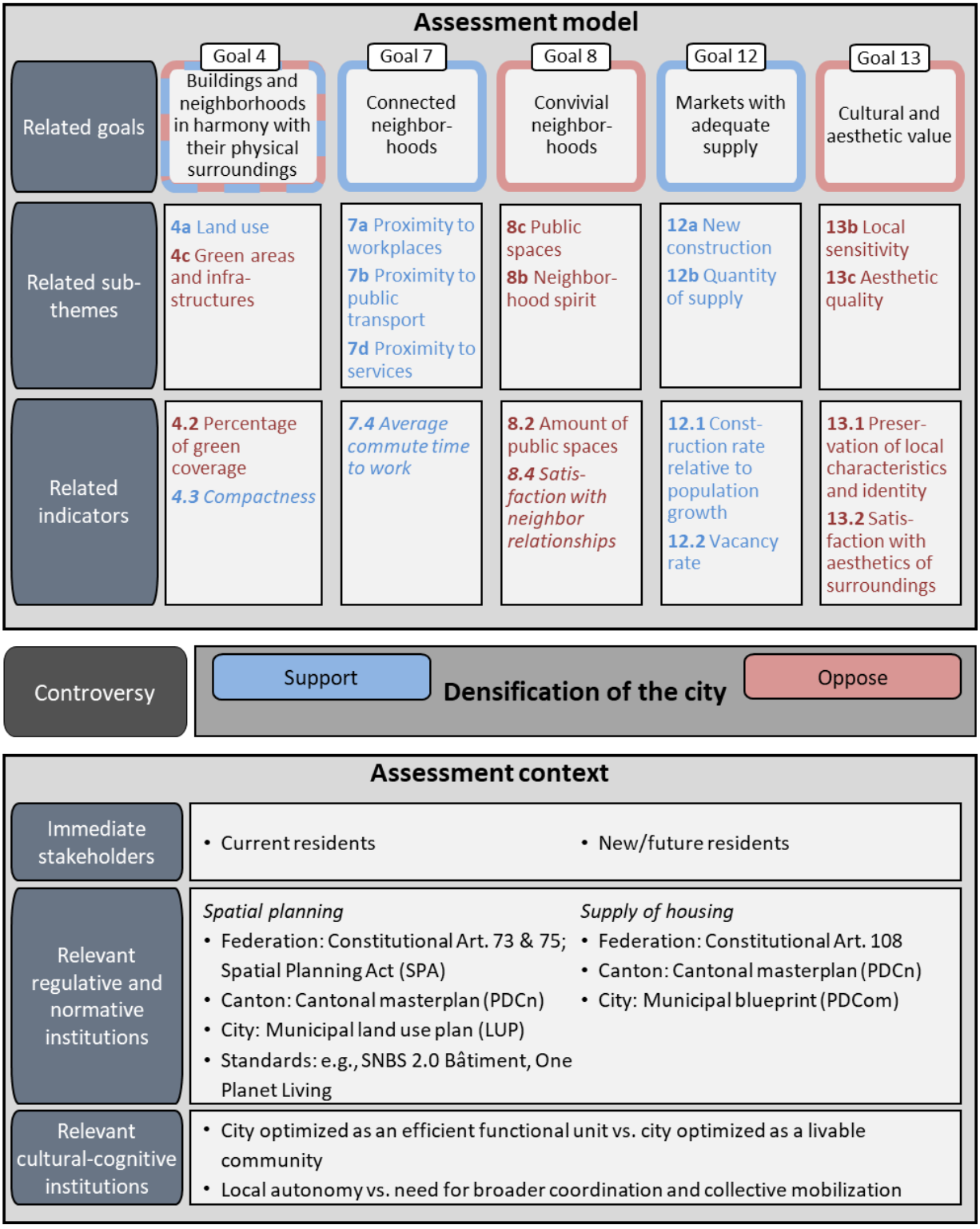

Fig. 5. Densification of the built environment controversy diagram (source: Authors). See explanatory notes in the caption of Fig. 4.

The densification of the city faces strong opposition, especially given that Geneva is already densely populated compared to other Swiss cities (see Table 1). The argument from this point of view is that densification leads to a less livable and attractive urban environment, with a loss of existing neighborhood spirit and identity. Thus, the opposition relates specifically to Goal 4 (sub-theme 'green areas and infrastructures'), Goal 8 (sub-themes 'neighborhood spirit') and Goal 13 (sub-themes 'local sensitivity' and 'aesthetic quality') of the assessment model. The argument is supported by Indicator 4.2 showing that the amount of green coverage in Geneva is already fairly low compared to Zürich (although high compared to Basel). Notably for this debate, the operationalization of Indicators 13.1 (Preservation of local characteristics and identity) and 13.2 (Satisfaction with aesthetics of surrounding architecture) would bring much needed evidence to support fact-based future policymaking.

In terms of regulations, the objective of densification features centrally in the Federal Spatial Planning Act (SPA), which explicitly obligates cantons to curb their land use by directing future construction activities to already built areas. The Canton of Geneva is responsible for implementing the objectives of the SPA through its cantonal masterplan. The latter, in turn, is translated to the municipal blueprint that sets goals for spatial development in The City of Geneva. The city also imposes its own land use plan (endorsed by the canton, which has the regulatory authority on this matter) aimed at a higher density of housing within the city. Importantly, all of these regulations state that densification must be accompanied by adequate attention to retaining the quality and livability of the urban environment. Apart from governmental regulations, interestingly, many newer certification standards have extended their scope to include spatial aspects such as density and livability of the urban environment. Despite being a clear priority at all levels of government, densification in practice remains a controversial topic. In fact, several referenda have taken place concerning densification measures of specific neighborhoods within the City and the Canton of Geneva, and in many cases the public has rejected these proposals.

Two underlying cultural-cognitive dilemmas can be detected in this controversy. The first concerns the selection of overarching principles to guide urban development. Specifically, in this case, the choice is between optimizing the city in terms of functional efficiency (e.g., in land use and mobility) or in terms of livability. The second dilemma relates to the tension between, on the one hand, the autonomy of (current) local residents to decide on the development of cities and neighborhoods, and on the other hand, the need for policy coordination and collective action on a broader scale, which may entail mandatory top-down requirements. This dilemma is particularly pertinent in the Swiss context, where there is a tradition of strong local autonomy and direct democracy.

5. Discussion

In this article, we have demonstrated a sustainability assessment approach targeted at supporting deliberative local urban governance. In particular, the approach is based on two principal ingredients: firstly, a participatory methodology, which aims to ensure that the assessment model is constructed in a manner that is locally pertinent and adequately comprehensive; and secondly, a conceptual framework that systematically integrates the assessment model into relevant contextual aspects affecting the governance of the assessed problem. In this section, we discuss the approach and its value concerning both of these aspects.

5.1 Assessment model and its application to Geneva

The assessment model elaborated in the case study complements the trend observed by Adamec et al. (2021) of research applying an increasingly comprehensive set of criteria for the sustainability assessment of housing. With our methodology, in which the definition of the problem is delineated based on the inputs of the stakeholder-interviewees, we produced an assessment model that makes explicit the range of goals that local urban governance needs to balance if the housing system is to be sustainable. As such, the assessment model is comparable in scope, for example, to the principles promulgated by the Geneva UN Charter on Sustainable Housing (UNECE, 2015). In other words, the assessment model gathers under a single umbrella the concerns of a broad set of stakeholders, all involved in the housing system in some way (Feige et al., 2011).

Assessment of Geneva's housing system highlighted the most critical aspects concerning its sustainability: (i) the energy performance of the housing stock; (ii) availability and affordability of housing; (iii) particular aspects of the urban environment, including noise, moderation of traffic, the number of green areas, and public and soft mobility. In fact, many of these challenges already feature centrally in the city's policy agenda[51]. In addition to these themes that are already receiving attention (and for which data exists that allows for monitoring), the case study also highlighted the difficulty of operationalizing certain key areas of the assessment model. These related mainly to the architectural aspects of the housing system. Until appropriate indicators and data are created to cover these aspects, they are at risk of remaining overlooked in future policymaking on housing, which in turn translates into an imbalance in attempts at creating a sustainable housing system in Geneva.

5.2 Conceptual framework for contextually rich sustainability assessment

As we have argued, the relevance of the indicator assessment presented above for informing governance can be enhanced by systematically embedding the indicators and the signals they send into the context of the assessment. In particular, such contextualization can elucidate a more complete picture of the challenges identified by the indicators and the possibilities of acting upon them. Using the example of the regulations on demolitions, transformations and renovations controversy (see Fig. 4), the following observations and assertions can be made:

- There is a tradeoff between two crucial sustainability challenges for Geneva's housing system identified by the indicators, namely, the energetic performance of the housing stock and the availability of affordable housing. Therefore, proposed solutions for moving forward on these challenges must consider simultaneous impacts on both sides of the tradeoff. (To generalize, the analysis of controversies can reveal tradeoffs between goals and indicators, thus laying the groundwork for comprehensive policymaking that acknowledges different positions and aspects of sustainability.)
- The controversy sets the interests of owners into opposition with those of the tenants, which makes the participation of these stakeholder groups crucial when developing policies concerning the tradeoff in question. (To generalize, the analytical approach makes explicit relevant stakeholder groups in the controversy. This is important, as the composition of these groups is not static across the entire broader problem – in this case, sustainable housing – but

[51] E.g. the municipal blueprint (PDCom)

is dependent on the controversy at hand. In participative policymaking, failure to acknowledge this can lead to the selection of participants that do not represent the diversity of stakeholder positions.)

- The analysis of the controversy shows that several competing regulations and norms are implicated in the tradeoff. For example, if meeting the energy efficiency targets set by the cantonal Energy Plan 2030 is given priority, the level of rent protection offered by the current regulations may need to be reconsidered and combined with financial carrots and sticks to incentivize further owner investment. (To generalize, by analyzing the regulative and normative institutions in place, the proposed approach highlights the structures within which local governance must maneuver when addressing the sustainability challenges revealed by the indicators.)
- The analysis also reveals that underlying the tradeoff are deeper conflicting meanings and expectations related to the housing system. In this case, these conflicts relate especially to conceptions related to the social and environmental priorities that housing should serve, as well as to ideas about the nature of housing as either a market commodity or a public good. (To generalize, by making explicit the underlying cultural-cognitive institutions, the approach elucidates not just the conflicting arguments related to a controversy, but also the assumptions and values that buttress these arguments; this expediates deeper and more productive debates on the sustainability problem at hand.)

The novelty offered by this kind of assessment relates to the fact that it straddles two kinds of literature. On one hand, it proposes a more systematic and in-depth contextualization of the information provided by sustainability indicators than what is found in existing assessment literature (see, e.g., Reed et al., 2006), in which such engagement with context is typically limited at most to the phase of goal and indicator selection. On the other hand, studies analyzing the institutional context of sustainability problems (see, e.g., Nicol, 2011; Debrunner et al., 2020 for studies on housing in Switzerland) do not normally combine this kind of analysis with quantitative indicator-based assessments.

5.3 The value, intended uses and limitations of the approach

The principal value of the overall assessment approach in this article is in addressing the three challenges (local pertinence, adequate comprehensiveness and contextual richness) that sustainability assessments must face when attempting to support local urban governance. It especially addresses the third challenge by using ongoing controversies as structuring lenses revealing connections and patterns between indicators and their contextual drivers. It is an attempt to ensure that making assessments is not merely providing numbers, but also looking behind these numbers with systematic discussions on their meanings and possible ways for influencing them going forward. As such, this approach strikes a balance between, on the one hand, lists of indicators measuring comprehensively different aspects of complex urban governance problems such as housing (i.e., approaches that are broad but not deep; see Merino-Saum et al., 2020 for examples), and on the other hand, detailed assessments of more specific segments of such problems (i.e., approaches that are deep but not broad; e.g., Heeren et al., 2013; Streicher et al., 2019).

The proposed assessment approach can be useful for local urban governance in two distinct ways. Firstly, it can serve as a basis for learning, dialogue and networking among local actors, which is crucial

for creating the needed social foundation for the sustainability transformations of cities (van Zeijl-Rozema et al., 2008). Here, connecting the assessment to ongoing debates is valuable, as it makes the goals and indicators of the assessment model more relatable for these local stakeholders.

Secondly, in terms of policymaking, the approach can serve as a preliminary agenda-setting stage in which the sustainability problem in question is defined and given structure. In particular, through the analysis of controversies, the approach helps to locate particular policymaking challenges (e.g., regulation on renovations and rent protection) within the broader sustainability problem (e.g., sustainable housing) and the multi-scale governance system that steers it, thus setting the stage for comprehensive policies that acknowledge the complexity involved in local urban governance. However, to make the approach more operational for policymaking, it should be combined with more precise, forward-looking analyses, such as qualitative or quantitative scenario analyses combined with multi-criteria decision- making analyses (Merino-Saum, 2020).

The approach employed in this work comes with certain limitations and challenges, many of which relate, in the first instance, to the inherent breadth of topics and concerns included in the analysis of a complex problem like sustainable housing. Given this breadth, reaching sufficient depth in the contextual analysis is a challenge. Another difficulty relates to the operationalization of the selected indicators, especially given that the assessment approach targets the local (municipal) scale. Indeed, considerable resources are required for the definition of appropriate metrics and collection of data, as also evidenced by our inability to fully operationalize the indicator dashboard within the scope and schedule of this work. Finally, benchmarking the indicator values of a city against those of others (in our case, Geneva against Zürich and Basel) should be taken only an *indication* of the status of the city in question, since the varying circumstances and ways in which municipal boundaries are drawn mean that cities are never fully comparable.

6. Conclusion

This article seeks to bridge the gap between indicator-based sustainability assessments and urban governance. As we have argued, a disconnect currently exists between indicator-based sustainability assessments and the challenging real-world decision-making situations faced by those involved in the governance of urban sustainability problems. Rather than simply offering facts, assessments aiming to serve governance should tell a ‘story’ that brings the indicators to life by discussing them in their context. Too often such contextualization is relegated to some sentences in a discussion section, instead of being an integral part of the assessment.

As we show, engaging with ongoing controversies can provide a fruitful avenue forward as they offer enlightening glimpses into the interconnections and conflicts within complex urban governance problems in a way that would otherwise be difficult to discern. In this way, indicator-based assessments can become richer and more useful for urban governance, especially if the latter is understood not simply as making decisions, but as a deliberative process that considers different points of view, and involves social learning and dialogue among the diverse set of stakeholders present in urban contexts.

In building on the approach presented in this paper, two possible interesting directions can be envisioned. First, the analysis of the controversies could be connected with qualitative and/or quantitative scenario analyses and multi-criteria assessments. As mentioned above, this would be a

way to make the approach more directly operational for policymaking. Secondly, the overall approach could be used to construct an initial assessment model, which could be periodically updated with new indicators and/or modules as new challenges and controversies arise. In this way, the model would serve as a modular assessment platform, dynamically responding to changing governance challenges over time.

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Part III : Appendices

Appendix A - Supplementary information on methodology of Manuscript 2

The intention behind the work reported in this article was to review and reflect on the importance and possible role of metaphors in research and debates concerning urban sustainability. From the beginning, the ambition was to work in an interdisciplinary team, with specialists from different disciplines and with different experiences in academia and practice contributing into a process of knowledge co-production (Norström et al., 2020). In particular, the research process was designed to follow the logic of 'collaborative participatory research' (Cornwall and Jewkes, 1995), whereby the group would work together as a whole within a rough agenda set by the initiating researchers.

Accordingly, the work on the article began by the group of initiating researchers (P.H., R.W., C.R.B) developing a set of core ideas related to the potential role of metaphors in promoting understanding on urban sustainability, based on preliminary work on the topic (Halla et al., 2020). In a two-step process, the core group first identified and invited scholars within their own institution (EPFL, Switzerland) to contribute from different theoretical and methodological angles to the interdisciplinary knowledge co-production process (A.A., G.D., V.K., S.K.). The group of researchers was then complemented by specialists from other institutions with complementary backgrounds (M.H., C.T., U.V.).

The work of the group evolved through a series of workshops (Ørngreen and Levinsen, 2017), and was kicked off by a two-day workshop in June 2020. In this initial workshop, held in a hybrid online-offline format due to the Covid-19 crisis, ideas and issues related to the use of metaphors in the urban sustainability domain were explored. The material collected during the workshop (notes and recordings) were afterwards analyzed by the initiating researchers and inductively formulated into a set of key areas of interest and related research questions (Mayring, 2000), which were to be further worked upon in the following steps.

From August 2020 to March 2021, seven follow-up workshops were held with the group of researchers. As mentioned above, the process was designed as collaborative participatory research (Cornwall and Jewkes, 1995) and accordingly during the workshops ample space was given for interdisciplinary exchange, mutual learning and knowledge creation (Pennington, 2016). Between the workshops, teams of two to three researchers worked on specific themes and questions, developing arguments and blocks of text that were then presented and discussed among the entire group at the following workshop.

Substantively, the work consisted of iterative conceptual analysis, leading from general ideas to more specific claims (Kerssens-van Drongelen, 2001; Bergdahl and Berterö, 2016). Specifically, through this collaborative and iterative process, the three theses presented in the article were formulated and the arguments to support them developed, including the demonstrative example of comparing three common urban metaphors (metabolism, rhythm, smart). Throughout this iterative process certain original ideas were also deferred for later exploration.

Following the workshops, the initiating researchers assembled and edited the contributions of the group into a manuscript adapted for the selected journal, as well as added a concluding section with potential pathways for future research. In the last stage before submission to the journal, the manuscript was subjected to two rounds of comments and edits from the entire group.

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Appendix B - Supplementary information on methodology of Manuscript 3

Criteria used to include or not an indicator set in our final sample (see section 3.1 of Manuscript 3)

(i) empirical orientation: only those indicator sets that had been empirically applied at least once were included in the final sample. Purely theoretical initiatives were thus omitted from the analysis;

(ii) recent activity: only those indicator sets that have been active within the last ten years (2010-2019) were considered;

(iii) clear and comprehensive focus on sustainability: all indicator sets included in the final sample mention either sustainability or sustainable development in the title of their respective key report/publication, or at least explicitly refer to it in the motivation or description of the initiative. Indicator sets focusing on a particular dimension of sustainability (i.e. environmental, social or economic), on specific sectors (e.g. energy, transports, water management), on related concepts (e.g. greenness, smartness, circularity) or on selected issues (e.g. natural hazards, environmental justice, urban sprawl) were also left out from further analysis.

(iv) urban scale: those indicator sets developed at the level of an *urban* system, a *town*, a *city* or a *neighborhood* were included in the sample. Those developed at a *local* scale or focusing on either a *municipality* or a *community* were analyzed on a case-by-case basis and considered only if the concerned settlement counted more than 5000 inhabitants.

(v) access to indicators: finally, we only took into account for the analysis those initiatives providing an accessible list of indicators.

Additional notes about the collection of indicators (see section 3.3 of Manuscript 3)

As a rule, each collected item corresponds to what is considered as being one indicator in each of the 67 indicator sets. Hence, we purposely tried to stay as faithful as possible to the structure of the original sets. Exceptionally, we merged into only one unit of analysis those *indicators* whose unique difference was about gender, age or area. The splitting was however included as additional information for further characterizing the indicator at hand.

Screening process (see section 3.5 of Manuscript 3)

During the consistency checking, the research team had to deal with two competing principles: global consistency and context-specificity. As explained before, two indicators with the same label and even potentially sharing similar measurement units, might convey quite different information depending on the particular context in which they were developed. Indeed, indicators are "relative and nested concepts" (Turnhout et *al.* 2007) and logically partially similar sequences (i.e. label-measurement units-anchoring) might require different screening results. For illustration, an indicator like *local food production* can be used alternatively as a proxy for the carbon footprint of a city, as a measure of local agricultural sector, or still in some particular cases as a way to measure how much the food sector is performing in accordance to specific health standards. Similarly, the *number of individuals who are engaged in sports activities* can be related to health issues, to leisure or to both simultaneously. In other words, we purposely screened the indicators taking into account the link between the "*what* is measured" and the "*why* it is measured", and interpreting the interaction of these two dimensions. We claim that the information brought by any indicator is linked to the intention that originates it, so that the same label can bear dissimilar information for the different assessors that chose to use it. Given this backdrop, the research team prioritized context-specificity over global consistency, which

was applied only subsequently. In other words, the codebook developed for the screening process (see Table B1 below) was not applied as a rule set in stone, but rather through a reflexive and critical procedure involving negotiation between the participating researchers.

Table B1. Extract of the codebook used in quantitative content analysis of Manuscript 3.

Indicator label	SDG category	STEEP category	MONET category
1. "PROXIMITY to…"		- SOC (always)	
1.1 Proximity to/convenience of amenities (in general)	- 11	- SOC	- **L, C**
1.2 Proximity to/convenience of transport	- 9 & 11	- SOC, TECH	- **L, C**
1.3 Proximity to/convenience of green areas	- 11 & 15	- SOC, ENV	- **L, C**
1.4 Access for those with disabilities	- 10 & 11	- SOC, TECH	- **D,** L ?
1.5 Proximity to health care facilities	- 3, 11	- SOC	- **L, C**
2. HEALTH		- SOC (always)	
2.1 n° hospital beds/hospitals/elderly care	- 3	- SOC	- **C,** L ?
2.1.1 if motivated by "access", add SDG 1			- **L, C**
2.2 n° physicians/nurses	- 3	- SOC	- **C,** L ?
2.2.1 if motivated by "access", add SDG 1			- **L, C**
2.3 Life expectancy	- 3	- SOC	- **L** (add D if particular group), C?
2.4 Median age (related to health, NOT to demographics)	- 3	- SOC	- **L** (add D if particular group)
2.5 Sport			
2.5.1 ex 1: practice	- 3	- SOC	- **L,** I/O ?
2.5.2 ex 2: sport infrastructures/facilities	- 3 & 11	- SOC, TECH	- **C,** L ?
2.6 Health-related behaviour			
2.6.1 Smoking/alcohol/drugs	- 3	- SOC	- **L,** I/O
2.6.2 Doctor visits	- 3	- SOC	- I/O, L
2.7 Overweight/obesity rate	- 2, 3	- SOC	- L
2.8 Infant health/mortality	- 3	- SOC	- L
2.9 Health statistics (e.g. prevalence of disease, mental health)	- 3	- SOC	- L
3. PERFORMANCE indicators (e.g. water losses, internet speed, electricity interruptions…)		~~- SOC~~	
3.1 electricity interruptions	- 7	- TECH	- L, C, E?
3.2 water losses/interruptions	- 6	- TECH, ENV	- E
3.3 energy efficiency/intensity (Kwh/GDP or GDP/Kwh)	- 7	- TECH, ENV, ECO	- E
3.4 (material) resource productivity	- 8 & 12	- TECH, ENV, ECO	- E
3.5 internet speed	- 9, 17	- TECH	- C
4. Access to BASIC SERVICES:	- 1 (always)	- SOC (always)	- L (always)
4.1 Access to basic services (in general)	- 1 & 11	- SOC	- **L, C**
4.2 **Access to water**	- 1, 3 (if health), 6 & 11 (if not health)	- SOC, ENV, TECH	- **L, C**
4.3 **Access to sanitation**	- 1, 3 (if health), 6 & 11 (if not health)	- SOC, ENV, TECH	- **L, C**
4.4 **Access to internet**	- 1, 9 & 17	- SOC, TECH	- **L, C**
4.5 **Access to energy/electricity**	- 1, 7 & 11	- SOC, TECH	- **L, C**
4.6 Access to (affordable) housing - including social housing, homelessness	- 1 & 11	- SOC, (affordable: ECO)	- **L**
4.7 **Access to health**	- 1 & 3	- SOC	- **L, C**
4.8 **Access to education** (Warning: dropouts/leavers is not about "access to". In that case, don't put SDG 1)	- 1 & 4	- SOC	- **L, C**

Appendix C – Lists of indicator categories discovered for different types of frameworks

Table C1. Domains found in the sample, including assimilated terms.

Domain	Assimilated terms	Number of appearances
ECONOMY	economic; profit	**24**
SOCIOECONOMY	socioeconomic	**4**
HUMAN		**2**
PEOPLE		**3**
SOCIETY	society and culture; social; societal; social-cultural	**22**
ENVIRONMENT	environmental; planet;	**26**
NATURAL ENVIRONMENT	natural	**4**
NATURAL RESOURCES	resources; ecological capital	**5**
BUILT ENVIRONMENT	infrastructure; physical; civil infrastructure	**6**
EXTERNAL CONNECTIONS	urban-rural relationship	**2**
GOVERNANCE	urban governance; government; institutional	**6**

Table C2. Domain appearances and co-appearances (used for computing Fig. 5 of Manuscript 4).

	TOTAL APPEA-RANCES	ECONOMY	SOCIO-ECONOMY	HUMAN	PEOPLE	SOCIETY	ENVIRONMENT	NATURAL ENVIRONMENT	NATURAL RESOURCES	BUILT ENVIRONMENT	EXTERNAL CONNECTIONS	GOVERNANCE
ECONOMY	24			1	2	20	20	3	5	1	2	3
SOCIO-ECONOMY	4						3			2		
HUMAN	2	1					2					
PEOPLE	3	2				1	2	1	1	1	1	
SOCIETY	22	20			1		18	2	4	2	2	4
ENVIRONMENT	26	20	3	2	2	18			3	2	1	4
NATURAL ENVIRONMENT	4	3			1	2			1	2	1	
NATURAL RESOURCES	5	5			1	4	3	1			1	
BUILT ENVIRONMENT	6	1	2		1	2	2	2				1
EXTERNAL CONNECTIONS	2	2			1	2	1	1	1			
GOVERNANCE	6	3				4	4			1		

Table C3. Full list of headline themes and sub-themes found in the sample.

WELL-BEING	ENVIRONMENTAL EXPOSURE	HEALTH AND HEALTHCARE
Socioeconomic well-being	Risk of natural disaster	Mental health
Social wellbeing	Vulnerability to climate change	Primary care
Personal well-being	**FOOD**	Early childhood care
Emotional well-being	Hunger and food security	Access to care
Quality of life	Urban agriculture	**TRANSPORTATION**
Human well-being	**NATURAL RESOURCE USE**	Transport infrastructure
BASIC NEEDS	Resource consumption	Mobility
Social security	Urban metabolism	Congestion
Poverty	Res. management and conservation	Transport structure and functionality
Affordability (cost of life)	Resource recovery	Accessibility (in and out of city)
DEMOGRAPHY	Resource sustainability	Transport proximity/accessibility
Workforce	Greenprint	**SECURITY**
Immigrant population	Environmental management	Crime
EMPLOYMENT	Ecological capital	Personal and community safety
Jobs and livelihoods	**WATER**	Gender-based violence
Work-life balance	Drinking water	Security systems
ECONOMIC SYSTEM	Water quality/pollution	Crime prevention
Economic productivity and growth	Water cycle	Peace and justice
Economic dynamism	Water sources	**SPORT AND RECREATION**
Income and wealth	Groundwater	Leisure
Structure and diversity of economy	Surface water	Recreational facilities
INDUSTRY AND TRADE	Hydrology, drainage	**CULTURE AND ARTS**
Creative industries	Wastewater	Cultural heritage
Business climate	Sanitation and hygiene	Heritage conservation
Distinctive local industries	**SOLID WASTE**	**ICT INFRASTRUCTURE**
Mining	Waste management/treatment	Connectivity
City branding	Waste generation	**URBAN PLANNING**
Tourism	**AIR**	Urban form
R&D AND TECHNOLOGY	Air quality	Complexity
Innovation	Atmosphere	Urbanization (urban development)
Research and development	**SOIL**	Economic Agglomeration
INVESTMENTS	Soil protection	Governance of Urbanization
Foreign investments	Soil pollution	Land use
Private investments	**EXTERNALITIES**	Land use planning and zoning
Public investments	Pollution	Infrastructure accessibility
Capital stocks	Noise	**NEIGHBOURHOODS**
ENVIRONMENTAL QUALITY	Nuisance	Local welfare
Ecosystems	**ENERGY**	Local management
Biodiversity	Energy/electricity consumption	**CIVIC ENVIRONMENT**
Life below water	Quality of energy	Civil participation
Life on land	Next-generation energy	Political participation
URBAN LANDSCAPE	Electricity supply	Community engagement
Green and blue spaces	**EDUCATION**	Democracy
Liveability	Human capital	**COMMUNITY**
Nature and landscape	Knowledge and know-how	Social participation and stewardship
Open and public space	Lifelong learning	Social capital
Appearance	Environmental education	Community connectedness
Urban heat island mitigation	**HOUSING**	Cultural diversity
CLIMATE	Green buildings	Community facilities
Climate protection	Residential environment	
Greenhouse gas emissions	Indoor environmental quality	

Table C3 (Continued). Full list of headline themes and sub-themes found in the sample.

PARTNERSHIPS	PUBLIC FINANCE	LIFESTYLES
Exchange	Public expenditure	Behaviours
Interregional solidarity	**SERVICES**	**INCLUSION AND EQUALITY**
PUBLIC SYSTEM	Social infrastructure and services	Social Inclusion/exclusion
Institutional Capacity	Public service delivery	Gender Inclusion and equality
Enforcement and monitoring	Digital public services	Social stratification
Participatory public management	Access to amenities	Income inequality
Modern public management		Empowerment
Transparency		

Table C4. The action components of goal-related categories of the sample, and assimilated terms.

Action	Assimilated terms	Number of appearances
promote	support; advance	**25**
develop	increase	**24**
assure	guarantee; ensure	**16**
create	establish; make happen; realize; achieve	**15**
reduce	decrease; mitigate; mitigate effects of	**14**
protect	preserve; maintain	**12**
enhance	improve; enrich; strengthen	**10**
prevent	zero; no	**7**
provide	meet the needs	**6**
restore	revitalize; reconstruct	**4**
build	raise; construct	**3**
implement		**2**
assess	monitor	**1**
attract		**1**
control		**1**
finance		**1**
organise		**1**
pay attention to		**1**
utilize		**1**
enable		**1**

Table C5. The attribute components of goal-related categories of the sample, and assimilated terms.

Attribute	Assimilated terms	Number of appearances
sustainable		**23**
good-quality	good; high-quality; high-level	**18**
efficient	effective; resource-efficient; optimal	**12**
adequate	proper; in proportion to demand	**10**
accessible		**9**
dynamic	active; vibrant; vital	**8**
clean		**7**
healthy		**6**
competitive		**6**
local		**6**
affordable		**5**
equitable	equal	**5**
safe		**4**
integrated		**4**
creative		**3**
inclusive	community-based; engaged	**3**
symbiotic	mutually-supportive; harmonious	**3**
responsible		**2**
diversified		**2**
eco-friendly	environmental [green]	**2**
socially cohesive		**2**
decent		**2**
resilient		**1**
attractive		**1**
available		**1**
beautiful		**1**
compact		**1**
concentrated		**1**
culturally rich		**1**
democratic		**1**
independent		**1**
meaningful		**1**
next generation		**1**
recycling-oriented		**1**
smart		**1**
verdant		**1**
viable		**1**
walker-friendly		**1**
at different levels		**1**
free of crimes		**1**
supportive		**1**
prosper		**1**

Table C5. The object components of goal-related categories of the sample, and assimilated terms.

Theme	Assimilated terms	Appearances
community	social cohesion; community life; neighborhoods; environment (community); society; residents	23
economic systems	economy; economic development; economies; activities; (economic) development; wealth; economic attractiveness	19
land use & urban planning	city; land use; urban development; urbanization; human habitat growth; life with the snowy climate; urban-rural; surroundings	15
education & childcare	educational facilities; spaces for educational fulfillment; child care; nurturing systems for children; awareness; knowledge; environment for youngs	13
natural ecosystems	environmental quality; environment(s); biodiversity; natural habitats	12
employment	work; jobs; opportunities; job markets; employment opportunities; types of employment; access to employment; human resources	11
housing	human habitat; (architectural) design; (construction) materials	10
transportation	transportation systems; urban transport; city (mobility); mobility	9
consumption & production	consumption & production of goods; consumption; industry; agriculture	8
health & healthcare	health services; public health care; public healthcare facilities; primary services; health-welfare industry	7
energy	energy systems; energy network	6
externalities	environmental health; impacts; pollution; GHG; carbon emissions; environmental load; community noise conflicts;	6
natural resource use	natural resources; energy consumption; resource management; consumption of natural resources	6
parks and open spaces	public spaces	5
food	food industry	5
public utilities & services	public utilities; services needs; social services; primary services; welfare services	5
government systems	mechanisms of governement; management structures; governance	4
inequalities	disadvantaged neighbouring areas; residents' isolation; inequality	4
adaptation & mitigation	local disaster prevention systems; climate change	4
partnerships	wide-area collaboration networks; external connection; work with other authorities; international strategies	4
infrastructure	connectivity; facilities	3
SD strategies	progress (towards SD); SD vision	3
public finance	management of revenue; management of expenditure; management of debt and fiscal obligations	3
participation	community management; social engagement	3
vulnerability	vulnerability to natural disasters; risk of exposure to industrial contaminants	3
culture & arts	cultural activities; cultural facilities & events; culture	3
water & sanitation	water; water management	3
poverty		3
sports & recreation	leisure activities; recreation facilities	2
tourism	city (tourism); resort experience	2
gender	gender conditions	2
hunger		2
city promotion		1
climate change		1
inclusion	social inclusion	1

Table C5. The object components of goal-related categories of the sample, and assimilated terms.

Theme	Assimilated terms	Appearances
inclusion	social inclusion	1
security	crime prevention	1
air quality		1
basic needs	daily goods	1
R&D and technology	innovation	1
well-being	life; quality of life	1
vitality (from overseas)		1
investments		1
solid waste		1

Appendix D - Supplementary information on interviews for Manuscript 5

Table D1. A stylized interview guide used in the stakeholder interviews of Manuscript 5.

Theme	Questions
Sustainability criteria for housing	1. How would you define sustainable housing? 2. What in your opinion are the criteria for evaluating make housing sustainable? What should we measure for such evaluations?
Challenges and measures	1. What are the challenges and obstacles currently with the sustainability of housing in Geneva? 2. What are the measures taken currently to address the sustainability of housing in Geneva? Do you see possible future developments and trends in this regard? 3. Are there some issues in this sector that are specific to this city, compared to other cities in Switzerland or to other countries?

Table D2. Stakeholders interviewed during research for Manuscript 5.

Type of interviewee	Date
Project manager, municipal government	12.11.2019
Project manager, municipal government	26.11.2019
Manager, cooperative association	18.12.2019
Manager, owners' association	21.01.2020
Project manager, municipal government	24.01.2020
Manager, cooperative association	28.01.2020
Director of department, municipal government	19.02.2020
Assistant professor	21.02.2020
Director, architecture firm	19.02.2020
Associate professor	26.02.2020
Director of department, municipal government	26.02.2020
Professor	03.03.2020
Sustainability manager, construction company	26.03.2020
Committee member, tenants' association	22.04.2020

Appendix E - Grey literature archive of Manuscript 5.

Table E1. The archive of analyzed grey literature.

NAME OF DOCUMENT/WEBSITE	AUTHOR/RESPONSIBLE ACTOR
FEDERAL	
Constitutional Articles 73, 75, 78, 89, 108, 109	Swiss Confederation
Sustainable Development Strategy 2016-2019; 2030	Federal Office for Spatial Development (ARE)
Loi fédérale sur l'aménagement du territoire	Federal Office for Spatial Development (ARE)
Loi fédérale encourageant le logement à loyer ou à prix modérés (LOG)	Federal Office for Housing (FOH)
Système d'évaluation de logements (SEL)	Federal Office for Housing (FOH)
Quartiers durables	Federal Office for Spatial Development (ARE); Federal Office of Energy SFOE (SFOE); Canton Vaud; City of Lausanne; Schéma directeur de l'Ouest lausannois (SDOL)
Energy Strategy 2050	Federal Office of Energy (SFOE)
Federal Act on the Protection of Nature and Cultural Heritage	Federal Inventory of Heritage Sites (ISOS)
CANTONAL	
Concept cantonal du développement durable 2030	Département du territoire (DT); Service Cantonal du Développement Durable
Plan climat cantonal	Département du territoire (DT); Service Cantonal du Développement Durable
Plan directeur cantonal	Département du territoire (DT); Office de
Plan directeur de l'énergie 2020-2030	Département du territoire (DT); Office cantonal de
MUNICIPAL	
Feuille de route du Conseil administratif (2015-2020)	Administrative Council
Plan directeur communal Gèneve 2020	Département de l'aménagement, des constructions et de la mobilité; Service d'urbanisme
Plan d'utilisation du sol	Département de l'aménagement, des constructions et de la mobilité; Service d'urbanisme
Politique énergétique	Département de l'aménagement, des constructions et de la mobilité; Service de l'énergie
Engagements et actions municipales en faveur d'un développement durable	Département des finances, de l'environnement et du logement; Service Agenda 21
Politique sociale du logement	Département des finances, de l'environnement et du logement; Gérance Immobilière Municipale
Plan stratégique de végétalisation de la Ville	Département des finances, de l'environnement et
Politique sociale de proximité	Département de la cohésion sociale et de la solidarité; Service social
NORMATIVE	
SIA 112/1; SIA 2040	The Swiss Society of Engineers and Architects (SIA)
SNBS 2.0 Bâtiment	Sustainable Construction Network Switzerland
Gestion Immobilière Durable	Interessengemeinschaft privater, professioneller Bauherren (IPB); Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (KBOB)
Qu'est-ce que Minergie?	Association Minergie
Certificat énergétique cantonal des bâtiments (CECB)	l'Assemblée plénière de l'EnDK; L'association CECB
Manuel relatif au certificat pour les Sites 2000 watts (2019)	Site 2000 watts
One Planet Living - Plan d'Action de Durabilité	Association suisse pour des quartiers durables
SméO	Canton Vaud; City of Lausanne

Appendix F - Supplementary information on candidate indicator collection for Manuscript 5

The academic literature for collecting candidate indicators was identified by the Scopus research engine using the search string “KEY (sustainab*) AND KEY (indicator*) AND KEY (housing) AND PUBYEAR > 2010 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (DOCTYPE , "ar"))”. The search yielded 56 articles, of which 29 were found to be pertinent for the purpose. Table E1 displays the references from which candidate indicators were drawn for each goal.

Table F1. Academic sources where candidate indicators were found for the assessment of Manuscript 5.

GOALS	Indicator sources		
1. Comfortable and healthy dwellings	Marjaba et al., 2020 Cooper et al., 2020 Adabre and Chan, 2020 Karji et al., 2019 Li Yulong et al., 2019 Ullah et al., 2018	Tupenaite et al., 2017 Rid et al., 2017 Vega-Azamar et al., 2017 Guangdong Wu et al., 2017 Ahmad and Thaheem, 2017 Sanni-Anibire et al., 2016	Castellano et al., 2016 Zhao, 2016 Yu et al., 2014 Xu and Coors, 2012 Feige et al., 2013 Pagani et al., 2020
2. Durable and adaptable buildings	Marjaba et al., 2020 Cooper et al., 2020 Adabre and Chan, 2020 Ahmad and Thaheem, 2018 Zarghami et al., 2018	Tupenaite et al., 2017 Rid et al., 2017 Sanni-Anibire et al., 2016 Castellano et al., 2016	Xue, 2012 Wallbaum et al., 2012 Pagani et al., 2020 Feige et al., 2013
3. Buildings with low energy and material footprint	Marjaba et al., 2020 Adabre and Chan, 2020 Martín-Gamboa et al., 2019 Karji et al., 2019 Saldaña-Márquez et al., 2019 Ullah et al., 2018 Zarghami et al., 2018	Tupenaite et al., 2017 Rid et al., 2017 Vega-Azamar et al., 2017 Guangdong Wu et al., 2017 Castellano et al., 2016 Hollberg and Ruth, 2016	Djokic et al., 2015 Burdova and Vilcekova, 2014 Xue, 2012 Wallbaum et al., 2012 Xu and Coors, 2012 Pagani et al., 2020
4. Buildings and neighborhoods in harmony with their physical surroundings	Karji et al., 2019 Saldaña-Márquez et al., 2019 Ullah et al., 2018 Zarghami et al., 2018 Tupenaite et al., 2017	Guangdong Wu et al., 2017 Ahmad and Thaheem, 2017 Sanni-Anibire et al., 2016 Castellano et al., 2016 Preval et al., 2016	Wissen Hayek et al., 2015 Djokic et al., 2015 Yu et al., 2014 Xue, 2012 Xu and Coors, 2012
5. Safe neighborhoods	Cooper et al., 2020 Adabre and Chan, 2020 Karji et al., 2019 Li Yulong et al., 2019 Ullah et al., 2018	Tupenaite et al., 2017 Azami et al., 2017 Rid et al., 2017 Guangdong Wu et al., 2017 Ahmad and Thaheem, 2017	Sanni-Anibire et al., 2016 Zhao, 2016 Djokic et al., 2015 Repetti and Desthieux, 2006 Feige et al., 2013
6. Participatory neighborhoods	Azami et al., 2017 Rid et al., 2017	Guangdong Wu et al., 2017	Djokic et al., 2015
7. Connected neighborhoods	Adabre and Chan, 2020 Karji et al., 2019 Saldaña-Márquez et al., 2019 Ullah et al., 2018 Zarghami et al., 2018	Tupenaite et al., 2017 Rid et al., 2017 Guangdong Wu et al., 2017 Ahmad and Thaheem, 2017	Sanni-Anibire et al., 2016 Castellano et al., 2016 Preval et al., 2016 Djokic et al., 2015
8. Convivial neighborhoods	Cooper et al., 2020 Adabre and Chan, 2020 Karji et al., 2019 Saldaña-Márquez et al., 2019 Ullah et al., 2018 Ahmad and Thaheem, 2018	Tupenaite et al., 2017 Rid et al., 2017 Guangdong Wu et al., 2017 Ahmad and Thaheem, 2017 Sanni-Anibire et al., 2016 Castellano et al., 2016	Djokic et al., 2015 Yu et al., 2014 Repetti and Desthieux, 2006 Pagani et al., 2020 Feige et al., 2013
9. Diverse neighborhoods	Adabre and Chan, 2020 Karji et al., 2019 Zarghami et al., 2018	Tupenaite et al., 2017 Rid et al., 2017 Guangdong Wu et al., 2017	Wissen Hayek et al., 2015 Djokic et al., 2015
10. Economically viable markets	Marjaba et al., 2020 Cooper et al., 2020 Adabre and Chan, 2020 Martín-Gamboa et al., 2019 Karji et al., 2019	Li Yulong et al., 2019 Ullah et al., 2018 Tupenaite et al., 2017 Rid et al., 2017 Guangdong Wu et al., 2017	Djokic et al., 2015 Xue, 2012 Wallbaum et al., 2012 Xu and Coors, 2012 Pagani et al., 2020

Table F1 (cont'd). Academic sources where candidate indicators were found for the assessment of Manuscript 5.

GOALS	Indicator sources		
11. Accessible and fair markets	Adabre and Chan, 2020 Ahmad and Thaheem, 2018 Tupenaite et al., 2017 Azami et al., 2017	Guangdong Wu et al., 2017 Zhao, 2016 Wissen Hayek et al., 2015	Djokic et al., 2015 Xue, 2012 Xu and Coors, 2012
12. Markets with adequate supply	Tupenaite et al., 2017 Zhao, 2016	Xue, 2012	Xu and Coors, 2012
13. Cultural and aesthetic value	Marjaba et al., 2020 Adabre and Chan, 2020 Karji et al., 2019	Tupenaite et al., 2017 Guangdong Wu et al., 2017 Ahmad and Thaheem, 2017	Sanni-Anibire et al., 2016 Djokic et al., 2015

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Appendix G - Shortlisted indicators of Manuscript 5

Table G1. The shortlisted indicators for each goal of the assessment model of Manuscript 5. The number in parentheses after the indicator title is the number of votes the indicator received in the stakeholder questionnaire (see the following Appendix H).

GOALS	SHORTLISTED INDICATORS	
1. Comfortable and healthy dwellings	1.1 Noise (9) 1.2 Natural light (7) 1.3 Thermal comfort (6)	1.4 Living space per person (4) 1.5 Accessibility for persons with reduced mobility (3) 1.6 View to outside (2)
2. Durable and adaptable buildings	2.1 Investments in maintenance, renovation or conversion (8) 2.2 Ease of refurbishing installations (7) 2.3 Structural adaptability (5)	2.4 Lifetime of appliances (4) 2.5 Service life of building (4) 2.6 Ease of changing the floor plan independently (2)
3. Buildings with low energy and material footprint	3.1 Energetic efficiency of buildings (9) 3.2 Share of renewable energy (9) 3.3 Grey energy (7)	3.4 Type of heating system in use (2) 3.5 Share of residential waste recycled (2) 3.6 Material use (non-recycled) in construction (0)
4. Buildings and neighborhoods in harmony with their physical surroundings	4.1 Construction considering the natural conditions of the site (6) 4.2 Percentage of green coverage (5) 4.3 Compactness (5)	4.4 Preservation of local ecosystems (5) 4.5 Natural water management (4) 4.6 Use of green roofs and walls (2)
5. Safe neighborhoods	5.1 Pedestrian and low speed limit zones (8) 5.2 Existence of risk maps (6) 5.3 Delinquent act density (6	5.4 Burglary rate (3) 5.5 Properties at risk of flooding (3) 5.6 Percent of drivers exceeding the speed limit (3)
6. Participatory neighborhoods	6.1 Availability of community facilities (8) 6.2 Membership in community associations (6) 6.3 Existence of participatory budgeting (5)	6.4 Citizen participation meetings (4) 6.5 Number of people in volunteer work (3) 6.6 Activity factor of senior citizens (2)
7. Connected neighborhoods	7.1 Capacity of public transport system (9) 7.2 Soft mobility infrastructure (9) 7.3 Availability of shared vehicles (6)	7.4 Average commute time to work (3) 7.5 Proximity to commercial centers (2) 7.6 Transport energy consumption (1)
8. Convivial neighborhoods	8.1 Architecture encouraging social links (10) 8.2 Amount of public spaces (5) 8.3 Shared spaces (5)	8.4 Satisfaction with neighbor relationships (4) 8.5 Share of inhabitants feeling they can get help from others (4) 8.6 Existence of sharing programs (1)
9. Diverse neighborhoods	9.1 Age distribution of residents (10) 9.2 Share of residents receiving social benefits (7) 9.3 Ethnic diversity of residents (7)	9.4 Mix of sizes of dwellings in one building (3) 9.5 Commercial and office space per dwelling (3) 9.6 Outdoor quiet spaces (1)
10. Economically viable markets	10.1 Cost of maintenance and retrofitting (7) 10.2 Access to funding for investment (6) 10.3 Cost of land (5)	10.4 Regionally added value in construction (4) 10.5 Return on investment over life-cycle (4) 10.6 Jobs in building retrofitting (1)
11. Accessible and fair markets	11.1 Average rental price per m2 (9) 11.2 Subsidized housing ratio (6) 11.3 Households whose housing costs are more than 40 % of income (6)	11.4 Number of years of salary required to purchase a home (4) 11.5 Tenure insecurity (2) 11.6 Mortgage interest rate (2)
12. Markets with adequate supply	12.1 Construction rate relative to population growth (7) 12.2 Vacancy rate (7) 12.3 Ratio of single and multifamily dwellings (6)	12.4 Available land for construction (3) 12.5 Investments in real estate development (2) 12.6 Housing designated for the elderly (1)
13. Cultural and aesthetic value	13.1 Preservation of local characteristics and identity (8) 13.2 Satisfaction with aesthetics of surroundings (6) 13.3 Satisfaction with landscape (5)	13.4 Satisfaction with aesthetics of dwelling (5) 13.5 Satisfaction with maintenance and cleanliness (3) 13.6 Protected buildings (2)

Appendix H - Stakeholder questionnaire of Manuscript 5

As part of the construction and validation of the assessment model, the 14 stakeholders that were interviewed in the beginning of the research were asked through an online questionnaire to express their opinions on the relative importance of the goals and the shortlisted indicators. More specifically, the first question was *"How do you estimate the importance of the following goals with regard to the sustainability of housing in the city of Geneva?*", with the respondents choosing between three options (Below-average importance; Average importance; Above-average importance) for each goal. Having relative response options rather than absolute (e.g., Not at all important; Important; Very important) was an attempt to elicit greater distinction between the goals, as the absolute scale could have easily led to every goal being evaluated as important or very important. The second question aimed at selecting the most pertinent indicators among the candidate indicators by asking the respondents "*Which of the following indicators do you think are most relevant for assessing the [respective goal]? Please choose a maximum of three indicators.*"

The results of the first question are displayed in the Table H1 below (N=10). The ranking of the goals is defined, firstly, by how many respondents estimated a given goal to be of above-average importance, and in case of a tie, secondly by the number of respondents rating the goal to be of average importance. The results of the second question are shown in Table G1 of Appendix G.

Table H1. The relative importance of the goals according to the stakeholders (N=10).

GOALS	Below-average importance	Average importance	Above- average importance	RANK
1. Comfortable and healthy dwellings	0	4	6	4
2. Durable and adaptable buildings	1	2	7	3
3. Buildings with low energy and material footprint	1	1	8	1
4. Buildings and neighborhoods in harmony with their physical surroundings	2	2	6	5
5. Safe neighborhoods	2	6	2	13
6. Participatory neighborhoods	3	3	4	8
7. Connected neighborhoods	0	6	4	6
8. Convivial neighborhoods	2	5	3	12
9. Diverse neighborhoods	0	3	7	2
10. Economically viable markets	1	6	3	9
11. Accessible and fair markets	1	5	4	7
12. Markets with adequate supply	1	6	3	9
13. Cultural and aesthetic value	1	6	3	9

Appendix I - Supplementary information on indicator operationalization in Manuscript 5

Table I1. Methodological notes and data sources for the indicators applied in research of Manuscript 5.

Indicator	Notes	Data source
1.1 Noise		**City Statistics – Quality of life in the cities** (FSO, 2021) • Noise: https://www.bfs.admin.ch/bfs/en/home/statistics/cross-sectional-topics/city-statistics/indicators-quality-life/housing-conditions/traffic-noise.html
1.2 Natural light		…
2.1 Investments in maintenance, renovation or conversion		**Statistics for construction and housing** (FSO, 2020a) • Expenditures for construction: https://www.bfs.admin.ch/bfs/fr/home/statistiques/construction-logement/depenses.assetdetail.13587539.html
2.2 Ease of refurbishing installations	Calculated based on price of renovating electric, heating, ventilation, and sanitary installations - Values for cantons of Geneva and Zürich from Oct 2020; base Oct 2015	**Price statistics** (FSO, 2020b) • Price index for construction (Switzerland): https://www.bfs.admin.ch/bfs/fr/home/statistiques/prix/prix-construction/indice-prix-construction.assetdetail.15044840.html **Cantonal Statistics** (République et canton de Genève, 2021) • Price index for construction (Geneva): https://www.ge.ch/statistique/domaines/05/05_03/tableaux.asp#2
3.1 Energetic efficiency of buildings	Values are averages from a sample of buildings; including inhabited buildings only.	**Le système d'information du territoire à Genève** (SITG, 2021) • Heat consumption index: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=idc&topic=tous&datatype=tous&service=tous&distribution=tous&sort=auto
3.2 Share of renewable energy		**Statistics for construction and housing** (FSO, 2020a) • Building statistics: https://www.bfs.admin.ch/bfs/fr/home/statistiques/construction-logement/batiments/domaine-energetique.assetdetail.1621740.html
4.1 Construction considering the site's natural conditions		…
4.2 Percentage of green coverage		**City Statistics – Quality of life in the cities** (FSO, 2021) • Land use: https://www.bfs.admin.ch/bfs/en/home/statistics/cross-sectional-topics/city-statistics/indicators-quality-life/environmental-quality/land-use.html
5.1 Pedestrian and low speed limit zones		**Cercle Indicateurs** (FSO, 2017)
5.2 Existence of risk maps	Maps available: Geneva (floods, major accidents); Zürich (floods, chemical accidents, polluted soil); Basel (floods, major accidents, earthquakes)	**Risk maps** • Geneva: https://ge.ch/sitg/ • Zürich: https://maps.zh.ch/ • Basel: https://www.geo.bs.ch/mapbs.html
6.1 Availability of community facilities	Population statistics from 2020	**Neighborhood spaces** • Geneva: https://www.geneve.ch/fr/demarches/reserver-salle-espace-quartier • Zürich: https://gz-zh.ch/standorte/ • Basel: https://www.qtp-basel.ch/ **City Statistics – Quality of life in the cities** (FSO, 2021) • Demographic statistics: https://www.bfs.admin.ch/bfs/fr/home/statistiques/themes-transversaux/city-statistics/indicateurs-qualite-vie/qualite-environment/utilisation-sol.assetdetail.15504142.html
6.2 Membership in community associations	Data from 2020; only for "Grande régions"	**Swiss Society for the Common Good** (SSUP, 2021) • Association membership: https://sgg-ssup.ch/wp-content/uploads/2020/11/Observatoire_2020_Fiches_Ass_locale.pdf

Table I1 (Cont'd). Methodological notes and data sources for the indicators applied in research of Manuscript 5.

Indicator	Notes	Data source
7.1 Capacity of public transport system		**City Statistics – Quality of life in the cities** (FSO, 2021) • Public transport stops: https://www.bfs.admin.ch/bfs/fr/home/statistiques/themes-transversaux/city-statistics/indicateurs-qualite-vie/revenue-travail/aide-sociale.assetdetail.14250661.html)
7.2 Soft mobility infrastructure	Index: 1. Distance traveled by bicycle; 2. Accidents with bi-cycles; 3. Bicycle-friendliness	**20 Jahre Schweizer Stadtpolitik** (Avenir Suisse, 2018)
8.1 Architecture encouraging social links		…
8.2 Number of public spaces	Calculated by dividing number of public benches by city area (unfortunately no longitudinal data available)	**Le système d'information du territoire à Genève** (SITG, 2021) • Number of public benches: https://ge.ch/sitg/sitg_catalog/sitg_donnees?keyword=banc+public&topic=tous&datatype=tous&service=tous&distribution=tous&sort=auto#
9.1 Age distribution of residents	Number of residents either under 20 or over 64 years per residents between 20 and 64 years - Data from 2020	**City Statistics – Quality of life in the cities** (FSO, 2021) • Demographic statistics: https://www.bfs.admin.ch/bfs/fr/home/statistiques/themes-transversaux/city-statistics/indicateurs-qualite-vie/qualite-environment/utilisation-sol.assetdetail.14250654.html
9.2 Share of residents receiving social benefits	Including recipients of social assistance, cantonal min. income, and recipients of suppl. benefits linked to AHV/IV; data from 2017	**Cantonal analysis of inequalities** (CATI-GE, 2020)
10.1 Cost of maintenance and retrofitting	Values for cantons of Geneva and Zürich from Oct 2020; base Oct 2015	**Price statistics** (FSO, 2020b) • Price index for construction (Switzerland): https://www.bfs.admin.ch/bfs/fr/home/statistiques/prix/prix-construction/indice-prix-construction.assetdetail.15044840.html **Cantonal Statistics** (République et canton de Genève, 2021) • Price index for construction (Geneva): https://www.ge.ch/statistique/domaines/05/05_03/tableaux.asp#1
10.2 Access to funding for investment		…
11.1 Average rental price /m^2		**Cercle Indicateurs** (FSO, 2017)
11.2 Subsidized housing ratio	Sum of subsidized housing and housing owned by the city (4900 dwellings); data from 2019	**Cantonal Statistics** (République et canton de Genève, 2021) • Subsidized housing: https://www.ge.ch/statistique/domaines/09/09_02/tableaux.asp#4 **Municipal housing** (Ville de Géneve, 2021) • Social housing owned by the city: https://omnibook.com/view/31c0a35e-6e23-458d-811c-93651c4aaa76/page-004.html
12.1 Construction rate in relation to population growth	Calculated as a ratio of new residents over new dwellings (from 2015 to 2019)	**City Statistics – Quality of life in the cities** (FSO, 2021) • Number of dwellings: https://www.bfs.admin.ch/bfs/fr/home/statistiques/themes-transversaux/city-statistics/indicateurs-qualite-vie/qualite-environment/utilisation-sol.assetdetail.14250634.html • Demographic statistics: https://www.bfs.admin.ch/bfs/fr/home/statistiques/themes-transversaux/city-statistics/indicateurs-qualite-vie/qualite-environment/utilisation-sol.assetdetail.14250654.html
12.2 Vacancy rate		**City Statistics – Quality of life in the cities** (FSO, 2021) • Vacancy rate: https://www.bfs.admin.ch/bfs/en/home/statistics/cross-sectional-topics/city-statistics/indicators-quality-life/housing-conditions/dwelling-vacancy.assetdetail.14250634.html
13.1 Preserva-tion of local characteristics		…
13.2 Satisfaction with aesthetics		…

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PEKKA HALLA

+41 77 405 1978

pekka.halla@gmail.com

Date of birth: 27.01.1981

Nationality: Finnish

WORK EXPERIENCE

07/2017-(ongoing) **Doctoral Assistant – EPFL, Switzerland**

- Conducting research for a doctoral degree at the Laboratory for Human Environment Relations in Urban Systems (HERUS) under the project title "Sustainability assessment of urban systems"
- Teaching assistant; supervision of students (two Master's theses, several semester projects)

08/2014-12/2016 **Project Coordinator – InnoAid, Denmark**

- Coordinator (part-time) in 'Street Food Project' of Denmark-based NGO InnoAid in Kolkata, India

06/2008-12/2011 **Senior Engineer, Product Development – Nokia DK A/S, Denmark**

- Responsible for the design and implementation of multiple R&D projects

01/2007-06/2008 **Project Engineer – Elcoteq Design Centre, Finland**

- Responsible for wireless designs and product development

01/2006-12/2006 **Research assistant – Radio Laboratory, Helsinki University of Technology, Finland**

EDUCATION

2014-2016 **MSc, Socio-Ecological Economics and Policy, WU Wien**

- Programme with a focus on sustainability, environmental economics and multilevel policy
- Graduated with honours; recipient of merit-based scholarship in both years of studying
- Thesis research on the institutionalization of companies' CSR strategies into their practices and incentives (Grade: Excellent)

2011-2014 **BSc, Business Administration and Sociology, Copenhagen Business School**

- Programme mixing economics and sociology, with a strong focus on both quantitative and qualitative methods
- Thesis research on a case study of establishing an innovation centre within a large health care organization (Awarded as best thesis in class)

2000-2008 **MSc, Technology (Electrical Engineering), Helsinki University of Technology**

- Thesis research specific absorption rate design of handsets

COMPETENCES	• Python programming; statistical analysis with Stata, SPSS; NetLogo agent-based modelling • Qualitative research methods, including interviewing, workshops, observation; MaxQDA
LANGUAGES	Native - **Finnish** Fluent - **English** Intermediate - **French, Swedish** Basic - **German, Spanish, Italian**
PUBLISHED OR SUBMITTED ACADEMIC ARTICLES	• Halla, P., Binder, C.R., 2020. Sustainability Assessment: Introduction and Framework, in: Binder, C.R., Wyss, R., Massaro, E. (Eds.), Sustainability Assessment of Urban Systems. Cambridge University Press, Cambridge, pp. 7–29. https://doi.org/10.1017/9781108574334 • Halla, P., Wyss, R., Binder, C.R., 2020. Conceptualizing Urban Systems for Sustainability Assessment: Four Powerful Metaphors, in: Binder, C.R., Wyss, R., Massaro, E. (Eds.), Sustainability Assessment of Urban Systems. Cambridge University Press, Cambridge, pp. 241–26. https://doi.org/10.1017/9781108574334.012 • Halla, P., Wyss, R., Athanassiadis, A., Drevon, G., Hensel, M.U., Kaufmann, V., Koseki, S.A., Turcu, C., Vilsmaier, U., Binder, C.R., forthcoming. Using metaphors for addressing urban sustainability. Publication pending. • Merino-Saum, A., Halla, P., Superti, V., Boesch, A., Binder, C.R., 2020. Indicators for urban sustainability: Key lessons from a systematic analysis of 67 measurement initiatives. Ecological Indicators, 119, 106879. https://doi.org/10.1016/j.ecolind.2020.106879 • Halla, P., Merino-Saum, A., forthcoming. Conceptual frameworks for urban sustainability indicators - an empirical analysis. Publication pending. • Halla, P., Merino-Saum, A., Binder, C.R., forthcoming. Contextually rich sustainability assessment for supporting local urban governance - connecting indicators to institutions and controversies. Publication pending.