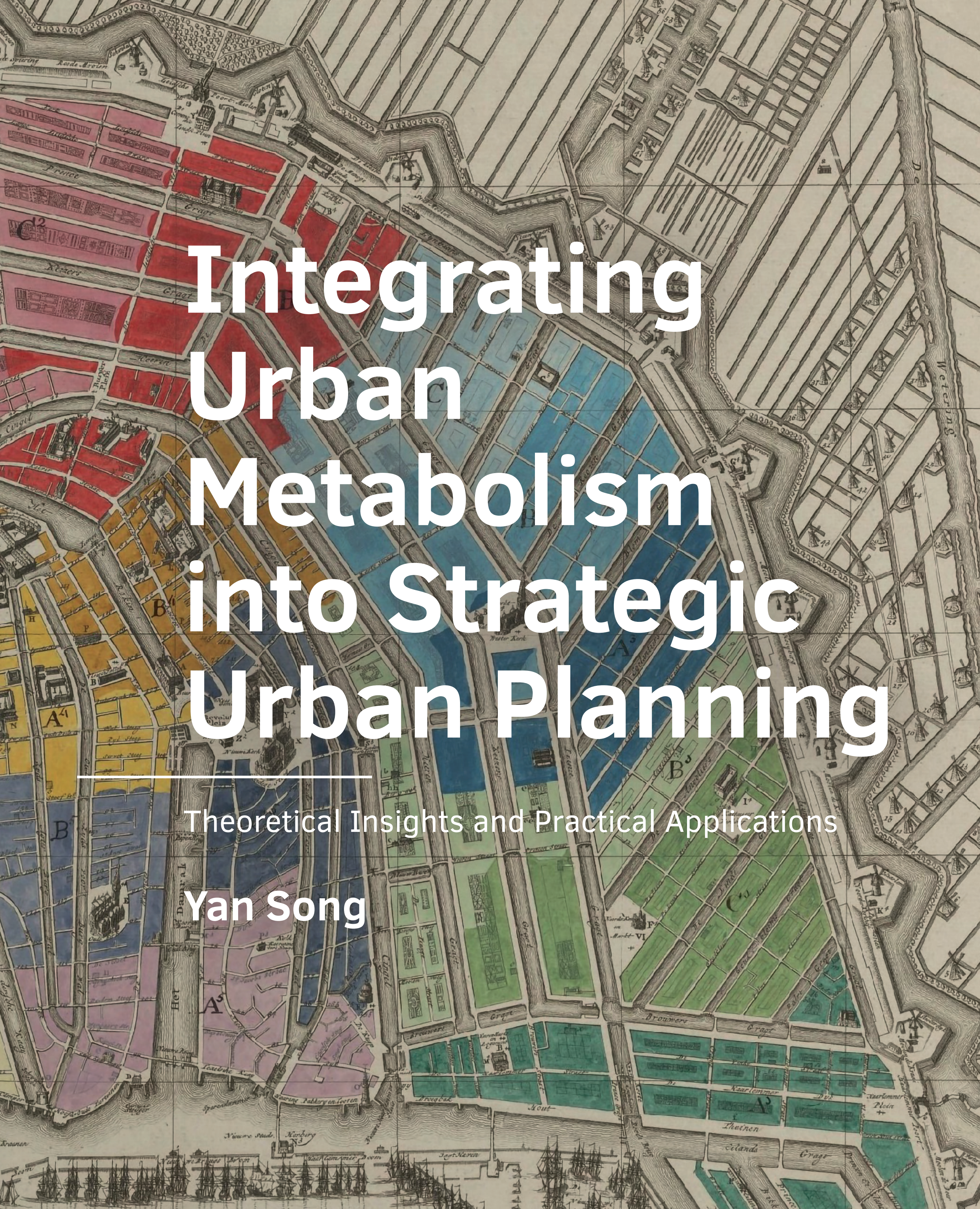

Integrating Urban Metabolism into Strategic Urban Planning

Theoretical Insights and Practical Applications

Yan Song

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Integrating Urban Metabolism into Strategic Urban Planning

Theoretical Insights and Practical Applications

Dissertation

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by

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Summary

This thesis examines Urban Metabolism (UM) as a critical framework for advancing sustainability in urban development, focusing on its theoretical underpinnings, practical applications, and integration into strategic urban planning processes. The study aims to address the challenges cities face in resource management and environmental resilience by developing and applying UM indicators as tools to guide planners and policymakers. Structured across several chapters, the research explores UM's conceptual evolution, methodological innovations, and practical implications for fostering circular and sustainable urban systems.

The introductory chapter contextualizes UM as an analytical lens to assess urban systems, akin to biological organisms, by tracking their resource flows and waste outputs. The concept has evolved over time, gaining relevance in addressing contemporary urbanization challenges such as resource depletion and environmental degradation. While aligning with global frameworks like the United Nations' Sustainable Development Goals (SDGs), UM faces practical implementation barriers, particularly in translating its theoretical insights into actionable strategies for urban planners. This chapter emphasizes the critical need for tools that integrate resource flow analysis into planning processes to achieve circular and resilient urban ecosystems.

Building on this foundation, the research question and methodology outlined in Chapter 2 set the stage for a systematic investigation of UM indicators. The central inquiry focuses on how these indicators can enhance strategic urban planning by addressing the perspectives of actors, spatial dimensions, and resource flows. A combination of literature reviews, case studies, and surveys guides the study, ensuring a robust and multi-dimensional exploration of the topic.

Chapter 3 delves into the categorization and evaluation of UM indicators based on an extensive review of existing literature. Using a hierarchical framework, the research identifies 38 key indicators, grouped under three domains: environment (e.g., air quality, water conditions, carbon sinks), resource flow (e.g., material inputs, outputs, and throughputs), and city development (e.g., population growth, economic transitions, land-use changes). The chapter advocates for material flow analysis as a practical and accessible method for integrating these indicators into urban planning, distinguishing it from the more complex emergy synthesis analysis.

The challenges of implementing UM indicators are explored in Chapter 4, which highlights cognitive and practical disparities between stakeholders and urban planners. Stakeholders prioritize indicators that emphasize socio-economic outcomes, while planners focus on technical and spatial resource flows. Surveys reveal barriers such as inconsistent data availability and the difficulty of aligning indicators with spatial frameworks. To address these gaps, the chapter proposes strategies for improved communication and the development of tailored frameworks that reconcile diverse priorities.

Chapter 5 examines how UM indicators function across different spatial scales, ranging from global to local levels. Through case studies in the Netherlands, the chapter illustrates how some indicators are specific to particular scales, while others are adaptable across multiple contexts. The analysis underscores the importance of aligning indicator goals with the unique objectives and constraints of each spatial scale, ensuring their relevance in supporting sustainable urban development.

The integration of UM indicators into the planning process is explored in Chapter 6, which maps their application across distinct phases, including initial assessments, vision setting, strategy formulation, implementation, and monitoring. This chapter demonstrates how indicators can enhance decision-making at each phase, fostering more informed and sustainability-oriented planning outcomes. The dynamic interplay of indicators across phases is emphasized as a key element in promoting circularity and resilience in urban systems.

The final chapter synthesizes these findings into a comprehensive framework for integrating UM indicators into strategic urban planning. The framework comprises two instruments: (i) an abstracted timeline of iterations, serving as a guide that directs and concentrates the selection process of UM indicators (fig 7.1); and (ii) a graph that consolidates factors related to people, scale, and process, clearly outlining the specific objectives that the selected indicators are intended to achieve, based on their position in the timeline iteration (fig 7.2). These instruments empower a planning team to select and optimize UM indicators tailored for a particular strategic urban plan. Furthermore, it guarantees the selection of indicators by stakeholders and their involvement throughout the planning process, accounting for scalar interrelations and contextual specificities. By ensuring stakeholder involvement and addressing scale-specific needs, the framework equips planners with actionable tools for embedding UM principles into decision-making processes.

This research significantly advances the field of UM by bridging the gap between theory and practice. It offers urban planners and policymakers a set of actionable strategies and tools to incorporate UM into their work, promoting sustainability and resilience in urban systems. By focusing on the practical application of UM indicators, the study contributes to a deeper understanding of how cities can transition toward more circular, resource-efficient futures.

Samenvatting

Dit proefschrift onderzoekt Stedelijk Metabolisme (‘Urban Metabolism’ in het Engels, afgekort: UM) als een kritisch kader voor het bevorderen van duurzaamheid in stadsontwikkeling. De focus ligt hierbij op de theoretische basis, praktische toepassingen en integratie ervan in strategische stadsplanologische processen. De studie pakt de uitdagingen op waarmee steden worden geconfronteerd op het gebied van hulpbronnenbeheer en ecologische veerkracht door het ontwikkelen van UM-indicatoren als instrumenten voor stadsplanners en beleidsmakers. De conceptuele evolutie van UM, methodologische innovaties en praktische implicaties voor het bevorderen van circulaire en duurzame stedelijke systemen komen in verscheidene hoofdstukken aan bod.

Hoofdstuk 1 introduceert UM als een analytische benadering van stedelijke systemen, waarbij de stromen van hulpbronnen en afval worden gevolgd, vergelijkbaar met de stofwisseling van een biologisch organisme. Het concept heeft zich in de loop der tijd verder ontwikkeld en heeft aan relevantie gewonnen bij de aanpak van hedendaagse verstedelijkingsproblemen, zoals de uitputting van hulpbronnen en aantasting van het milieu. Hoewel UM aansluit bij mondiale kaders zoals de duurzameontwikkelingsdoelstellingen (‘Sustainable Development Goals’, SDG’s) van de Verenigde Naties, stuit het op praktische implementatiebarrières, met name bij het vertalen van theoretische inzichten naar werkbare strategieën voor stadsplanners. Dit hoofdstuk benadrukt de dringende behoefte aan instrumenten die de analyse van hulpbronnenstromen integreren in planningsprocessen voor circulaire en veerkrachtige stedelijke ecosystemen.

Hierop voortbouwend begint Hoofdstuk 2 het systematisch onderzoek naar UM-indicatoren met het uiteenzetten van de onderzoeksvraag en de gebruikte methodologie. De onderzoeksvraag richt zich op de wijze waarop deze indicatoren strategische stadsplanning kunnen verbeteren door de perspectieven van actoren, ruimtelijke dimensies en hulpbronnenstromen te incorporeren. Een combinatie van literatuuronderzoek, casestudies en enquêtes is de leidende methode, die zorgt voor een grondige en multidimensionale verkenning van het onderwerp.

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Hoofdstuk 3 gaat dieper in op de classificatie en evaluatie van UM-indicatoren op basis van een uitgebreid literatuuronderzoek. Door gebruik te maken van een hiërarchisch kader worden 38 sleutelindicatoren geïdentificeerd en ingedeeld in drie domeinen: milieu (bijvoorbeeld: luchtkwaliteit, wateromstandigheden, koolstofopslag), hulpbronnenstroming (bijvoorbeeld: materiaalinvoer, -uitvoer en -doorvoer) en stadsontwikkeling (bijvoorbeeld: bevolkingsgroei, economische transities, veranderingen in landgebruik). Het hoofdstuk pleit voor materiaalstroomanalyse als een praktische en toegankelijke methode voor het integreren van deze indicatoren in stadsplanning en maakt daarbij een onderscheid ten opzichte van de complexere emergiesyntheseanalyse.

De uitdagingen bij het implementeren van UM-indicatoren worden verkend in Hoofdstuk 4, met nadruk op de cognitieve en praktische verschillen tussen belanghebbenden en stadsplanners. Terwijl belanghebbenden prioriteit geven aan indicatoren die sociaal-economische uitkomsten benadrukken, richten planners zich vooral op technische en ruimtelijke hulpbronnenstromen. Enquêtes tonen barrières zoals de wisselende beschikbaarheid van gegevens en de moeilijkheid om indicatoren af te stemmen op ruimtelijke kaders. Om deze knelpunten te overwinnen stelt het hoofdstuk strategieën voor om de communicatie te verbeteren en op maat gemaakte kaders te ontwikkelen die verschillende prioriteiten met elkaar verzoenen.

Hoofdstuk 5 onderzoekt de werking van UM-indicatoren op verschillende ruimtelijke schalen, van globaal tot lokaal niveau. Aan de hand van casestudies in Nederland laat het hoofdstuk zien hoe sommige indicatoren zijn gekoppeld aan specifieke schalen, terwijl andere kunnen worden aangepast aan verschillende niveaus. De analyse onderstreept het belang van het afstemmen van de rollen van de indicatoren op de doelstellingen en beperkingen die horen bij elke ruimtelijke schaal, waardoor de indicatoren relevant blijven voor de bevordering van duurzame stadsontwikkeling.

De integratie van UM-indicatoren in het planningsproces wordt onderzocht in Hoofdstuk 6 door hun toepassing in verschillende planningsfasen in kaart te brengen, waaronder initiële beoordelingen, visievorming, strategieformulering, implementatie en monitoring. Het hoofdstuk laat zien hoe indicatoren de besluitvorming in elke fase kunnen verbeteren, wat leidt tot meer geïnformeerde en op duurzaamheid gerichte resultaten. De dynamische wisselwerking van indicatoren over de verschillende fasen heen wordt benadrukt als een essentieel element in het bevorderen van circulariteit en veerkracht in stedelijke systemen.

Tot slot brengt Hoofdstuk 7 de bovenstaande bevindingen samen in een uitgebreid kader voor de integratie van UM-indicatoren in strategische stadsplanning. Het kader bestaat uit twee instrumenten: (i) een algemene tijdlijn voor de selectie van UM-indicatoren (zie figuur 7.1); en (ii) een grafiek die de rollen van de geselecteerde indicatoren beschrijft afhankelijk van hun positie op de tijdlijn en hun categorie (zie figuur 7.2). Deze instrumenten stellen planningsteams in staat om geschikte UM-indicatoren te kiezen en af te stemmen op een specifieke stedenbouwkundige strategie. Bovendien waarborgen ze de betrokkenheid van belanghebbenden gedurende het planningsproces, met oog voor schaalinterrelaties en specifieke behoeften per schaalniveau. Het ontwikkelde kader biedt stadsplanners daarmee bruikbare hulpmiddelen voor het inbedden van UM-principes in besluitvormingsprocessen.

Dit proefschrift brengt het veld van UM vooruit door de kloof tussen theorie en praktijk te overbruggen. Het biedt stadsplanners en beleidsmakers concrete strategieën en hulpmiddelen om UM in hun werk op te nemen en zodoende de duurzaamheid en veerkracht van stedelijke systemen te bevorderen. Door de nadruk te leggen op de praktische toepassing van UM-indicatoren draagt deze studie bij aan een dieper begrip van hoe steden zich kunnen bewegen richting een meer circulaire en hulpbronnenefficiënte toekomst.

论文概要

本论文以城市代谢（Urban Metabolism, UM）为核心框架，探讨其在推动城市可持续发展中的理论基础、实际应用以及在城市战略规划中的整合路径。研究目的是通过开发和应用城市新陈代谢指标，应对城市资源管理和环境复原能力方面的挑战，为规划者和政策制定者提供决策工具。论文分为多个章节，系统阐述了城市新陈代谢的概念演进、方法创新及其在建设可持续循环城市系统中的实践价值。

城市新陈代谢已发展为评估城市系统的分析工具，通过追踪物质流动和废弃物排放，将城市比作一个生物体。随着时间的推移，这一概念不断发展，已成为应对现代城市化过程中资源枯竭和环境恶化等问题的有效手段。尽管城市新陈代谢与联合国可持续发展目标（SDGs）等全球框架紧密相关，但其理论在实际规划中的转化仍面临诸多挑战。论文第一章强调了将资源流分析整合到规划过程中的必要性，以实现具有循环性和复原力的城市生态系统。

在此基础上，第二章提出了研究问题及方法框架，为城市新陈代谢指标的系统性研究奠定了基础。研究的核心问题是如何通过综合参与者、空间维度和资源流的视角，利用城市新陈代谢指标提升城市战略规划的能力。文献综述、案例研究和问卷调查的结合，为研究提供了多维度的视角和坚实的依据。

第三章深入探讨城市新陈代谢指数的分类和评估，通过文献综述回顾构建了分层框架。研究识别了38项关键指标，分为三大领域：环境（如空气质量、水资源状况、碳汇）、资源流动（如物质输入、输出及流通）和城市发展（如人口增长、经济变迁、土地利用变化）。该章倡导将物质流分析作为整合这些指标到城市规划中的实际方法，因其相比复杂的能值分析（Emergy synthesis analysis）更具可操作性和实用性。

第四章分析了城市新陈代谢指数在实施过程中的挑战，尤其是利益相关者与城市规划师之间的认知和实践差异。利益相关者更关注社会经济结果的指标，而规划师则重视技术性和空间性资源流动的指标。问卷调查揭示了数据不一致性及指数与空间框架难以对接等障碍。该章提出，通过优化沟通和制定符合多方需求的指数框架，可以弥合这些差距。

第五章探讨了城市新陈代谢指数在不同空间尺度上的应用，包括全球、区域、城市和地方层面。通过荷兰案例研究，该章展示了一些指标具有特定尺度适用性，而另一些则可在多尺度下灵活应用。分析强调，需根据每个空间尺度的独特目标和限制，调整指数的应用，以确保其相关性和有效性。

第六章研究了城市新陈代谢指数在规划过程中的整合，具体体现在不同阶段的应用，包括初步评估、愿景设定、策略制定、方案执行和后期监测。该章展示了如何在各阶段选择最适用的指数，从而提升决策质量，推动更加可持续的规划成果。本章特别强调了指数在各阶段之间的动态相互作用，这是促进城市系统循环性和复原力的关键因素。

最后一章将研究成果整合为城市新陈代谢指标的综合框架，支持城市战略规划。该框架包括两个工具：一个概括的迭代时间线，用来指导城市新陈代谢指数的选择过程；一个综合参与者、尺度和过程方面的图表，清晰地勾画出所选城市新陈代谢指数在时间线迭代中应达成的具体目标。这两个工具使规划团队能够选择并优化针对特定战略城市计划的城市新陈代谢指数。此外，它确保了利益相关者选择指数并在整个规划过程中的参与，考虑到尺度间关系和规划方案的特定性。通过确保利益相关者的参与和解决特定尺度的需要，该框架为规划者提供了将城市新陈代谢嵌入决策过程中的可行工具。

本研究在理论与实践之间架起了桥梁，为城市新陈代谢的应用提供了显著的推进。通过提供一套可操作的策略和工具，它为城市规划者和政策制定者提供了融入城市新陈代谢方法的指导，推动城市系统的可持终性和复原力。通过聚焦城市新陈代谢指数的实际应用，研究为城市如何向循环、资源高效的未来转型提供了全新视角。

Palazzo Reale di Milano, Milan (Photo by Yan Song 2023)

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1 Introduction

1.1 Urban metabolism (UM): a new approach to improve sustainability

The advent of the Industrial Revolution has propelled the modern world into an era marked by unprecedented levels of resource exploitation and intensity. The rapid processes of industrialization and urbanization have brought significant changes to human civilization, but they have also given rise to serious challenges such as resource depletion, energy consumption, environmental pollution, and excessive waste.
To address these pressing issues, it is imperative to quantify resource usage and comprehend the ecological, economic, and social consequences associated with it.

Furthermore, the ongoing trend of urbanization has the potential to exacerbate resource depletion, energy consumption, and environmental pollution. As cities continue to grow at a rapid pace, the pressure on the environment and available resources escalates, underscoring the urgent need for more resilient and sustainable urban development. In response to these challenges, cities are actively seeking transition methods to achieve sustainability in their future developments. Several urban-centric propositions have emerged, including the Compact City (Burton et al., 2003; Dempsey, 2010), Smart Growth (Dierwechter, 2017; Kolbadi et al., 2015), Eco-city (Caprotti, 2014; Yang, 2017), the Zero-carbon City (Abbasi et al., 2012; Premalatha et al., 2013), the Smart City (Townsend, 2013), and the Just City (Fainstein, 2010), among others. These proposals share a common focus on optimizing resource flows to foster sustainability (van Timmeren & Henriquez, 2013).

The concept of urban metabolism has been in use for over half a century. It views cities as functioning like organisms, consuming resources from their surroundings and producing waste (see Fig 1.1) (Nelson, 2010). Urban metabolism (UM) aims to comprehend and analyze cities as systems of resource and waste flows (Kennedy et al., 2011; van Bohemen, 2012). The concept was initially introduced by the renowned

German chemist and medical doctor Theodor Weyl and further developed by Abel Wolman (1965), who sought to provide a comprehensive account of all the resources required by an urban system for economic production processes, as well as the resulting total waste streams generated from consumption (Lederer & Kral, 2015).

When it comes to urban development, an important milestone was reached in 2015 when all member states of the United Nations endorsed the 2030 Agenda for Sustainable Development. This agenda serves as a collaborative framework to ensure global well-being and sustainability, both in the present and for future generations (United Nations, 2015). At the core of this agenda are the 17 Sustainable Development Goals (SDGs), which call for immediate action and global partnership from all countries, regardless of their level of development. Urban metabolism is closely intertwined with several of these goals, including SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). It is recognized as an effective approach to achieving these goals (Feiferytė-Skirienė et al., 2020; Maranghi et al., 2020; Totin Vodounon et al., 2022). Consequently, optimizing urban metabolism can play a significant role in advancing numerous SDG targets.

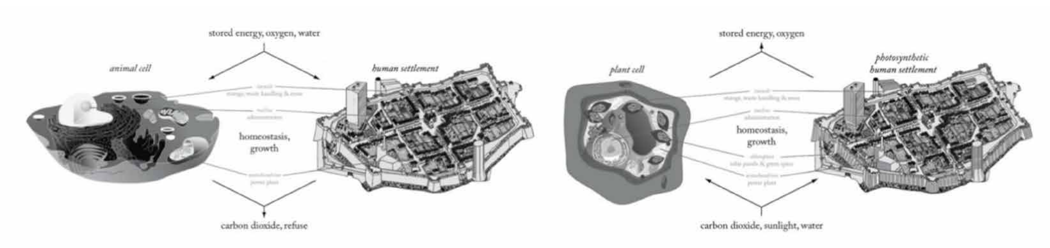

FIG. 1.1 Metabolism comparison between an animal/plant cell and a (photosynthetic) human settlement (Nelson, 2010)

To quantify energy and resource use in modern urban systems, UM has been introduced as an analytical approach (Acebillo & Alessandro, 2012; Ferrão & Fernández, 2013). By analyzing relevant resource flows at different scales, UM studies can reveal important trends in anthropic resource consumption (Ethan H. Decker et al., 2000). Adopting an UM-based analytical approach allows cities to design effective urban planning policies that foster a more circular pattern of resource use, which is crucial for sustainable development (Dinarès, 2014; Moles et al., 2008; Niza et al., 2009; Pincetl et al., 2012).

In addition, Kennedy et al. (2007) suggested that a thorough evaluation of urban sustainability requires a broad scope of analysis, including a social perspective. After the concept UM was proposed, many scholars have developed a range of interpretations and extensions of the UM concept. In the review article by Kennedy et al. (2011), the authors underline the value of the UM concept and its application (e.g. UM indicators) for an urban planning and design process. However, UM studies are still missing effective methods to guide urban planning and design towards more sustainable outcomes.

In terms of resource use, a city can be considered sustainable when the inflow of material and energy resources, as well as waste disposal, remains within the capacity of its surrounding environment (Kennedy et al., 2007). Therefore, it is imperative for urban policymakers to have comprehensive knowledge about the resource consumption, waste flows, and emissions within their cities, enabling them to understand the 'metabolism' of their cities.

1.2 UM from concept to practice

Since its inception, UM has witnessed the emergence of various interpretations and extensions by numerous scholars. In the comprehensive review conducted by Zhang et al. (2015), the evolution of UM studies can be categorized into three distinct periods: the initial period, the stabilized period, and the mainstreaming period.

1.2.1 Initial period: exploring UM methods

During the initial period, research on UM gave rise to two primary methods: material and/or energy flow analysis and preliminary 'emergy' analysis. Scholars not only explored theoretical approaches but also focused on their practical applications.

After Wolman (1965), numerous researchers directed their efforts towards achieving quantitative analysis of UM, often employing cities as case studies (refer to Fig 1.2). Examples include Miami (Zucchetto, 1975), Tokyo (Hanya & Ambe, 1975), Brussels(Duvigneaud et al., 1977), and Hong Kong (Newcombe et al., 1978). These studies utilized material and/or energy flow analysis, measuring the flows of materials and energy through urban systems using mass or energy units (Baccini & Brunner, 1991). Building upon the material flow analysis method from the 1970s, Odum (1977) developed a model that captured the heterotrophic characteristics of urban systems, serving as the foundation for quantitative UM analysis.

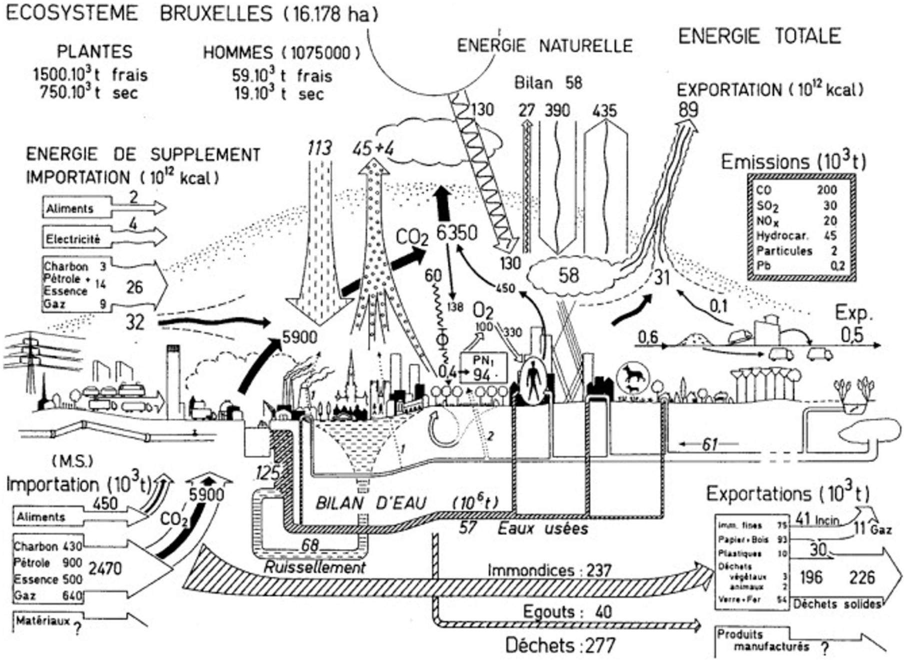

FIG. 1.2 The urban metabolism of Brussels, Belgium in the early 1970s (Duvigneaud et al., 1977)

Odum (1970) expanded upon previous work by utilizing metabolic energy to represent the production and consumption of organic matter within ecological systems, drawing an energy-based perspective on the relationship between humans and their environment. He introduced the concept of embodied energy ('emergy'), which laid the groundwork for emergy analysis (Odum, 1977; Zucchetto, 2004). By employing the concept of emergy, different resource flows (materials, energy, and currency) could be compared using a consistent unit system, enabling a comprehensive examination of the interactions between socio-economic systems and their external environment (Zucchetto, 1975). However, this stage of emergy analysis faced challenges such as double counting, apportioning emergy among outputs of multi-output systems, and the accuracy of transformative values. Consequently, these issues led to the development of emergy synthesis analysis, expanding the scope of emergy analysis.

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1.2.2 Stabilized period: developing UM models

During this period, UM research underwent further development, focusing on four key research topics: the standardization of traditional material/energy flow analysis, the exploration of black box and sub-system models, the investigation of circular metabolism, and the expansion of input-output models. These areas of inquiry played a crucial role in advancing our understanding of UM.

Standardization became necessary as the concept of UM gained widespread acceptance. Researchers focused on material flow analysis to account for resource storage and flow, with Baccini and Brunner (1991) describing the characteristics of material stocks and flows in human settlements and introducing the method of material flow analysis. Additionally, Baccini and Bader (1996) introduced the concept of 'Regionaler Stoffhaushalt' (Regional material budgets) to track material flows. The European Union also initiated research on material flows in Vienna and the Swiss lowlands, while case studies on Taipei, Sydney, Brisbane, five coastal cities, and the world's 25 largest cities applied material/energy flow analysis (Ethan H. Decker et al., 2000; Zhang et al., 2015).

In parallel with standardization efforts, researchers began exploring models to systematically analyze UM. Akiyama (1989) proposed two main models: the black box model and the sub-system model, which served as prototypes for Black-box and Grey-box models. The black box model led to the development of the concept of 'circular metabolism.' Girardet (1996) introduced a circular metabolic model for sustainable cities, distinguishing between linear and circular metabolic flows and emphasizing the need to promote material circularity and transform waste into resources (Fig 1.3). This approach aimed to reduce consumers and increase transformers within cities (Zhang et al., 2015).

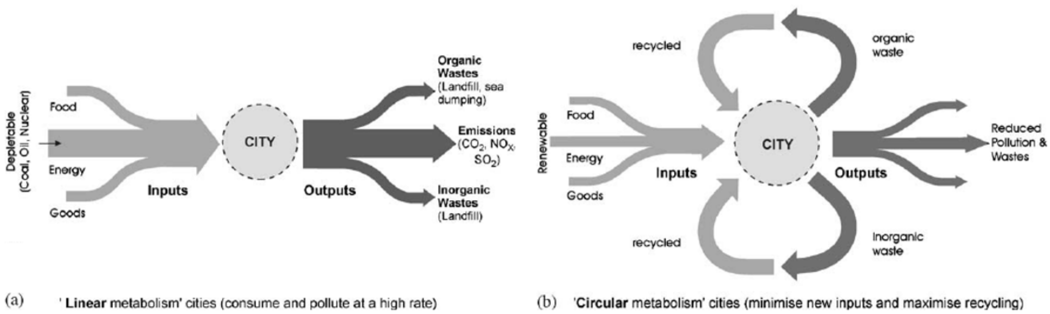

FIG. 1.3 'Linear metabolism' cities and 'Circular metabolism' cities (Girardet, 1996)

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In pursuit of sustainability goals, Newman (1999) proposed an extension of the traditional input-output model of urban metabolism. He incorporated liveability and health factors into the model, recognizing that urban sustainability involves not only reducing metabolic flows but also enhancing human vitality and infrastructure (Fig 1.4). This extended input-output model was applied to explore a liveability model of Sydney, becoming a significant tool in the Department of Environment's report in Australia (Newton et al., 1998).

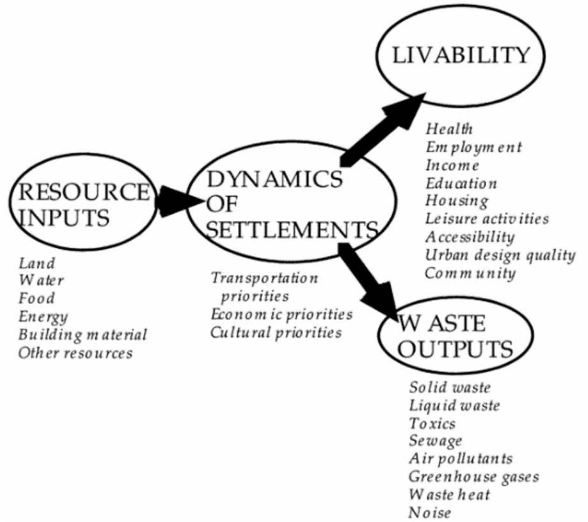

FIG. 1.4 Extended metabolism model of human settlements (Newman, 1999)

1.2.3 Mainstreaming period: utilizing UM studies

From the 2000s onwards, research both widened in scope and made steps to the further deepening of tools and approaches. Kennedy et al. (2007) defined UM as 'the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste', which includes consideration of ecological and economic aspects. With a more consistent focus on UM, a large number of articles, reports, conferences, journals, and projects began to explore it further. In this rising period, the research can be summarized as applying the methods developed in the previous periods. This is reflected by the main topics of this period: multi-scale urban metabolism, the metabolic network model, and its application in other domains.

All cities exist within a specific environmental context, and it is difficult to understand the characteristics of an UM by examining only the city itself (Zhang et al., 2015). Therefore, it is necessary to consider urban systems within a hierarchy that accounts for multiple scales. Current research divides the research scope into several levels, which are supra level (global), macro level (national and regional), meso level (urban), and micro level (neighborhood and household) (See Fig.5). At the supra level, research focuses on the environmental effects of human activities by applying either the MRI/O (Multi-Region Input-Output) framework (Goldstein et al., 2013; Herfray & Peuportier, 2010) or emergy values (Huang et al., 2007; Liu et al., 2011; Zhang et al., 2009b) for the global assessment of impacts and solutions for better environmental performance. Studies that consider the regional environmental effects of urban metabolism and its links to the hinterlands environments at the macro level analyze the flows of materials within the entire region (Browne et al., 2012). At the meso level, studies only assess the metabolic processes that occur inside the city, neglecting to include background processes beyond the city's borders, which only limits them to the use of the Black-box or Grey-box model (Barles, 2009; Kennedy et al., 2007). Due to the limited scale of the micro level, these studies only focus on the consumption of buildings and transport within the communities or of a single household (Codoban & Kennedy, 2008; Engel-Yan et al., 2005).

Meanwhile, other studies try to explore the application of UM in other research domains. Kennedy et al. (2011) discussed the four typical applications of urban metabolism research in urban design and planning: urban sustainability indicators; greenhouse gas emissions calculation; mathematical models for policy analysis; and sustainable urban design. Baynes et al. (2011) used input-output analysis to understand urban energy futures and economic transitions. Su et al. (2009) used emergy synthesis combined with set pair analysis to establish the urban ecosystem health assessment system. In addition, there were attempts to apply the UM concept in global warming (Kendall, 2012), public and private transportation systems (Kennedy, 2002), the industrial process (Krausmann & Haberl, 2002), 2002), land use (Lu et al., 2016), and the water environment (Baker et al., 2001).

1.2.4 UM analytical models

The development of the urban metabolism concept has progressively enhanced our understanding of urban metabolic processes. According to Beloin-Saint-Pierre et al. (2017), there are three analytical models that describe the flows and sections of a city's UM: the Black-box model, the Grey-box model, and the Network model.

The Black-box model characterizes the inputs and outputs of UM flows, simplifying data retrieval through city-level aggregation. This ease of analysis has made it a popular choice during the early stages of UM research. Researchers continue to employ this model extensively, utilizing techniques such as input-output analysis (Baynes et al., 2011), material flow analysis (Browne et al., 2012; Conke & Ferreira, 2015; Douglas et al., 2002; Newman, 1999; Sahely et al., 2003), and ecological footprint assessment (Neset & Lohm, 2005; Swilling, 2016; Wackernagel et al., 2016). Despite its utility, the Black-box model treats the city as a single unit, which allows for the analysis of external systems but limits the ability to identify dynamic and complex resource patterns within the urban area. Although extensive research has produced numerous indicators for assessing UM through this model (Beloin-Saint-Pierre et al., 2017; Newman, 1999; Wackernagel et al., 2016), urban designers and planners often find these indicators challenging to integrate with spatial city planning and design.

The Grey-box model, unlike the Black-box model, disaggregates the input and output flows of UM into different components. This model requires consideration of the environmental impacts across entire supply chains, from resource extraction (cradle) to waste management (grave) for products, services, and systems (Beloin-Saint-Pierre et al., 2017). It incorporates both top-down and bottom-up data collection approaches. Frequently used methodologies include life cycle assessment (Goldstein et al., 2013), emergy synthesis analysis (Huang & Hsu, 2003; Huang et al., 2006), and material flow analysis (Alfonso Piña & Pardo Martínez, 2014; Baldasano et al., 1999; Barles, 2009; Kennedy et al., 2014). These methods facilitate the use of indicators to assess sustainability, although the Grey-box model lacks a systematic set of indicators like those found in the Black-box model (Beloin-Saint-Pierre et al., 2017). Employed for its ability to combine complex data acquisition with large-scale system analysis, the Grey-box model is particularly useful for identifying key environmental impact flows within UM. In urban design and planning, the linear processes it identifies can offer insights into metabolic products to enhance the efficiency and sustainability of material flows. However, this model's linear approach does not encompass the entire urban spatial area, potentially overlooking unsustainable 'grey' areas.

Zhang et al. (2009a) introduced the network analysis method as an advancement beyond the traditional Black-box and Grey-box models. This method aims to analyze the internal characteristics of an urban metabolic system and the interactions among its components by mathematically describing the flows between component pairs. Building on this approach, subsequent research has not only disaggregated component inputs and outputs in UM but also detailed the links between different components. This approach, known as the Network model, is recognized for its comprehensive and systematic analysis of UM (Baccini, 2007; Zucchetto, 1975). However, the Network model is time-intensive and challenging to implement due to the extensive data requirements. Theoretically, it utilizes bottom-up data to quantify the material in each node and flow, though current research often employs top-down data as proxies for all processes. It is extensively applied in material flow analysis (Barles, 2009; Sun et al., 2016), life cycle analysis(Lei et al., 2016), and emergy synthesis analysis (Yang et al., 2012; D. Yang et al., 2014; Zhang et al., 2009b). The Network model has seen preliminary applications in various urban-related studies, including those focusing on water, energy, and materials (D. Yang et al., 2014). Although some researchers have attempted to use indicators to analyze the network system within UM, the development of indicators in the Network model remains at an early stage.

In summary, the complexity of data requirements and model analysis escalates progressively from the Black-box model to the Network model. This escalation is mirrored in the integration with urban spaces and the potential utility for urban designers and planners, as outlined in Table 1.1.

TABLE 1.1 Comparison of three models that are used to assess UM

	Data availability	Combination with urban space	Indicators	Utilization by urban designers/planners
Black Box	Top-down	No possibility	Yes.	Hardly possible.
Grey Box	Top-down & bottom-up	Design from a linear perspective	Yes, but not complete.	Limited possibility (cannot design for the overall urban area)
Network	Bottom-up (currently mostly top-down)	Design from linear and nodes perspective	Yes, but not complete.	Strong potential.

1.3 Development of UM indicators for urban planning

Several researchers have attempted to relate UM to urban planning or design (Claudia M. Agudelo-Vera et al., 2012; Codoban & Kennedy, 2008; Montrucchio, 2012; Oswald et al., 2003). In their book ‘Netzstadt’, Oswald et al. (2003) proposed a combination of morphological and physiological tools that aim to move beyond UM analysis towards design. MIT students used material flow analysis to develop a more ecologically sensitive urban design proposal for New Orleans (Quinn & Fernandez, 2007). Similarly, students at the University of Toronto traced the flows of water, energy, nutrients, and materials through an urban system and redesigned an urban neighborhood to close the loops (Codoban & Kennedy, 2008; Engel-Yan et al., 2005). Transitioning cities towards circular models has become a focus in many places such as Amsterdam, Copenhagen and Naples (De Martino, 2022; Mazzarella & Amenta, 2022), and there is increasing research on decision-making processes to facilitate UM projects (Mousavi et al., 2020; Obersteg et al., 2021; Padovan et al., 2022).

Current applications of UM still primarily revolve around resource flow analysis, focusing on existing or past data (Huang & Hsu, 2003; Zhang et al., 2013; Zhang et al., 2009b). However, there is uneven geographic distribution of case studies in UM research (Wang, 2023). On a global scale, discussions around planetary urbanization and metabolism are emerging, although they are still in the early stages (Ala-Mantila et al., 2022; Furlan et al., 2022; Pernice, 2022). Additionally, there is a shift towards cross-territory flow research in the context of city-rural metabolism (Pianegonda et al., 2022). At the microscale, the analysis of materials circularity plays a significant role in understanding neighborhood metabolism (Fu et al., 2022). While urban design projects have incorporated UM principles, many of these attempts have focused on tracking energy and material flows to reduce environmental impacts within specific areas.

To apply the concept of UM into practical applications, the European Union has initiated several research projects, including SUME, BRIDGE, ECO-URB, Urban_Wins, and REPAiR. The SUME project (Sustainable Urban Metabolism for Europe) focused on analyzing the influence of spatial structure on resource utilization from the perspective of the construction environment (Schremmer et al., 2010). The BRIDGE project (SustainaBle uRban plannIng decision support accountinG for urban mEtabolism) quantified flows of energy, water, carbon, and waste, considering the influences of the environment and society (González et al., 2013). The Urban_Wins project (Urban metabolism accounts for building Waste management Innovative Networks and Strategies) aimed to develop and test methods for designing and implementing innovative and sustainable strategic plans for waste prevention and management in various urban contexts (Longato et al., 2019). Lastly, the REPAiR project (REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism) aimed to provide local and regional authorities with an innovative trans-disciplinary open-source geo-design decision support environment (GDSE) developed and implemented in living labs in six metropolitan areas (Amenta et al., 2019a; Geldermans et al., 2018; Remøy et al., 2019).

1.4 Strategic urban planning, Ecopolis, and Circular Economy

1.4.1 Strategic urban planning: a roadmap

In the realm of urban development, strategic planning serves as a pivotal process involving the creation of a long-term roadmap defined by specific goals, objectives, and actionable steps (DiNapoli, 2003). This approach not only enhances action-orientation but also fosters a novel governance style that incorporates the strategic priorities of various stakeholders (Bolger & Doyon, 2019; Healey, 2004; United Nations Human Settlements Programme, 2009). Strategic planning provides a coherent and integrated vision through a long-term materialized logic (Albrechts, 2017a). In contrast to conventional planning methods like master planning and land-use planning, which often uphold existing social orders, strategic urban planning exhibits greater flexibility and adaptability, making it more conducive to transformative changes (Albrechts & Balducci, 2013). Its focus on action-orientation enhancement and open multi-level governance enables cities and regions to transition towards a circular, sustainable, and resilient future (Albrechts, 2017a). Several municipalities, including Amsterdam, Cape Town, Charlotte, Tel Aviv, and Seoul, have adopted strategic planning to advance their cities toward circularity and resilience (Circle Economy et al., 2015; Gladek, van Exter, et al., 2018).

1.4.2 Ecopolis: a perspective

A range of strategic urban plans have been studied to improve urban sustainability. Newman (1999) noted that it is essential to reduce resource usage and waste emissions to reach sustainability goals for a city. Concerning the perspectives to process urban planning, Tjallingii (1995) proposed the Ecopolis strategy[1] to merge the ecological approaches into urban planning in order to achieve urban sustainability (See Fig 1.5).

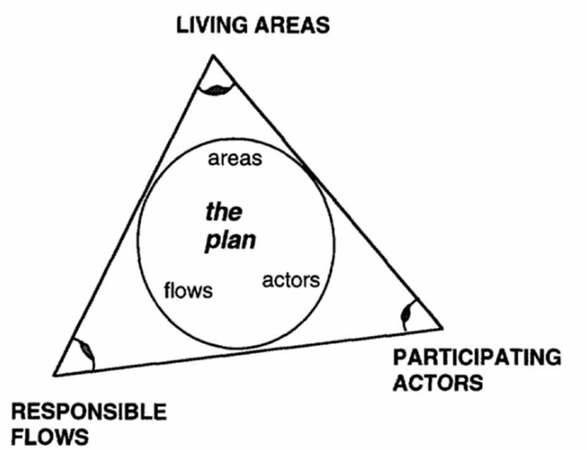

FIG. 1.5 The Ecopolis framework (Tjallingii, 1996)

Ecopolis strategy states that urban sustainability is determined by three layers: durable diversity of the area, sustained use of resources, and sustained involvement of actors. The framework was established to address the ecological significance of urban projects and to determine which plans merit support from an urban ecological perspective. It aims to serve as a criterion during the evaluation of completed projects. The primary focus of the framework is to provide practicality. Its effectiveness in meeting this requirement can be demonstrated by evaluating urban ecological projects based on the formulated goals and strategies (Tjallingii, 1996).

1 The Ecopolis strategy later deepened and widened to the Ecological Conditions Strategy (Tjallingii, 1996, 2015).

Within the Ecopolis framework, various actors (layer one), including planners, experts, and stakeholders, are encouraged to cultivate their expertise in their respective areas while maintaining an overarching perspective on the entire plan. The second layer of Ecopolis involves establishing strategic priorities for the sustainable development of flows, areas, and actors. The third layer introduces guiding models and integrated concepts that provide planning options, helping planners devise alternatives for specific situations. Together, these three decision fields contribute to the overall structure of the plan (Tjallingii, 2002).

1.4.3 Circular Economy: a new policy concept

The circular economy, as a policy concept, has reinvigorated the focus of policymakers on UM, the complex, dynamic interplay of material and energy flows within cities (Furlan et al., 2022; Ghisellini et al., 2016; Kalmykova et al., 2018). Unlike the traditional linear economy, which follows a 'take-make-dispose' model, the circular economy emphasizes sustainability through the principles of reducing, reusing, and recycling resources (Moraga et al., 2019). This paradigm shift aims to minimize waste, lower resource consumption, and reduce environmental impact, which aligns closely with the principles of UM. By viewing cities as living organisms that process inputs and generate outputs, policymakers are now better equipped to understand and optimize the cyclical flows of resources. This approach fosters more sustainable urban planning, encourages the development of green infrastructure, and supports innovations in waste management and resource efficiency (State Environmental Protection Admiunistration of China & The World Bank, 2007; The Ministry of Infrastructure and the Environment & The Ministry of Economic Affairs, 2016). As a result, the integration of circular economy principles into urban policy has not only highlighted the importance of UM but has also provided a practical framework for creating resilient, sustainable cities that can better manage their ecological footprints.

1.5 Problem statement

Over the past few decades, there has been a notable shift in scientific studies towards urban domains, driven by the significant urbanization processes occurring worldwide. The trends in urbanization are strongly influenced by the principles of sustainable development, which prioritize the investigation of urban energy and material flows, such as resource efficiency and waste management (Chrysoulakis et al., 2013; Kennedy et al., 2015). It is evident that the concentrated and substantial increase in resource consumption, waste generation, and emissions has a direct impact on sustainable development (Tillie et al., 2014; Zhang et al., 2015).

Currently, research in UM enables the quantification of imported resources, pollution emissions, and the storage and export of such flows within an urban area. However, as discussed in Section 1.3, there are still gaps in translating UM-based strategies into practical solutions for improving urban sustainability. Many concepts remain theoretical and lack a planning-informative approach, particularly regarding the application of UM indicators. The following points highlight these gaps:

Stakeholders and planners exhibit divergent preferences for UM indicators, leading to challenges in their practical application.

UM indicators serve as vital tools in evaluating a region's performance within the urban metabolism framework, enabling planners to make informed policy decisions (Kennedy et al., 2011). However, the effective application of UM indicators encounters obstacles during the planning process. Firstly, policymakers and planners often hold contrasting opinions on UM topics, resulting in different perspectives on the significance of specific indicators. Consequently, the selection of key indicators becomes a subject of contention. Secondly, planners face difficulties when attempting to implement UM indicators due to factors such as limited availability of relevant data and the complexity of integrating indicators with spatial elements. To overcome these challenges, it is crucial to conduct a comprehensive analysis of the factors that influence the feasibility of UM indicators, taking into account the viewpoints of both stakeholders and planners. By doing so, a more explicit understanding of the diverse preferences and practical constraints can be attained, facilitating better utilization of UM indicators in urban planning and decision-making processes.

Inefficient application of UM indicators across different scales poses a significant challenge

As discussed earlier, UM research encompasses multiple levels, ranging from the global to the household scale (Patrício et al., 2015; Zhang et al., 2015). However, the application of UM indicators is often limited to specific scales, leading to difficulties when attempting to utilize them across different scales. The current state of UM projects demonstrates a growing trend of cross-scale initiatives, showcasing diverse applications for implementation. However, this introduces a significant challenge in effectively applying UM indicators across varying scales due to the inadequate availability of information and the complexity of integrating data from different scales. Therefore, the inefficient application of UM indicators across different scales necessitates a more explicit and comprehensive approach to ensure their effective utilization.

Limited utilization of UM indicators in strategic urban planning hinders its potential.

The adoption of UM and similar methodologies in strategic urban planning is driven by their quantifiable nature. Among these approaches, the Network model holds significant promise for urban planners to apply in their work. However, a notable gap exists in the research, as there has been limited focus on developing feasible and systematic UM indicators. This gap impedes the approach's ability to inform the planning process effectively, particularly in the context of the built environment. To fully unlock the potential of UM in strategic urban planning towards circularity, it is crucial to address this issue and invest in the development of comprehensive and practical UM indicators. By doing so, urban planners can gain a more accurate understanding of resource flows, enabling them to better support the strategic development towards circularity of cities and the establishment of circular economy systems (Kennedy et al., 2011).

Hafencity, Hamburg (Photo by Yan Song 2018)

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2 Research question and approach

2.1 Research objective and question

The objective of this research project is to contribute to a better understanding and utilization of UM in strategic urban planning processes by studying and developing a framework for selecting Urban Metabolism (UM) indicators to support strategic urban planning for urban planners.

Building upon the aforementioned objective, the main research question for this study is formulated as follows:

- **How can urban metabolism indicators support strategic urban planning process from the perspectives of actors, areas, and flows?**

To address the main research question effectively, the following research sub questions will be investigated:

- **SQ1:** What are the current research trends in UM and which indicators are used to describe UM?
- **SQ2:** Which strategies can be employed to bridge the gap in implementing UM indicators by stakeholders and planners?
- **SQ3:** What are the different applications of UM indicators at various scales?
- **SQ4:** How can UM indicators be effectively utilized across different phases of the strategic urban planning process?
- **SQ5:** How do the UM indicators contribute to strategic urban planning from the perspective of participant actors, focusing scales, and planning process?

2.2 Approaches and methods

Adjusted from Tjallingii's Ecopolis strategy model, this research is structured into five main sections: theoretical context, participating actors, focusing scales, planning process, and methodological framework. Each section addresses one sub-research questions, as illustrated in Figure 2.1.

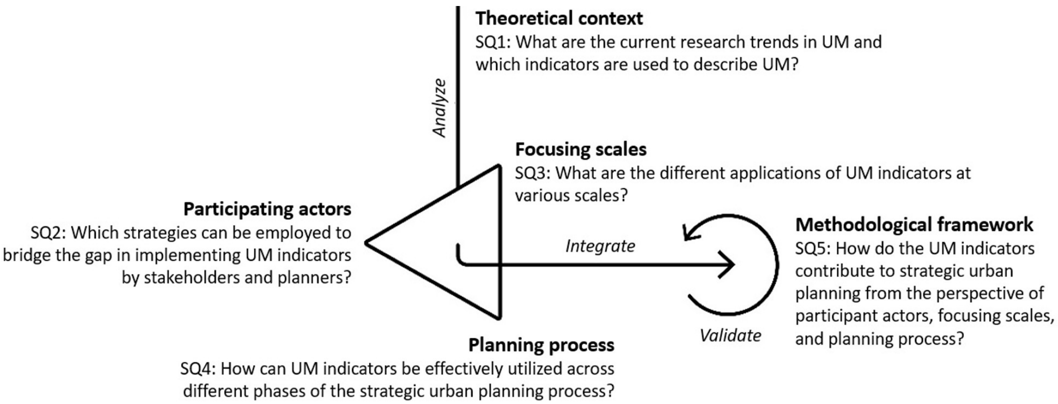

FIG. 2.1 Thesis structure

2.2.1 Theoretical context

To address the main research question, the first step is to define a set of selected UM indicators. This is accomplished through an analysis of current research trends in UM and the identification of key indicators utilized to characterize it. This is addressed through the sub research question:

- **SQ1: What are the current research trends in UM and which indicators can be used and adapted to describe UM?**

Chapter 3 aims to propose a set of selected UM indicators from the current UM research. The selection and development of these indicators are guided by a literature review methodology that integrates both multi-topic and in-depth research. The multi-topic research phase establishes the initial set of UM indicators

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by considering findings from various research topics. The subsequent in-depth research phase focuses on indicator analysis, involving the reformulation of existing UM indicators or the proposal of new ones. This comprehensive approach results in a robust UM indicator set.

Insights derived from this UM indicator set are examined from the perspectives of indicator categories and analytical models. By studying these aspects, a deeper understanding of UM dynamics is attained, facilitating a more comprehensive evaluation of a region's performance.

Following the selection of UM indicators, the subsequent chapters of the research explore these indicators from different perspectives. These perspectives include the participating actors, focus scales, and the planning process. The research aims to develop a comprehensive understanding of UM indicators and their applicability within the strategic urban planning process, ultimately contributing to the development of an effective UM tool for supporting strategic urban development towards circularity.

2.2.2 Participating actors

Chapter 4 explores the roles of key participants in the urban planning process, focusing specifically on stakeholders and planners. These individuals play crucial roles in the successful implementation of UM indicators. The main objective of this chapter is to assess the feasibility of incorporating UM indicators within existing planning frameworks and to identify effective strategies that can help bridge the implementation gap faced by stakeholders and planners. To this end, the chapter addresses the following sub-question:

- **SQ2: Which strategies can be employed to bridge the gap in implementing UM indicators by stakeholders and planners?**

To study the implementation gap of UM indicators, two surveys are conducted targeting stakeholders and planners, respectively, considering their distinct focuses and roles.

For stakeholders, who play a crucial role in decision-making processes, their perspectives on the significance of UM indicators are explored. The first survey is conducted in workshops using a structured questionnaire. The questionnaire is designed to assess the stakeholders' attitudes towards the significance of

UM indicators. The responses are analyzed using Likert-style rating, allowing for the identification of differing attitudes among stakeholders. The results of the questionnaire are presented and discussed, shedding light on the varying perspectives of stakeholders regarding the importance of UM indicators.

For planners, the focus of the implementation gap lies in the application of UM indicators in their projects. Therefore, the second survey aims to explore the criteria for selecting UM indicators in the planning process. The participants are provided with pre-selected criteria that serve as evaluation aspects for the selection of UM indicators. The results of the returned surveys highlight the differences in indicator selection based on the characteristics of UM indicators and the specific requirements of planners.

By conducting these surveys among stakeholders and planners, Chapter 4 contributes to understanding the challenges and barriers faced in implementing UM indicators in the planning process. The findings provide insights into the differing perspectives of stakeholders and the criteria used by planners when selecting UM indicators. This knowledge can help bridge the implementation gap and inform strategies to enhance the utilization of UM indicators in the planning process.

2.2.3 Focusing scales

UM is a concept widely applied at metropolitan, city, and neighborhood scales. Numerous studies have explored its application across different contexts. However, the functionality and limitations of UM indicators vary by scale. Some indicators are versatile, applicable across multiple scales, while others are scale specific. Additionally, different indicators may prioritize certain scales over others. Chapter 5 investigates the following sub-question:

- **SQ3: What are the different applications of UM indicators at various scales?**

This chapter examines empirical case studies of UM-related projects in the Netherlands to address this question. It begins by defining the scales for categorizing these projects according to their spatial scope. After establishing the scales, it analyzes the indicators used and their relationships with corresponding responses qualitatively. This analysis aims to uncover the goals of UM indicators at various scales.

The qualitative review of these projects identifies the goals associated with UM indicators at different scales. These insights reveal how indicators serve distinct purposes and support sustainable urban development at specific scales. The discussion, informed by these results, highlights the potential benefits and limitations of UM indicators, guiding the selection and application of these tools in future strategic urban planning.

By examining empirical cases in the Netherlands, Chapter 5 enhances our understanding of UM indicators' goals and implications at different scales, thereby improving the effectiveness of UM indicators in urban planning and supporting sustainable urban development.

2.2.4 Planning process

Chapter 6 introduces another perspective on the application of UM indicators within the strategic urban planning process by focusing on its different phases. This chapter aims to answer the sub-question:

- **SQ4: How can UM indicators be effectively utilized across different phases of the strategic urban planning process?**

Building on the foundation laid in Chapter 3, which proposed various types of UM indicators, this chapter explores their practical application throughout the different stages of the planning process. It systematically breaks down the planning process into distinct phases, such as initial assessments, vision development, goal setting, strategy formulation, implementation, and monitoring. Each phase is meticulously analyzed to determine the most suitable UM indicators that can be implemented.

The chapter begins by outlining these phases, highlighting the specific responsibilities and flows associated with each. This setup facilitates a detailed discussion on how UM indicators can be strategically applied to enhance both the process and outcomes of urban planning.

Further, the analysis delves into the specific UM indicators that align with the goals and objectives of each phase, contributing to the overall sustainability of the planning process. The chapter also examines the interconnections between different phases, illustrating how UM indicators can foster informed decision-making and support the achievement of desired outcomes.

By elucidating the relationship between UM indicator types and the various phases of the planning process, Chapter 6 offers valuable insights for planners. It underscores the importance of selecting appropriate indicators for each phase and demonstrates how these indicators can guide decision-making and promote sustainable development within the strategic planning framework.

2.2.5 Methodological framework

Chapter 7 of the research project introduces an integrative framework for selecting UM indicators in a strategic urban planning process, aimed at addressing the sub-question:

- **SQ5: How do the UM indicators contribute to strategic urban planning from the perspective of participant actors, focusing scales, and planning process?**

The proposed UM indicator framework consists of two key instruments: (i) an abstracted timeline of iterations that directs and concentrates the selection process of UM indicators, and (ii) a graph that integrates people, scale, and process to define the objectives that the chosen indicators must fulfill, depending on the iteration on the timeline. These instruments empower a planning team to carefully select and optimize UM indicators that are well-suited for a particular strategic urban plan. Furthermore, the framework ensures the involvement of stakeholders and their proper inclusion throughout the planning process, considering the interrelations between different scales and the specific contextual factors at play.

In summary, Chapter 7 presents a UM indicator framework that enhances strategic urban planning by providing a visual representation of UM indicators in relation to actors, areas, and actions. The framework facilitates a comprehensive evaluation and selection of indicators, enabling planners to make informed decisions and effectively integrate UM considerations into the strategic planning process. By utilizing this framework, planners can better understand the relationships between various aspects and leverage UM indicators to support sustainable and strategic urban development.


Daduhe Road, Shanghai (Photo by Yan Song 2013)

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3 An insight of current urban metabolism indicators

Indicators serve as a widely utilized and integrated tool within the Urban Metabolism(UM) framework to assess a region's performance (Kennedy et al., 2011). By leveraging the information provided by these indicators, planners gain valuable insights into the development status of a region, facilitating informed policymaking.

The primary objective of this chapter is to categorize the current UM indicators that have been studied in research or implemented in projects, drawing upon a comprehensive literature review. The selection and development of these indicators are guided by a literature review methodology that integrates both multi-topic and in-depth research. The multi-topic research phase establishes the initial set of UM indicators by considering findings from various research topics. The subsequent in-depth research phase focuses on indicator analysis, involving the reformulation of existing UM indicators or proposing new ones. This approach results in a robust UM indicator set.

Insights derived from this UM indicator set are examined from the perspectives of indicator category and analytical models. By examining these aspects, a deeper understanding of UM dynamics is attained, facilitating a more comprehensive evaluation of a region's metabolism performance.

Moreover, this UM indicator set serves as the foundation for subsequent chapters[2], which explore challenges in utilizing indicators within the planning process. These challenges encompass planning participants, scales, and processes. By addressing these complexities, a more effective and efficient utilization of indicators in strategic urban planning can be achieved.

3.1 Research method

This chapter consists of a literature review to answer the question of current research trends in UM and identify suitable indicators to describe UM. The review followed four steps:

Step 1: Literature search and review of UM indicator-related articles

As a starting point, a search of UM indicator literature in the Scopus database was conducted in June 2023. The literature was selected using three filters. Firstly, articles focusing on UM indicators were selected based on the content of their abstracts, title and keywords containing ‘urban metabolism’ and ‘indicator’, which results in a total of 531 articles. Subsequently, these articles were filtered by subject area (‘environmental science’), year (‘after 2013’), source type (‘journals’), document type (‘article’), but limited in language to ‘English and Chinese’, resulting in 275 articles. By studying the abstract of these articles, they are categorized into groups based on different research topics. The research selected the articles related to UM indicator development or testing in all the topics except for environmental technology. These articles are selected for further in-depth reading, resulting in 54 articles.

2 In the following chapters, the UM indicator research is based on a literature review conducted in May 2019. However, a new literature review was conducted in June 2023, and the old indicator set remains applicable to the updated findings. This demonstrates the enduring relevance and reliability of the previously established literature review process.

Step 2: 'Context, Indicator, Mechanism, and Outcome' approach

Afterwards, the CIMO (Context, Intervention, Mechanism, Outcome) method, originating from planning research (Soria-Lara et al., 2016; Straatemeier et al., 2010), was utilized to systematically process the information in the 54 selected articles. According to the CIMO method, a problematic Context (C) can be addressed by using a Mechanism (M) to explore a generative Intervention (I) that leads to desired Outcomes (O) (Aken, 2004; Denyer et al., 2008). This method provides a valuable framework to identify and assess the mechanism and indicator sets within the selected literature. This research applies the CIMO approach by substituting the Intervention component with UM indicators (Song, van Timmeren, & Wandl, 2019). Therefore, the CIMO method involves examining and categorizing the articles based on the following aspects:

- **Context (C):** *This includes the research background and objective, providing a contextual understanding of the study.*
- **Mechanism (M):** *This refers to the method or approach used to measure or evaluate the indicator.*
- **Indicator (I):** *This represents the specific quantification item related to each aspect under investigation.*
- **Outcome (O):** *This encompasses the expected effects or outcomes that can be implemented in other cases.*

Applying the CIMO method helps organize and analyze the information obtained from the selected articles.

Step 3: Indicator reformulation

A total of 156 UM indicators were initially identified from the analysis of 54 articles using the CIMO approach. However, due to the presence of repeated, duplicated, or similarly defined indicators with different titles, another round of analysis was conducted to refine the list. Drawing from the work of Song et al. (2018), the analysis focused on four aspects: analytical model, accounting method, indicator type, and indicator level. Based on the results, specific criteria were established for the selection process, including:

- **Definition:** Do these indicators share the same definition?
- **Calculation method:** Are these indicators calculated using the same method?
- **Level:** Do these indicators operate at the same level?
- **Emergy-related:** Are these indicators related to emergy?

Following the application of these criteria, indicators that met the established criteria were retained, resulting in a simplified list that effectively addressed redundancy and duplication issues.

Step 4: Indicator categorization

These 38 indicators offer a comprehensive and integrated collection for the measurement and assessment of the UM process and are further categorized based on their characteristics and topics. For this research, we organized the previous set of 38 UM indicators into three levels (category, theme, and indicator) from the perspective of strategic urban planning. This indicator categorization can provide a more systematic and explicit framework for urban planners to apply UM indicators and build the analysis basis for the following chapters.

The following sections will present the output of each research step:
Section 3.2 corresponds to Step 1, Section 3.3 to Step 2, Section 3.4 to Step 3, and Section 3.5 to Step 4.

3.2 Muti-topic: diverse UM research

Based on step 1, 275 articles are searched and reviewed. To gain a deeper understanding of the objectives of each article, the abstracts were carefully studied, and the articles were categorized into different research topics (see Table 3.1). These topics included ecosystem health, energy, environmental technology, urban planning, waste management, and water technology. Each article had a specific purpose for utilizing indicators, such as developing new indicators, establishing indicator frameworks, testing indicators in empirical cases, using indicators in decision-making support, or emphasizing the importance of specific indicators.

By categorizing the articles based on research topics and understanding their objectives, a comprehensive overview of the literature on UM indicators was obtained, providing valuable insights into the diverse applications and perspectives within the field. It showcases the wide range of topics covered by the articles and highlights the different aspects of UM that researchers have focused on.

TABLE 3.1 A summary of the categories of 275 urban metabolism articles

	Research aims	The purposes of indicator
Ecosystem health	1. Analyze the relationship between specific components and ecosystems. 2. Track carbon flows in the city area by a metabolism thought. 3. Analyze the impact of urban metabolism on ecosystem health.	1. Develop specific indicators for ecosystem health. 2. Address carbon-related indicator to reflect ecosystem health. 3. Apply urban metabolism as a significant indicator aggregation.
Energy	1. Explore lower energy consumption strategy. 2. Explore the relationship between energy and sustainability dimensions.	1. Use an indicator to assess energy performance. 2. Amplify energy-related indicators in sustainability assessment.
Environmental technology	1. Explore the influence of specific chemicals on microbial communities to track the metabolism of the city. 2. Analyze key elements in metabolism. 3. Analyze chemical amount change due to urban development.	1. Propose a new indicator to quantitatively reflect the flow of nutrients. 2. Propose an efficient indicator to indicate metabolism procedure.
Urban planning	1. Develop a procedure to achieve sustainability from an urban metabolism perspective. 2. Explore the impact of specific material/flow on urban metabolism. 3. Involve social aspects into urban metabolism research. 4. Explore urban metabolism differences between cases by specific analysis model/tool. 5. Apply urban metabolism approach to support the urban transition towards sustainable urban development.	1. Use an indicator to evaluate the proposal procedure/project. 2. Propose new indicators to improve urban metabolism indicator framework. 3. Test indicator applicability in different cases. 4. Address using urban metabolism as a tool for decision making support.
Waste management	1. Analyze the relationship between waste and urban flows to support policy. 2. Analyze waste composition.	1. Use waste indicator as a tool to support decision making. 2. Develop proper indicators to evaluate waste management. 3. Establish an indicator framework to evaluate waste plant performance.
Water technology	1. Explore water metabolism among different cases. 2. Optimize urban water evaluation to achieve sustainability goals. 3. Use metabolism approach to model water service. 4. Analyze future potential based on current water cycle situation. 5. Develop a new decision support system in an urban water system.	1. As evaluation tool to complete the comparison/assessment procedure. 2. Propose a new evaluation method to apply indicators efficiently. 3. Propose a systematic indicator framework to evaluate water cycle. 4. Propose new indicator to assess water use efficiency. 5. Use indicator as a decision support tool to guide water management.

3.3 The outcome of CIMO approach

To align with the main research objective, articles focusing on the development or testing of UM indicators were selected from all topics. These selected articles underwent a detailed and comprehensive reading process. Only those articles that provided specific indicator sets, using a qualitative content analysis approach as outlined by Bryman (2012), were chosen. This rigorous selection process resulted in 54 key focused articles.

The results generated through CIMO approach serve as a foundation for further indicator analysis. An example of the review result of the CIMO method can be found in Table 3.2, illustrating the different elements and their interrelationships within the articles. Due to space constraints, the detailed CIMO analysis of all 54 articles will not be presented in the main body of the text. However, readers can refer to Appendix I for the complete CIMO analysis of each article. This appendix provides a more in-depth exploration of the contextual backgrounds, mechanisms, indicators, and outcomes associated with the selected articles.

TABLE 3.2 An example of the CIMO analysis of articles presenting CIMO approach

	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Chrysoulakis et al. (2013)	Improve the communication of new biophysical knowledge to end-users (such as urban planners, architects and engineers) with a focus on sustainable urban metabolism.	The indicators set used in BRIDGE evaluations: 1) Energy; 2) Thermal comfort; 3) Water; 4) Greenhouse gases; 5) Land use; 6) Mobility/accessibility; 7) Social inclusion; 8) Human well-being; 9) Cost of proposed development; 10) Effects on local economy (employment and revenue)	Based on sustainability objectives and associated indicators addressing specific aspects of urban metabolism.	A tool like the BRIDGE DSS may not simplify urban planning. process, but it can help urban planners to deal more adequately with its complexity. Although implementation of the DSS during planning processes may be constrained by lack of resources and skills at municipalities, practitioners can gain significant insight for more informed decision making.

3.4 In-depth: UM indicator reformulation and analysis

The 154 urban metabolism indicators were reformulated based on the criteria described in Step 3. During this selection process, 154 UM indicators were added, deleted, or merged into 53 indicators. The following analysis is conducted from four aspects, namely analytical model, accounting method, indicator type, and indicator level. Analytical model focuses on the suitable model that each indicator uses (Black-box, Grey-box, or Network); accounting method deals with the methods for summarizing the indicator (material flow analysis, or emergy synthesis analysis); indicator type indicates if the indicator is descriptive or performative; indicator level can show the indicator measures/assesses the material in the general level or a finer-grained level. An example of the analysis of UM indicator is presented in Table 3.3, and the complete table can be found in the Appendix II.

TABLE 3.3 An example of the analysis of UM indicators

Indicator	Analytical model	Accounting method	Indicator type	Indicator level
Air temperature	Black box model	Material Flow Analysis	Descriptive	Measures

Following the reformulation, it was observed that out of
the 53 indicators, 38 indicators were based on material flow analysis, while the rest of the indicators relied on emergy synthesis analysis. Emergy, initially proposed by Odum (1970), aims to convert different resource types (such as materials, energy, and currency) into consistent units. However, emergy-related indicators pose challenges for urban planners. Firstly, most emergy indicators operate at a functional level, requiring detailed bottom-up data that may be difficult to obtain for national or regional design purposes (Dinarès, 2014; Zhang et al., 2013); secondly, emergy synthesis analysis necessitates comprehensive data for the studied area, and the absence of resource flow data can significantly affect the results (Huang & Hsu, 2003; Huang et al., 2006). Considering the practical and urban-focused contexts, material flow analysis indicators are deemed more suitable for supporting urban planners. Consequently, the final selection comprises 38 material flow analysis indicators sourced from the literature, as outlined in Table 3.4.

TABLE 3.4 The final selected urban metabolism indicator set

Indicator	Definition	Related literature
Air pollutant concentration	The concentration of air pollutants or toxins emitted from sources such as industrial plants, vehicular traffic or accidental chemical releases.	(Chrysoulakis et al., 2013; González et al., 2013; Hoornweg et al., 2012; Li et al., 2016)
Air temperature	A measure of how hot or cold the air is.	(Chrysoulakis et al., 2013b; Goldstein et al., 2013)
Biomass	The gross amount of organic materials, such as food, wood, and agricultural crops.	(Barles, 2009; Chen & Chen, 2014a; Goldstein et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Li et al., 2016; Rosado, Kalmykova, & Patrício, 2016; Lu Sun et al., 2016; D. Yang, Gao, Xiao, & Wang, 2012; D. Yang, Kao, Zhang, & Zhang, 2014; Zhai, Huang, Liu, & Su, 2018; Zhang et al., 2013)
Carbon sinks	An area that accumulates and stores some carbon-containing chemical compounds for an indefinite period.	(Hoornweg et al., 2012)
Construction	The amount of the materials used to build or make something.	(Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Li et al., 2016)
Demographic composition change	The change of human population composition over time.	(Goldstein et al., 2013)
Effects on the local economy	Local economy development due to the city development.	(Chrysoulakis et al., 2013b; González et al., 2013; Rosado et al., 2016)
Electricity	The amount of electric energy produced by transforming other forms of energy into electrical energy.	(González et al., 2013; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Li et al., 2016; D. Yang et al., 2012, 2014; Zhang et al., 2013)
Employment condition	The change of employment level.	(Chrysoulakis et al., 2013b; Chris Kennedy et al., 2014)
Evapo-transpiration	The amount of water that is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.	(Chrysoulakis et al., 2013b; Hoornweg et al., 2012)
Exceedance	The concentration of air pollutants exceeding the limit values.	(Chrysoulakis et al., 2013b; González et al., 2013; Chris Kennedy et al., 2014; Li et al., 2016)
Fossil fuels	The amount of a natural consumed fuel, such as coal or gas.	(Barles, 2009; Browne et al., 2012; Chen & Chen, 2014b; Goldstein et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; C. A. Kennedy et al., 2015; Chris Kennedy et al., 2014; Rosado et al., 2016; Lu Sun et al., 2016; D. Yang et al., 2012, 2014; Zhai et al., 2018; Zhang et al., 2013)

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TABLE 3.4 The final selected urban metabolism indicator set

Indicator	Definition	Related literature
Gas emissions	The gross of atmospheric gases that contribute to the greenhouse effect by absorbing infrared radiation produced by solar warming of the Earth's surface.	(Barles, 2009; Browne et al., 2012; Chen & Chen, 2014b; Chifari et al., 2017; Chrysoulakis et al., 2013b; González et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Li et al., 2016; Rosado et al., 2016; Zhai et al., 2018)
GDP	Gross domestic product	(Chrysoulakis et al., 2013b; Goldstein et al., 2013; González et al., 2013; C. A. Kennedy et al., 2015; Chris Kennedy et al., 2014)
Heat balance	The distribution of the heat energy supplied to a thermomechanical system among the various drains upon it including both useful output and losses.	(Chrysoulakis et al., 2013b; C. A. Kennedy & Hoornweg, 2012; Li et al., 2016)
Heat island effect	An urban area or metropolitan area that is significantly warmer than its surrounding rural areas due to human activities.	(Chris Kennedy et al., 2014)
Industrial products	The amount of exported machinery, manufacturing plants, materials, and other goods or component parts for use or consumption by other industries or firms.	(Barles, 2009; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; C. A. Kennedy & Hoornweg, 2012)
Infiltration rate	Velocity or speed at which water enters the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour.	(Chrysoulakis et al., 2013b)
Land-use transformation	The area that the land use is changed.	(Chrysoulakis et al., 2013b; Chris Kennedy et al., 2014)
Minerals	The gross of minerals, metals, rocks and hydrocarbons (solid and liquid) that are extracted from the earth by mining, quarrying and pumping.	(Barles, 2009; Chen & Chen, 2014b; Goldstein et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Li et al., 2016; Rosado et al., 2016; Lu Sun et al., 2017; D. Yang et al., 2012, 2014; Zhai et al., 2018; Zhang et al., 2013)
New urbanized area	The area that is developed into a density of human structures such as houses, commercial buildings, roads, bridges, and railways.	(Chrysoulakis et al., 2013b; C. A. Kennedy et al., 2015; Chris Kennedy et al., 2014)
Other input	Other materials were imported into the city.	(Barles, 2009; Hoornweg et al., 2012; C. A. Kennedy & Hoornweg, 2012)
Population characteristic change	The change of qualities and characterization of various types of populations within a social or geographic group.	(Goldstein et al., 2013)
Precipitation	The amount of rain, snow, sleet, or hail that falls to or condenses on the ground, it is a major component of the water cycle.	(Chrysoulakis et al., 2013b; Hoornweg et al., 2012)
Public transportation accessibility	The quality of transit serving a particular location and the ease with which people can access that service.	(Chrysoulakis et al., 2013b; González et al., 2013; Inostroza, 2014; C. A. Kennedy et al., 2015)

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TABLE 3.4 The final selected urban metabolism indicator set

Indicator	Definition	Related literature
Renewable energy	The amount of energy from a source that is not depleted when used, such as wind or solar power.	(Chrysoulakis et al., 2013b; Goldstein et al., 2013; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Lu Sun et al., 2017; Zhai et al., 2018)
Solid waste	The amount of solid waste consists of everyday items that are discarded by the public.	(Barles, 2009; Browne et al., 2012; Chen & Chen, 2014a; Chifari et al., 2017; González et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Rosado et al., 2016; Lu Sun et al., 2017; D. Yang et al., 2012, 2014; Zhai et al., 2018; Zhang et al., 2013)
Stored industrial products	The amount of stored machinery, manufacturing plants, materials, and other goods or component parts for use or consumption by other industries or firms.	(Hoekman & von Blottnitz, 2017; Inostroza, 2014; C. A. Kennedy & Hoornweg, 2012)
Surface run-off	The amount of water flows that occurs when excess stormwater, meltwater, or other sources flows over the Earth's surface.	(Chrysoulakis et al., 2013b)
Thermal comfort	The condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.	(Chrysoulakis et al., 2013b)
Transportation construction growth	The amount of construction for building new transportation.	(Browne et al., 2012)
Transportation method change	The composition of different transportation methods over time.	(Chrysoulakis et al., 2013b; González et al., 2013)
Waste input	The amount of unwanted or unusable materials imported into the city.	(Barles, 2009; Chifari et al., 2017; Voskamp, Spiller, et al., 2016)
Waste management accessibility	The quality of waste management facilities and the ease with which people can access them.	(Chifari et al., 2017)
Waste management organization	The numbers and efficiency of waste management organizations in a particular area.	(Chifari et al., 2017; González et al., 2013)
Wastewater	The amount of water that has been affected by human use and exported to nature.	(Barles, 2009; Browne et al., 2012; Chen & Chen, 2014a; Chifari et al., 2017; González et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Rosado et al., 2016; Lu Sun et al., 2017; D. Yang et al., 2012, 2014; Zhai et al., 2018; Zhang et al., 2013)

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TABLE 3.4 The final selected urban metabolism indicator set

Indicator	Definition	Related literature
Water input	The amount of water imported into the city.	(Barles, 2009; Chen & Chen, 2014a; Chrysoulakis et al., 2013b; Goldstein et al., 2013; González et al., 2013; Hoekman & von Blottnitz, 2017; Hoornweg et al., 2012; Inostroza, 2014; C. A. Kennedy et al., 2015; C. A. Kennedy & Hoornweg, 2012; Chris Kennedy et al., 2014; Rosado et al., 2016; Lu Sun et al., 2016; Zhai et al., 2018)
Water storage	The amount of water stored in the city.	(Hoornweg et al., 2012; C. A. Kennedy & Hoornweg, 2012)

3.5 Categorization of current UM indicators

UM studies provide insights into the metabolic processes of a specific area, and a comprehensive set of indicators is crucial for effectively assessing the performance of these processes (Kennedy et al., 2014; Pulido Barrera et al., 2018). In the context of strategic urban planning, it is essential for the indicator set to align with the paradigm through which urban planners diagnose urban problems. In this study, the set of 38 UM indicators, derived from the literature, has been organized into three distinct levels in Step 4, aiming to offer a more explicit UM indicator structure for better understanding (refer to Table 3.5).

TABLE 3.5 A categorized UM indicator set based on literature review

Category	Theme	Indicator
Environment	Water condition	Precipitation
		Evapotranspiration
		Infiltration rate
		Surface run-off
	Air quality	Air temperature
		Air pollutant concentration
		Exceedance
	Carbon	Carbon sinks
	Thermal	Heat island effects
		Heat balance
		Thermal comfort
Resource flow	Resource input	Biomass
		Minerals
		Water
		Fossil fuels
		Renewable energy
		Waste
		Others
	Resource output	Solid waste
		Wastewater
		Gas emission
		Electricity
		Industrial products
	Resource throughput	Construction
		Water storage
		Stored industrial products
City development	Population growth	Population characteristic ratio change
		Demographic composition change
	Economic development	GDP
		Employment condition
		Effects on local economy
	Land-use transition	New urbanized area
		Land-use transformation
	Transportation changes	Transportation construction growth
		Public transportation accessibility
		Transportation method change
	Waste management	Waste management accessibility
		Waste management organization

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At the category level, a city is metaphorically compared to an organism that consumes resources from its surroundings and generates waste (Nelson, 2010). Hence, three main categories are defined for UM: environment, urban development, and resource flow.

At the theme level, indicators within each category are further organized based on different urban themes. The diverse nature and scale of these themes determine the range of suggested indicators (Mega & Pedersen, 1998). Themes are determined by the various aspects considered during the urban planning process and can be distinguished by different biophysical types (e.g., air, carbon, thermal) or by different stages in material flow analysis (e.g., input, output, throughput).

At the indicator level, all the indicators are listed, representing the bottom level of the indicator set. Urban planners can choose relevant UM indicators from this level, building upon the framework provided by the higher category and theme levels.

Overall, this hierarchical organization of the UM indicator set facilitates the selection and application of indicators in strategic urban planning practice, promoting a more systematic and comprehensive approach to understanding and addressing urban challenges.

3.6 Various perspectives to understand UM indicators

3.6.1 Indicator theme

Environment category

Environment indicators are designed to measure and assess the geographical conditions of the city, specifically focusing on elements that influence urban resource flow. These indicators are categorized under different themes, namely water condition, air quality, carbon, and thermal, based on their respective aspects.

Within the theme of water condition, researchers have addressed indicators related to the hydrological cycle occurring on, above, and below the surface of the region (Arora et al., 2022; Browne et al., 2012; Chrysoulakis et al., 2013; González et al., 2013; Kennedy et al., 2015; Landa-Cansigno et al., 2020). Additionally, Kennedy et al. (2014) emphasize the inclusion of precipitation in their framework, which is used to evaluate the vulnerability of the urban area to the risks associated with global warming. The theme of air quality encompasses two aspects: air temperature and air pollution. Air temperature serves as an indicator of the urban heat island effect, which reflects the imbalance in urban energy metabolism (Chrysoulakis et al., 2013; Kennedy et al., 2015). Air pollution is measured through indicators such as pollutant concentration and pollutant exceedance (Chrysoulakis et al., 2013; González et al., 2013). Carbon sink indicators are a new method used to track the carbon cycle in relation to material life cycle assessment (Stremke & Koh, 2011). Urban heat is primarily studied in relation to heat balance indicators that reflect the heat island effect (González et al., 2013; Li et al., 2016). However, for a comprehensive understanding of metabolism from the heat perspective, additional indicators are proposed, such as thermal comfort (González et al., 2013) and heat island effects (Chrysoulakis et al., 2013).

Resource flow category

Resource flow indicators, as a key category in UM, are measured and assessed based on the life cycle period. These indicators are primarily performative, characterized by their neutral characteristics without explicit signs in the assessment process. Since the inception of UM, input-output flows have garnered the most attention due to their concentration in highly populated areas (Rotmans, 2006; Tan et al., 2016; Zhai et al., 2019). Many trade-dominated cities exhibit a higher percentage of material flows during the throughput period, leading to the categorization of resource flow indicators into inputs, outputs, and throughputs (Voskamp et al., 2017).

Resource flow indicators are differentiated based on various materials. The commonly used input indicators include biomass, minerals, water, and fossil fuels, following the Eurostat method (Chrysoulakis et al., 2013; Kennedy et al., 2014; Rosado et al., 2016; Sun et al., 2017; Yang et al., 2012). With the rise of renewable energy, the assessment of this indicator has gained prominence in urban metabolism, as it addresses the goal of reducing environmental pressures in urban areas (Pakina & Mukhamedina, 2023; Sun et al., 2017; Yang et al., 2012; Z. Yang et al., 2014). Based on material flow analysis conducted in Paris by Barles (2009) and in Amsterdam by Voskamp et al. (2018), waste can be considered an input material, taking into account its origin, type, process, and treatment location. The output indicators comprise solid waste, wastewater, gas emissions, and industrial production, which are categorized based on their respective forms. In this context, electricity, which does not leave behind any usage remnants during production, is considered an output indicator. Throughput flows are materials that are neither consumed nor processed within the city (Feiferytė-Skirienė & Stasiškienė, 2021; Niza et al., 2009; Rosado et al., 2016; Voskamp et al., 2017). Such flows can either pass through the city or be stored. Construction materials, water storage, and stored industrial products are examples of throughput flow indicators.

City development category

To achieve sustainability goals, Newman (1999) proposed an extension of the traditional input-output model of metabolism by including indicators related to livability and health. Since then, the field of UM research has increasingly incorporated social indicators pertaining to city development (García-Guaita et al., 2018; Neves et al., 2023). Several European research projects, such as the SUME project (Sustainable Urban Metabolism for Europe), Urban_Wins project (Urban metabolism accounts for building Waste management Innovative Networks and Strategies), and BRIDGE project (SustainaBle uRban plannIng decision support accountinG for urban mEtabolism), have also integrated social indicators into their UM studies (Berigüete et al., 2023; González et al., 2013; Gravagnuolo et al., 2019; Moraga et al., 2019; Schremmer et al., 2010).

City development can be described in various ways, but this indicator set focuses on the indicators that are influenced by changes in resource flows. In general, these indicators can be categorized into population growth, economic development, land-use transition, transportation changes, and waste management. Population growth leads to changes in population characteristics and demographic composition (Browne et al., 2012; Kennedy et al., 2015). Economic development encompasses indicators such as GDP, variations in employment conditions, and impacts on the local economy, providing insights into the overall, sectoral, and environmental aspects of the economy (Browne et al., 2012; Chrysoulakis et al., 2013; Ning et al., 2023). Land-use transition indicators are the most direct indicators that can be interpreted in urban design, focusing on new urbanized or transformed areas (Kennedy et al., 2015; Marcone et al., 2022). Transportation is another aspect influenced by material flows, as addressed in the research conducted by . Furthermore, the accessibility to waste management facilities and the number of waste management organizations reflect different levels of urban metabolism efficiency (Bruvoll et al., 2002; den Boer et al., 2007; Hua et al., 2023; Niza et al., 2009; Sun et al., 2023).

3.6.2 Analytical model

UM indicators play a crucial role in providing quantitative information and analysis for the accounting and assessment of a city's metabolism. Indicators serve as a means of presenting information on the state or condition of various aspects. They offer valuable insights into the impacts and challenges of sustainable policies and plans on the urban environment (Munier, 2007). Furthermore, indicators facilitate urban planning by providing information and allowing for comparisons across different municipalities, cities, and regions. Many researchers have focused on UM indicators in the realms of material flow analysis, emergy synthesis, industrial ecology, and life cycle assessment (Chen & Chen, 2014; Inostroza, 2014; Zhang et al., 2009a). As the concept of UM has evolved, our understanding of the urban metabolic process has significantly improved. As mentioned earlier in section 1.2, there are three analytical models used to describe the flows and sectors of a city's UM: the black-box model, the grey-box model, and the network model (Beloin-Saint-Pierre et al., 2017).

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Black-box model

The black-box model is primarily focused on describing the inputs and outputs of flows within the metabolism of a city. It offers a simplified approach to data retrieval as it aggregates information at the city level, making it easier to analyze. Consequently, it has been commonly used in the early stages of UM research. Many studies continue to employ this model to explore the metabolism of cities, particularly in methods such as input-output analysis (Baynes et al., 2011), material flow analysis (Browne et al., 2012; Conke & Ferreira, 2015; Douglas et al., 2002; Newman, 1999; Sahely et al., 2003), and ecological footprint analysis (Neset & Lohm, 2005; Swilling, 2016; Wackernagel et al., 2016).

However, since the black-box model considers the entire city or urban area as a single unit, it is not well-suited for identifying the dynamic and complex patterns of resource flows within the city. It lacks the ability to support the identification of intricate resource patterns within the urban area. While numerous studies have provided indicators for assessing UM within this model (Beloin-Saint-Pierre et al., 2017; Newman, 1999; Wackernagel et al., 2016), it remains challenging for urban planners to utilize these indicators effectively due to the difficulty of integrating them with spatial elements.

Grey-box model

In contrast to the black-box model, the grey-box analysis model aims to disaggregate the input and output flows of UM for different material components. It involves considering the environmental effects associated with the entire supply chains of products, services, and systems, from resource extraction to waste management (Beloin-Saint-Pierre et al., 2017). The grey-box model combines both top-down and bottom-up data collection approaches. Commonly used methods within this model include life cycle assessment (Goldstein et al., 2013; González-García et al., 2021; Peponi et al., 2022; Rufí-Salís et al., 2021), emergy synthesis analysis (Huang & Hsu, 2003), and material flow analysis (Alfonso Piña & Pardo Martínez, 2014; Baldasano et al., 1999; Barles, 2009). These methods provide various attempts to use indicators for analyzing sustainability. However, unlike the black-box model, the grey-box model does not have a systematic set of indicators (Beloin-Saint-Pierre et al., 2017). Given its complex data acquisition and large-scale system analysis, the grey-box model is particularly useful for identifying the most relevant environmental impact flow(s) within UM. When applied to strategic urban planning, the identified linear processes can offer insights into the metabolic products, facilitating improvements in the metabolic efficiency and/or suitability of material flows for sustainable development. However, it’s important to note that the linear process may not encompass the entire urban spatial area, potentially leading to the neglect of spaces that are not traversed by the material flows.

Network model

Zhang et al. (2009a) introduced the network analysis method as an advancement beyond the traditional black-box and grey-box models in UM research. This method aims to analyze the internal characteristics of an urban metabolic system and the interactions among its components by mathematically describing the flows between pairs of components. Unlike the black-box and grey-box models, the network model not only disaggregates the inputs and outputs of components but also captures the links between different components, making it a more comprehensive and systematic analysis model of urban metabolism (Baccini, 2007; Gao et al., 2021).

However, implementing the network model can be challenging due to its time-consuming nature and the significant amount of data required. While the model theoretically uses bottom-up data to specify the material amounts in each node and flow, current research often relies on top-down data as proxies for these processes. The network model has found extensive application in material flow analysis (Barles, 2009; Brunner, 2007; Sun et al., 2016), life cycle analysis (Lei et al., 2016), and emergy synthesis analysis (Z. Yang et al., 2014; Zhang et al., 2009a). It has also been applied in preliminary studies within the urban domain (Samaniego & Moses, 2008), water (Hong & Park, 2023; Zhang et al., 2009a), energy (Zhang et al., 2009b), waste (Hua et al., 2023; Voukkali et al., 2023), material-related studies (Z. Yang et al., 2014) and ecosystem services (Cárdenas-Mamani & Perrotti, 2022; Zheng et al., 2019). While several researchers have attempted to use indicators to analyze the network system in UM, the study of indicators within the network model is still in the early stages of development (Beloin-Saint-Pierre et al., 2017; Niza et al., 2009).

3.7 Summary

This chapter focuses on to categorizing the current UM indicators that have been studied in research or implemented in projects, drawing upon a comprehensive literature review. The selection and development of these indicators are guided by a literature review methodology that integrates both multi-topic and in-depth research. It answers *SQ1: What are the current research trends in UM and which indicators can be used and adapted to describe UM?*

To accomplish this, the study employs the 'Context, Indicator, Mechanism, and Outcome' approach to search and analyze the existing urban metabolism literature. Through this process, 38 relevant and practical indicators are selected and organized into a set with a 3-level hierarchy, consisting of categories, themes, and specific indicators. These indicators are grouped under the categories of 'environment', 'resource flow', and 'city development'. Furthermore, the chapter discusses the insights gained from UM indicators by considering their category and the analytical models used. This exploration contributes to the practical application of UM indicators in strategic urban planning. The three-level hierarchy of the indicator set enables better understanding for urban planners and has the potential to provide support in the planning process. Moreover, this UM indicator set establishes the foundation for further analysis of participating actors, focusing scales, and planning processes in the subsequent chapters.

Museum Gouda, Gouda (Photo by Yan Song 2023)

4 Different attitudes towards urban metabolism indicators among stakeholders and planners

As discussed in section 1.5, the practicality of incorporating UM indicators into the planning process can pose a challenge within the planning process. This challenge primarily stems from two factors: cognitive disparities and implementation complexities. Regarding cognitive disparities, stakeholders and planners often interpret UM-related concepts differently, resulting in diverse perspectives. This divergence in viewpoints consequently influences their perception of the significance of UM indicators, leading to distinct priorities in selecting key indicators. On the implementation front, planners face hurdles when integrating UM indicators due to various factors. These include insufficient data availability and difficulties in establishing connections between the accessible data and spatial elements. The nature of these obstacles can vary based on the specific UM indicator being considered.

Due to the adverse impact of these challenges on the practical implementation of UM indicators, a more comprehensive examination of these hurdles is essential, particularly from the vantage points of stakeholders and planners. As a result, the objective of this chapter is to investigate the successful integration of UM indicators into the planning process, with a specific focus on stakeholders and planners. This inquiry is aimed at addressing SQ2: Which strategies can be employed to bridge the gap in implementing UM indicators by stakeholders and planners?

The exploration begins with section 4.1, which presents findings from a survey on UM indicators. This survey employed a structured questionnaire administered during three Peri-urban Living Lab (PULL) workshops within the EU H2020 project REPAiR. The analysis of the survey results, categorized by UM indicator categories, illuminates disparities in perspectives among various participants in the planning process, shedding light on their varying attitudes toward the importance of UM indicators. Subsequently, section 4.2 introduces another survey that investigates the perspectives of urban planners concerning the incorporation of UM indicators. This survey employs five criteria for evaluating indicators: relevant, unique and precise, easy to communicate, data available and accessible, and spatial/structural applicable. Participants are asked to assess UM indicators against these criteria. Drawing insights from the analysis of these two surveys, section 4.3 outlines strategies for effectively and systematically integrating UM indicators and related people (including both stakeholders and planners) into the planning process. This section discusses approaches to bridge gaps and fostering collaboration among these critical stakeholders.

4.1 Stakeholders' perspective: perceived significance of UM indicators

In his book "Strategic Management: A Stakeholder Approach," Freeman (1984) coined the term 'stakeholders' as referring to "any group or person who is affected by or can affect the achievement of the firm's objectives." This definition has since become widely accepted and is a fundamental concept in stakeholder theory. In the context of UM research, González et al. (2013) view stakeholders as 'end-users' within the UM framework, acknowledging their pivotal role in addressing urban resource challenges and influencing decision-making processes. However, this perspective has been critiqued for its narrow focus compared to Freeman's comprehensive definition, which encompasses a broader range of individuals involved in policymaking.

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To address this limitation, this research adopts a broader scope of stakeholders as defined by the Horizon 2020 Project REPAiR (Acke et al., 2020; Wandl et al., 2019). In line with this expanded view, UM-related stakeholders are categorized into four main groups: government, industry, research and education, and civil society. To explore stakeholder opinions on UM indicators, this research utilized a structured questionnaire administered during the stated three Peri-Urban Living Lab workshops. The questionnaire-based approach facilitated the investigation of stakeholder perspectives on UM indicators and their relevance to diverse stakeholder groups.

4.1.1 Introduction of three PULL workshops

The Peri-urban Living Lab (PULL) workshops constituted a series of collaborative sessions integrated into the EU Horizon 2020 research project REPAiR. These workshops convened diverse participants, including local authorities, policymakers, representatives from local businesses, international partners, and the TU Delft REPAiR team. The primary objective of these workshops was to foster the co-creation of eco-innovative solutions aimed at implementing circular economy practices. Notably, these workshops held significance as vital action research endeavors within the project, contributing invaluable input for the refinement and validation of the Geo-design Decision Support Environment (GDSE).

During the course of this study, three workshops were convened in Amsterdam and Ghent, where research questionnaire surveys were administered across three separate sessions. It is crucial to note that precautions were taken to prevent returning participants from encountering the questionnaire multiple times. This approach was employed to guarantee diversity in the response data collected. For further details regarding the specifics of these workshops, the reader is directed to the information presented in Table 4.1.

TABLE 4.1 Workshop details wherein the questionnaires are conducted

Date	Location	Number of participants	Types of participants	Objective of the workshop	Questionnaire responses received
18 Sep 2018	**Amsterdam**	27	Local authorities, policymakers, local business representatives, international partners of the REPAiR consortium, and the TU Delft REPAiR team	The main objective of this workshop was to co-develop eco-innovative solutions for developing the circular economy in the Amsterdam Metropolitan Area (AMA), starting from draft-solutions that were developed earlier by participants in previous AMA PULL workshops by the TU Delft REPAiR research team and TU Delft Urbanism MSc students.	21
6 Sep 2019	**Ghent**	6	Municipality, local businesses, international partners and Ghent REPAiR team	The objective of this workshop was to develop eco-innovative strategies, based on the eco-innovative solutions developed during the previous workshops (REPAiR, 2019b).	4
30 Sep 2019	**Amsterdam**	12	National authorities, policymakers, local business representatives, and international partners of the REPAiR consortium	The main purpose of this workshop was to co-develop eco-innovate strategies that address the circular economy objectives defined for the AMA, utilizing the eco-innovative solutions for food waste previously defined in the PULL process (REPAiR, 2019a).	5[3]

3 Another 4 stakeholders participated in previous workshops are not counted.

4.1.2 Data collection and methods

Data for this study were gathered via a survey administered to policymakers, planners, and professionals at the conclusion of the workshops. The primary aim of the survey was to solicit feedback from stakeholders concerning their perceptions of the significance of UM indicators. Participants engaged in this questionnaire designed to evaluate UM indicators, focusing on three distinct objectives:

- **Assessing Awareness:** To gauge stakeholders' awareness of UM indicators, thereby understanding their level of familiarity and engagement with these indicators.
- **Exploring Attitudinal Differences:** To investigate variances in attitudes towards UM indicators and the resultant prioritization of these indicators among different groups, notably stakeholders and planners.
- **Capturing Requirements for Framework Development:** To identify the specific needs and requirements of stakeholders for the development of an effective UM indicator framework that can robustly support urban planning processes.

To preserve the impartiality of the survey, key researchers from the TU Delft REPAiR team, who had played a pivotal role in developing the list of UM indicators, were precluded from participating. The questionnaire was disseminated among 43 non-organizer participants, yielding 30 responses, which represents approximately 70% of the distributed questionnaires. These responses were subsequently categorized by stakeholder type, details of which are delineated in Table 4.2.

Consistent with the methodology employed by González et al. (2013), this study delineates stakeholders into two primary groups based on their engagement in the planning process: front-users and end-users. Front-users are those who integrate UM indicators directly into their workflow, utilizing the results from UM indicator analysis to inform urban development strategies. This group predominantly consists of urban designers, city planners, and researchers focused on urban strategies. Conversely, end-users employ UM indicators to assess projects post-strategy proposal, using the outcomes of UM indicator analysis to aid decision-making and policy formulation. This category includes public officials, policymakers, corporate entities, NGOs, and similar organizations.

The roles of these diverse stakeholders are further detailed in Table 4.2, which presents a broad array of organizations and companies that participated in the survey. Notably, the collected responses encompass all four stakeholder types identified in the REPAiR project's stakeholder categorization, ensuring a balanced representation between front-users and end-users.

TABLE 4.2 Survey respondents from REPAiR PULL workshops

Workshop	Organization	Project partners	Government	Industry	Research & education	Civil society	Front- or End-user
18 Sep 2018 Amsterdam	Alba Concepts	No		√			End-user
	Albron	No		√			End-user
	Arup	No		√	√		Front-user
	Deltametropolis Association	No		√		√	End-user
	EVOLV	Yes		√			End-user
	Freelancer	No			√		Front-user
	Haarlemmermeer Municipality	Yes	√				End-user
	Hogeschool van Amsterdam	No			√		Front-user
	Metabolic	No		√	√		Front-user
	RKK Institute for Regional Studies	Yes			√		Front-user
	SUSMETRO	No			√	√	Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	TU Delft master student	No			√		Front-user
	University Ghent	Yes			√		Front-user
	Utrecht Municipality	Yes	√				End-user
6 Sep 2019 Ghent	City of Ghent	Yes	√				End-user
	OVAM	Yes		√			End-user
	OWS-Gent	No		√	√		End-user
	Suez	Yes		√			End-user
30 Sep 2019 Amsterdam	Cleantech Flanders	No		√	√		End-user
	Deltametropolis Association	No		√		√	End-user
	Platform 31	No			√	√	End-user
	Platform 31	No			√	√	End-user
	RWS Rijkswaterstaat	No	√				End-user

To ascertain the varying significance attributed to UM indicators across different stakeholder groups, a Likert-style rating system with a five-point scale was employed. This method was designed to capture respondents' perceptions regarding the importance of each indicator, with the comprehensive details of the questionnaire available in Appendix III.

In analyzing the survey data, the mean response for each indicator category and its corresponding standard deviation were calculated to provide a statistical measure of central tendency and variability. Furthermore, a comparative analysis was conducted for each individual indicator, contrasting the scores provided by front-users and end-users. This comparison is instrumental in identifying possible differences in perspective and prioritization between the two stakeholder groups.

4.1.3 Outcomes on the perceived significance of UM indicators

Key findings emerge from the survey results, shedding light on various aspects:

1 **The participants generally acknowledge the significance of the selected UM indicators, yet there is considerable room for enhancing these indicators.**

Drawing on insights from other studies on indicator selection processes, such as Alvarez Etxeberria et al. (2015) and Mapar et al. (2017), this research aligns with the idea that UM indicators perceived as unnecessary by stakeholders should be considered for elimination. Evaluating the survey responses, an indicator with an average score below 3.00 (neutral) signifies its perceived less significance from the stakeholders' standpoint.

To establish a clear criterion for indicator elimination, the study defines the following condition: either an average score below 3.00 or agreement from more than 20% (6 or more) of participants to eliminate the indicator. Employing this criterion, the evaluation results of UM indicators by stakeholders (refer to Figure 4.1) demonstrate that all 38 selected indicators exceed an average score of 3.00 and fewer than 6 participants agree to eliminate any indicator. Consequently, none of the indicators meet the elimination criteria.

However, specific indicators such as 'evapotranspiration' (3.13), 'stored industrial products' (3.22), 'GDP' (3.30), and 'other inputs' (3.30) are recognized as having relatively lower significance compared to others. Most of indicators fall within the range of 3.40 to 4.30 in terms of perceived importance. Notably, certain UM indicators, including 'renewable energy' (4.48) and 'air pollutant concentration' (4.43), receive exceptionally high significance scores.

These findings highlight both the collective agreement on the importance of UM indicators and the areas where further refinement could contribute to a more precise and effective indicator framework.

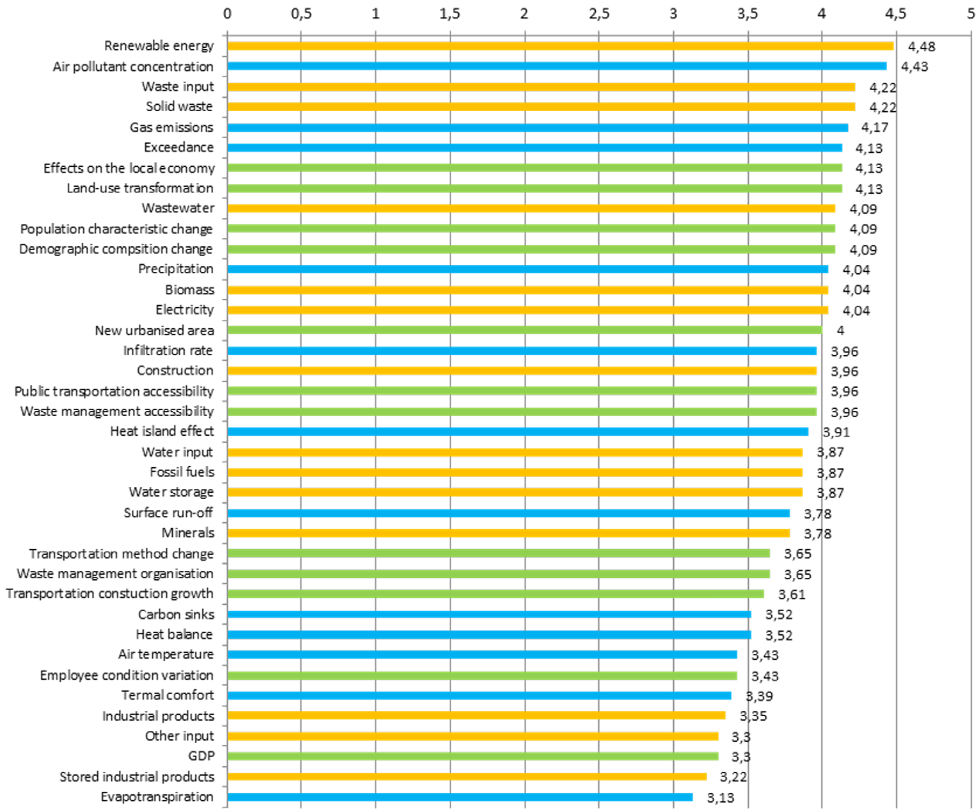

FIG. 4.1 Average scores and the count of participants who agreed to eliminate UM indicators, as assessed by stakeholders (Colored by category: blue-environment, yellow-resource flow, green-city development)

2 **Across various categories, stakeholders perceive indicators related to city development as slightly less significant.**

In the preceding chapter, UM indicators were classified into three primary categories: environment, resource flow, and city development. Generally, stakeholders' perceptions of UM indicators within different categories do not exhibit significant disparities, as indicated by the results of the surveys. The distribution of indicators across these three categories is even. This pattern is closely tied to planners' comprehensive approach to various planning processes, which necessitates thorough consideration of all aspects.

It's important to note, however, that even the highest-scoring indicator, "Renewable energy," received a score of only 4.48 out of 5. No indicator achieved an average score of 5 or even exceeded 4.50. This underscores the ongoing need in current UM indicator evaluations for one or more indicators to be unequivocally recognized as highly important by all stakeholders.

Nevertheless, these categories are not perceived with equal significance from the stakeholders' viewpoint. The mean scores for each category do not significantly differ. Both environment and resource flow indicators received scores close to 3.90, while city development indicators lag slightly behind (refer to Figure 4.2). Despite their similar average scores, the distribution deviation varies notably between the environment and resource flow indicators on one hand, and the city development indicators on the other.

FIG. 4.2 Stakeholder assessment: average scores and participant preferences for eliminating UM indicators (Colored by category: blue-environment, yellow-resource flow, green-city development)

City development indicators encapsulate changes in urban population structure, GDP, transportation methods, and land use—outcomes directly resulting from UM. This emphasis on city development is often overlooked in discussions of UM, which predominantly concentrate on material resource flows and the environmental impacts of human activity. This observation is reflected in existing UM research, with most studies delving into resource flow and environmental impacts, while fewer focus on the outcomes of UM on urban development itself. Although several studies have analyzed the environmental impact of UM, such as Dijst et al. (2018) and Kalmykova et al. (2016), the socioeconomic ramifications still warrant further exploration (Chrysoulakis et al., 2013).

4.1.4 Findings on different stakeholders’ divergent perspectives

Furthermore, this study provides a comprehensive overview of the perceptions of both front-users and end-users regarding UM indicators and conducts an in-depth analysis of the disparities between these two groups (Refer to Fig 4.3 and Table 4.3).

A Perspectives across indicator categories

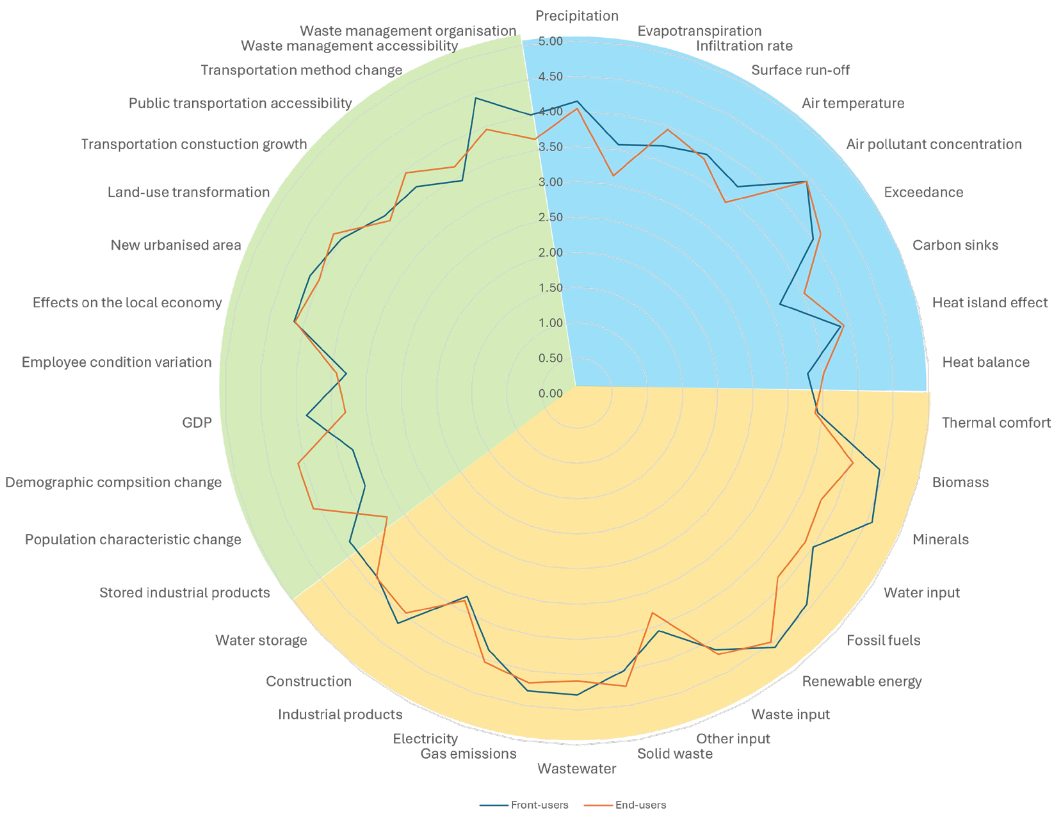

FIG. 4.3 Average scores of the UM indicators assessed by front- and end-users

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Significant observations arising from the survey results are:

1 **Front-users' perception of UM indicators shows more significant compared to end-users.**

Front-users, who actively integrate UM indicators into their work processes, exhibit a slightly higher average score of 3.89 for total UM indicators, in contrast to end-users who record an average score of 3.84. Upon evaluating the significance of various UM indicators, front-users consistently display marginally elevated scores, particularly for indicators related to material flow and environmental aspects. For instance, indicators like biomass input (scoring 4.43 vs 4.04) and evapotranspiration (scoring 3.57 vs 3.13) reflect this trend. It's important to note that this doesn't necessarily imply a stark difference in optimism or pessimism between the two groups. Rather, this points towards front-users perceiving these indicators as better tools for assessing the outcomes of their planning endeavors.

2 **Divergent views on environmental category UM indicators between front-users and end-users.**

In the context of UM indicators within the environment category (depicted in the blue segment of Figure 4.3), a notable disparity in opinions emerges between front-users and end-users. The most pronounced differences materialize in the assessment of indicators such as precipitation (scoring 4.14 vs 4.04), evapotranspiration (scoring 3.57 vs 3.13), air temperature (scoring 3.71 vs 3.43), and thermal comfort (scoring 3.43 vs 3.39). Front-users ascribe greater significance to these indicators, perceiving them as vital for encapsulating the vision and intent of planning projects. Conversely, end-users do not attribute the same level of importance to these factors.

Interestingly, a reverse pattern is evident when addressing UM indicators necessitating intricate computations. For instance, front-users award lower scores compared to end-users in indicators such as infiltration rate (scoring 3.71 vs 3.96), carbon sinks (scoring 3.14 vs 3.52), and heat balance (scoring 3.29 vs 3.52). In such cases, end-users appear to prefer more intuitive evaluation outcomes. However, challenges in data accessibility or calculation methodologies seem to elevate uncertainty for front-users when applying these indicators.

3 **Contrasting priorities on material flow-related UM indicators between front-users and end-users.**

The analysis indicates a noteworthy variance in the perception of material flow-related UM indicators between front-users and end-users. Front-users exhibit heightened concern for indicators linked to resource input, reflecting their emphasis on innovative approaches to address urban consumption patterns in city development. Notably, there exists a substantial difference between front-users and end-users in the evaluation of certain indicators, such as biomass input (scoring 4.43 vs 4.04) and minerals input (scoring 4.57 vs 3.78).

Conversely, end-users attribute relatively higher scores to specific resource output indicators, exemplified by solid waste (scoring 4.00 vs 4.22). This divergence may be attributed to the prevalent adoption of circular economy concepts, prompting stakeholders to prioritize efficient waste management strategies within urban contexts. Notably, regions like Amsterdam and Western Europe are spearheading the transition from linear to circular economies, emphasizing resource reuse and reimagining production cycles to minimize resource waste (Circle Economy et al., 2015). This collaborative effort between governments and designers aims to cultivate a more sustainable and resilient urban landscape.

However, the analysis also underscores significant disparities in the perspectives of planners and policymakers concerning the significance of various substances within material flows. Bridging this gap will necessitate concerted efforts to establish a common understanding and shared priorities.

4 Dissimilar perceptions between front-users and end-users on demographic, transportation, and waste management-related UM indicators

While the evaluation outcomes for indicators linked to land-use transformation appear quite similar between front-users and end-users, significant disparities emerge in their perspectives on other city development themes. Notably, divergences arise in the perceived significance of UM indicators across various topics.

Front-users assign relatively lower significance to demographic indicators ("population characteristic change" and "demographic composition change") compared to end-users, yielding notably different values (approximately 4.1 vs 3.3). It is noteworthy that UM analyses often overlook the influence of UM on demographic changes, despite its integral role in metabolic dynamics (Kennedy et al., 2014).

Conversely, end-users manifest heightened concern for transportation-related indicators. In the case of GDP and waste management-related indicators, a contrasting pattern emerges: front-users attribute higher significance to these indicators than end-users (GDP: 3.86 vs 3.30; waste management accessibility: 4.43 vs 3.96; waste management organization: 4.00 vs 3.65). These UM indicators are deemed valuable tools by planners and researchers to assess and enhance facets of waste management, including spatial allocation and waste management strategies (Longato et al., 2019). This underscores the necessity for enhanced communication and collaboration between planners and policymakers to effectively address waste management challenges.

B Perspectives across stakeholder type

TABLE 4.3 Result of significance evaluation based on different types of stakeholders (Score above 4.0 is highlighted and score below 3.0 is marked underlined)

Stakeholder type		Government (n=4)	Industry (n=11)	Research & Education (n=19)	Civil society (n=5)
Average		3.62	3.85	3.85	3.97
Environment Indicators	Precipitation	4.25	4.08	3.95	3.20
	Evapotranspiration	4.00	3.17	3.05	2.60
	Infiltration rate	3.25	4.25	3.80	4.40
	Surface run-off	3.50	4.00	3.75	4.60
	Air temperature	3.50	3.42	3.55	3.80
	Air pollutant concentration	3.50	4.25	4.55	4.60
	Exceedance	3.25	3.92	4.35	4.00
	Carbon sinks	1.75	3.67	3.60	4.00
	Heat island effect	3.25	4.00	4.00	4.20
	Heat balance	3.25	3.67	3.25	3.80
	Thermal comfort	3.25	3.42	3.30	3.00
Resource flow indicators	Biomass	4.00	3.92	4.30	4.00
	Minerals	3.50	4.00	4.00	3.40
	Water input	3.50	3.92	3.75	4.40
	Fossil fuels	3.75	3.75	4.15	3.20
	Renewable energy	4.25	4.33	4.60	4.80
	Waste input	4.00	4.08	4.25	4.80
	Other input	3.25	3.17	3.50	3.20
	Solid waste	3.75	4.25	4.15	4.60
	Wastewater	3.75	4.25	4.00	4.60
	Gas emissions	3.25	4.25	4.25	4.20
	Electricity	4.00	4.08	3.85	4.20
	Industrial products	3.25	3.33	3.20	3.60
	Construction	4.50	3.92	3.95	3.80
	Water storage	3.75	3.75	3.85	4.00
	Stored industrial products	3.50	3.00	3.55	3.20

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TABLE 4.3 Result of significance evaluation based on different types of stakeholders (Score above 4.0 is highlighted and score below 3.0 is marked underlined)

Stakeholder type		Government (n=4)	Industry (n=11)	Research & Education (n=19)	Civil society (n=5)
Average		3.62	3.85	3.85	3.97
City development indicators	Population characteristic change	4.00	4.00	3.75	4.20
	Demographic composition change	4.00	4.17	3.85	3.80
	GDP	3.50	3.25	3.60	3.20
	Employee condition variation	3.25	3.50	3.30	3.80
	Effects on the local economy	4.00	4.25	4.10	4.40
	New urbanized area	3.75	4.00	4.15	4.00
	Land-use transformation	3.75	4.08	4.15	4.80
	Transportation construction growth	4.25	3.58	3.50	3.40
	Public transportation accessibility	3.75	4.08	3.90	4.20
	Transportation method change	3.75	3.58	3.60	4.20
	Waste management accessibility	3.50	4.25	4.10	4.40
	Waste management organization	3.25	3.75	3.85	4.40

1 Positive stakeholder attitudes towards UM indicator significance across different sectors

An analysis of stakeholder perceptions regarding the significance of UM indicators across various sectors yields insightful findings. The outcomes are summarized in Table 4.1. Stakeholders from government, industry, research & education, and civil society display distinct viewpoints on the significance of UM indicators. Specifically, the average scores for perceived significance are 3.62, 3.85, 3.85, and 3.97, respectively, for stakeholders from these sectors. Notably, all average scores surpass the neutral threshold of 3.0, indicative of the positive stance stakeholders hold towards the selected UM indicators. Agreement is evident among the four stakeholder groups concerning the importance of specific UM indicators, including ‘renewable energy’, ‘waste input’, and ‘effects on the local economy’. The perception of indicator significance by stakeholders often influences the selection of UM indicators, influencing decision-making in associated projects. By heightening stakeholders’ awareness of the significance of these indicators, a more cohesive and appropriate selection of UM indicators can be achieved in project-related decision-making processes.

2 **Different perceptions among stakeholders: government stakeholders' less attention to carbon sinks and civil society stakeholders' relatively lower importance of evapotranspiration**

In the survey, two indicators received relatively low scores from distinct stakeholder groups: carbon sinks for government stakeholders (1.75) and evapotranspiration for civil society stakeholders (2.60). According to Tcvetkov et al. (2019), indicators associated with carbon sinks have limited public recognition. Despite considerable efforts by researchers and institutions to implement the technology, initial public reactions to this lesser-known concept tend to be negative. Regarding evapotranspiration, it has been utilized as a climate parameter to assess water balance and circulation, applicable not only in rural but also urban settings (Kanwal et al., 2020). When asked about the relatively lower importance assigned by civil society respondents to evapotranspiration, 4 out of 5 participants indicated that they "do not perceive this indicator as closely linked to urban metabolism resulting from human activities." This perspective contrasts with the findings of Kanwal et al. (2020) and Renouf et al. (2018), who emphasized the significance and representativeness of evapotranspiration in urban water metabolism. This disparity may stem from a potential knowledge transfer gap between academic research and practical understanding, possibly influenced by the broad spectrum of urban metabolism research areas.

4.1.5 Conclusion

In conclusion, the stakeholders and planners who participated in the survey have acknowledged the significance of the 38 UM indicators selected for this study. Based on their evaluations, no indicators should be eliminated due to lack of representativeness. However, due to the diverse perspectives of stakeholders, there exist variations in the perceived levels of significance for these indicators.

When comparing the opinions of front-users and end-users, differences in viewpoints are particularly pronounced for specific UM indicators, such as "minerals input" and "population characteristic change." To bridge this gap, front-users should consider the challenges of transferring technical content and strive to select accessible entry points for expressing UM indicators. Simultaneously, end-users should provide front-users with opportunities to analyze and elucidate indicator meanings, fostering a deeper understanding of their importance. Moreover, stakeholders from government, industry, research & education, and civil society also exhibit differing emphases on the significance of UM indicators, particularly notable in the case of carbon sinks and evapotranspiration. Addressing these perception disparities necessitates the implementation of diverse approaches and methods to mitigate knowledge transfer barriers, including living lab workshops and informational communication seminars. Both front-users and end-users need to recognize these discrepancies and work toward establishing a common understanding of UM indicators within a given project.

However, the challenges faced in applying UM indicators extend beyond mere differences in stakeholder and planner comprehension. Practical issues related to UM indicators also pose obstacles. Section 4.2 will delve into this problem through an analysis of another UM indicator evaluation survey conducted specifically among planners.

4.2 Planners' perspective: practicability of UM indicators

Urban planning projects are guided by specific development goals, which are further operationalized through measurable outcomes known as indicators. Indicators play a pivotal role in the evaluation of urban and regional metabolism within the current research paradigm (Kennedy et al., 2015). The rationale underpinning the selection of these indicators is of paramount importance, as it significantly enhances their precision and significance. In this context, this study has undertaken an additional survey, targeting urban planners exclusively, to delve into the feasibility and potential challenges associated with the application of UM indicators.

4.2.1 Criteria for the evaluation of UM indicators

The 'Discussion paper on Principles of Using Quantification to Operationalize the SDGs and Criteria for Indicator Selection' by the United Nations Statistics Division (2015) offers a pragmatic and systematic framework for selecting appropriate Sustainable Development Goals (SDGs) indicators tailored to various organizations. Although slightly diverging in its overarching objective, this study has adapted and enhanced the criteria from the SDGs perspective to the realm of UM.

Consequently, the ensuing key attributes that urban metabolism indicators should embody are as follows:

1 **Relevance: "Does this urban metabolism indicator align with my planning project?"**

The foremost consideration for urban planners is whether an indicator aligns with the thematic focus of their project. Indicators employed in planning projects should be closely intertwined with the project's overarching theme. Planning initiatives typically entail the formulation of novel development strategies from multiple perspectives. However, achieving equitable coverage across all facets of urban development is often unfeasible. Hence, planners are tasked with judiciously selecting and prioritizing relevant urban metabolism indicators that harmonize with the distinct context of their projects. This criterion is inherently project-specific and therefore is excluded in the analysis presented in this section.

2 **Uniqueness and Precision: "Is this urban metabolism indicator unambiguously defined?"**

Indicators carry the critical attribute of precision and clarity. Their definitions, calculation methods, and associated policy implications must be clearly delineated. Furthermore, indicators should be subject to peer review or international evaluation mechanisms to ensure accuracy and consistency. By maintaining unambiguous definitions, the selected indicators circumvent misinterpretation and divergent interpretations. An illustrative instance is the work of Kennedy et al. (2015), who employed a standardized indicator set to evaluate energy and material flows across 27 megacities. Moreover, this criterion underscores the necessity for methodological robustness. The methodology underpinning an indicator's computation, treatment of missing data, and related aspects should be thoroughly documented and accessible (United Nations Statistics Division, 2015).

3 **Communication and Accessibility: "Is this urban metabolism indicator comprehensible to a broad audience?"**

The findings from section 4.1 highlight the potential consequences of indicator miscommunication, which can inadvertently diminish their value. This underscores the significance of selecting indicators that are readily communicable and accessible. Indicators should possess a level of clarity that allows not only planners but also policymakers, the public, and other stakeholders to comprehend them without ambiguity. The avoidance of interpretive uncertainty is paramount. Additionally, cross-cultural considerations, language nuances, and presentation formats need careful deliberation to prevent misunderstandings (United Nations Statistics Division, 2015). For example, in East Asia, the term "urban metabolism" encompasses not only resource analysis but also references the Metabolism Movement advocated by Japanese architect Kisho Kurokawa.

4 **Data Availability and Accessibility: "Are the necessary data available for evaluating this urban metabolism indicator?"**

Data availability and accessibility hinge on two aspects: 1) The data pertinent to an indicator should be systematically collected and managed by designated responsible entities. Urban metabolism research often draws from government statistical reports and documents. Additionally, specialized data aggregation companies operating within specific domains can also furnish relevant data. 2) Data should be conveniently accessible and ideally non-confidential. The study of urban metabolism frequently grapples with data-related challenges. These hurdles arise not only from the sheer volume of data but also from the inaccessibility of certain data in specific regions for public research. For instance, a considerable amount of city-level resource flow data is confidential, rendering it arduous for researchers to access, except for analyses informed by internal governmental decisions. Consequently, possessing a repository of easily accessible and non-confidential data assumes pivotal importance in the indicator selection process.

5 **Spatial/Structural Applicability: "Can this urban metabolism indicator be spatially or structurally represented?"**

This criterion is uniquely pertinent to urban planning. Given that development strategies frequently align with spatial distribution patterns or the components of an urban functional structure, indicators must be amenable to integration with these dimensions. Failure to account for this alignment can impede the practical implementation of indicators post-analysis. As underscored by Schandl et al. (2020), the spatial arrangement aspect is often overlooked in assessments of metabolic outcomes.

4.2.2 Data collection

Between September 2019 and January 2020, a comprehensive survey was undertaken, targeting a diverse group of urban-planning students, practitioners, researchers, and stakeholders. The survey questions can be found in Appendix IV. The core objective of this survey questionnaire revolved around exploring urban planners' perspectives regarding the UM indicator criteria expounded in section 4.2.1. The survey meticulously examined how these professionals perceived the strengths and limitations of each UM indicator, based on their cumulative urban planning experiences.

To ensure the survey's precision, the "(1) Relevance" criterion, inherently project-dependent, was omitted from the questionnaire. Instead, the respondents were presented with the remaining four criteria (unique and precise, easy to communicate and access, data available and accessible, and spatial/structural applicable). These parameters served as the yardsticks by which the respondents could evaluate the various UM indicators. Drawing insights from their hands-on involvement in urban planning, the participants weighed the indicators' merits against these criteria.

Notably, the survey yielded a corpus of 63 returned questionnaires. This pool of responses originated from an expansive array of planning organizations and institutions spanning numerous countries and regions. The diversity of participants ensured that the collected opinions and insights encapsulated a broad spectrum of perspectives, bolstering the survey's comprehensiveness and representativeness.

4.2.3 Results of the survey

A detailed breakdown of the respondents' profiles can be gleaned from Figure 4.4. A comprehensive analysis of the collected questionnaires has yielded several notable outcomes:

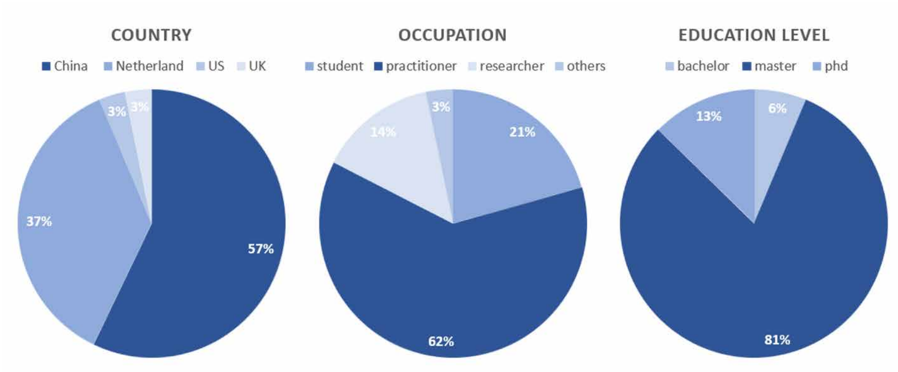

FIG. 4.4 Description of respondents in the second survey

1 **In general, the respondents believe that the UM indicators have certain problems to meet the evaluation criteria, making it hard for them to be widely adopted.**

Figure 4.5 is the average percentage of the UM indicators that meet each criterion based on the respondents' opinion. From the pie chart, we can see that only around 54% state that UM indicators fit the criteria in average. Overall, this shows that there are certain (perceived) limitations in satisfying indicator selection criteria in urban planning.

The combination of UM and urban planning emerged after 2010, through studies such as by Caputo et al. (2016) and Kennedy et al. (2011), and to this day researchers are constantly exploring more aspects of this idea. But this result indicates that although already after nearly 15 years of development, there are still (perceived) obstacles for planners related to the implementation of UM (especially when it comes to indicators). Due to their characteristics, indicators still need to be tailored to make themselves more suitable for urban planning.

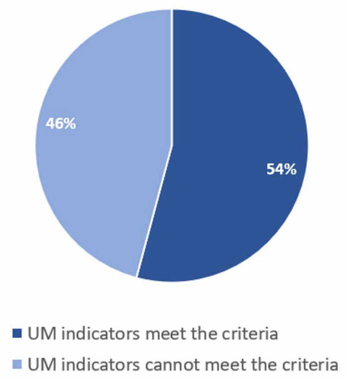

FIG. 4.5 Average percentage of UM indicators meeting each criterion according to respondents' perspective

2 **Among the four criteria, "data available and accessible" and "spatial/structural applicable" are the most challenging to fulfill.**

As demonstrated in Figure 4.6, the survey results indicate that over half of the UM indicators are perceived to meet the criteria of being "unique and precise" (61.30%) and "easy to communicate and access" (58.73%). However, a significant portion of the responses, more than half, consider "data available and accessible" (49.11%) and "spatial/structural applicable" (47.67%) as difficult to achieve.

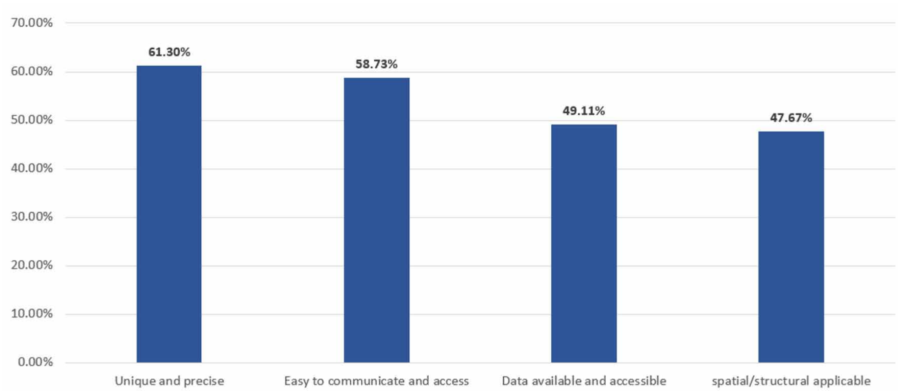

FIG. 4.6 Average percentage of UM indicators meeting each criterion according to respondents' opinion

3 The number of UM indicators meeting all four criteria simultaneously is limited

Table 4.4 illustrates the count of respondents who assess UM indicators (listed in the left column) as fulfilling the four specified criteria. Indicators meeting the criteria with scores below 50% are highlighted in orange. Notably, when “unique and precise” is not met, the other three criteria also tend to lack high recognition. Additionally, if “unique and precise” is satisfied while “easy to communicate and access” is not, positive results in “data available and accessible” and “spatial/structural applicable” are unlikely. The latter two criteria themselves appear to have minimal impact on the other criteria. Meeting the criteria of “unique and precise” and “data available and accessible” is a necessary, though not sufficient, condition for satisfying the remaining two criteria.

The complexity of the theoretical foundation behind each UM indicator contributes to its varying scores among respondents. Organizing these UM indicators into categories based on their alignment with at least one of the four criteria, as determined by most respondents, is the focus of the subsequent section.

TABLE 4.4 Percentage of respondents assessing UM indicators to meet the criteria (orange scores below 50%)

Urban metabolism Indicators	Unique and precise	Easy to communicate and access	Data available and accessible	Spatial/structural applicable
Precipitation	50.8%	81.0%	82.5%	66.7%
Evapotranspiration	41.3%	38.1%	31.7%	38.1%
Infiltration rate	55.6%	52.4%	36.5%	44.4%
Surface run-off	54.0%	61.9%	42.9%	50.8%
Air temperature	50.8%	87.3%	81.0%	61.9%
Air pollutant concentration	69.8%	54.0%	61.9%	54.0%
Exceedance	71.4%	44.4%	44.4%	30.2%
Carbon sinks	44.4%	42.9%	14.3%	34.9%
Heat island effect	74.6%	84.1%	31.7%	66.7%
Heat balance	50.8%	50.8%	38.1%	57.1%
Thermal comfort	54.0%	66.7%	30.2%	57.1%
Biomass input	50.8%	39.7%	41.3%	27.0%
Minerals input	57.1%	36.5%	38.1%	30.2%
Water input	69.8%	79.4%	74.6%	66.7%
Fossil fuels consumption	61.9%	55.6%	47.6%	39.7%
Renewable energy usage	76.2%	68.3%	41.3%	54.0%
Waste input	50.8%	36.5%	34.9%	30.2%
Solid waste	57.1%	52.4%	47.6%	38.1%
Wastewater	68.3%	69.8%	58.7%	54.0%
Gas emissions	65.1%	57.1%	55.6%	46.0%
Electricity usage	74.6%	73.0%	73.0%	66.7%
Industrial products export	55.6%	39.7%	39.7%	30.2%
Construction storage	69.8%	61.9%	46.0%	55.6%
Water storage	54.0%	54.0%	49.2%	46.0%
Stored industrial products	52.4%	39.7%	27.0%	31.7%
Population characteristic change	74.6%	81.0%	61.9%	54.0%
Demographic composition change	81.0%	81.0%	77.8%	63.5%
GDP	77.8%	63.5%	82.5%	36.5%
Employee condition variation	66.7%	55.6%	54.0%	39.7%
Effects on the local economy	65.1%	65.1%	31.7%	38.1%
New urbanized area	74.6%	79.4%	73.0%	74.6%
Land-use transformation	73.0%	69.8%	52.4%	71.4%
Waste management accessibility	46.0%	38.1%	36.5%	38.1%
Waste management organization	44.4%	36.5%	30.2%	27.0%

4.2.4 Aggregation of UM indicators

Based on their scores in meeting the criteria, the 38 selected UM indicators can be categorized into six groups, as illustrated in Figure 4.7 and summarized in Table 4.5:

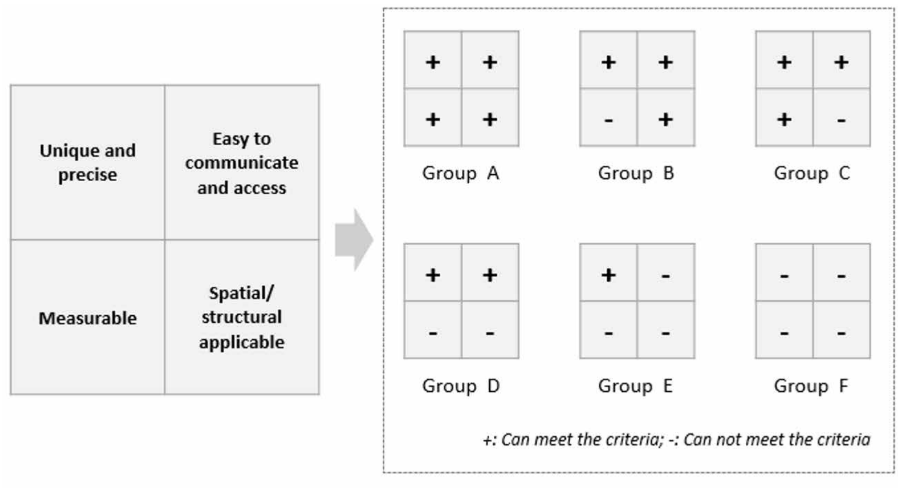

FIG. 4.7 Six groups of UM indicators based on their corresponding to the criteria

In Group A, most respondents consider the UM indicators to fulfill all four criteria. In essence, these indicators are acknowledged and applicable in urban planning. They face minimal obstacles in implementation, leading to positive responses from most urban planners in the questionnaire. This group includes indicators like “air temperature,” “water input,” “demographic composition change,” and “new urbanized area.” These indicators are frequently discussed and utilized in planning practice, with planners generally agreeing that they meet the criteria for effective indicators.

UM indicators in Group B face difficulty in meeting the criterion “data available and accessible.” These indicators either lack maintenance by responsible agencies or have inaccessible data. Among representative indicators such as “surface runoff,” “heat island effect,” “thermal comfort,” and “renewable energy usage,” several fall into this group. Often, when introducing a new term, time is needed for it to be embraced and understood within the field, including its connotations and representative significance. Typically, data availability isn’t an issue for these indicators, but planners struggle to access the required data. Clear communication regarding sources, calculation methods, and significance can address this challenge.

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TABLE 4.5 UM indicator categorization groups

	Environment	Material Flow	City Development
Group A	– Precipitation – Air temperature – Air pollutant concentration	– Water input – Waste water – Electricity usage	– Population characteristic change – Demographic composition change – New urbanised area – Land-use transformation
Group B	– Surface run-off – Heat island effect – Heat balance – Thermal comfort	– Renewable energy usage – Construction storage	
Group C		– Gas emissions	– GDP – Employee condition variation
Group D	– Infiltration rate	– Fossil fuels consumption – Solid waste – Water storage	– Effect on the local economy
Group E	– Exceedance	– Biomass input – Minerals input – Waste input – Industrial products export – Stored industrial products	
Group F	– Evapotranspiration – Carbon sinks		– Waste management accessibility – Waste management organisation

Group C mirrors Group B's situation, but here the difficulty lies in meeting the "spatial/structural applicable" criterion. Indicators such as "GDP," "employee condition variation," and "gas emissions" are part of this group. These indicators usually undergo evaluation on a larger scale. For broader acceptance and application, Group C's UM indicators should be refined to allow assessment at smaller scales, enabling planners to obtain spatial differentiations with ease.

Indicators in Group D, in line with the majority of respondents, struggle to fulfill both "data available and accessible" and "spatial/structural applicable" criteria. These indicators require optimization for both data accessibility and spatial/structural representation to enhance their applicability in urban planning. Group D includes a diverse set of UM indicators: "infiltration rate," "fossil fuels consumption," "solid waste," "water storage," and "effects on the local economy."

Group E encompasses several UM indicators related to Material Flow Analysis (MFA), such as "biomass input," "minerals input," "waste input," "industrial product export," and "stored industrial products." Typically, meeting criteria like "easy to communicate and access," "data available and accessible," and "spatial/structural applicable" is challenging for MFA-related indicators due to their focus on intricate urban material flows. Material flow visualization platforms, such as those developed in the Horizon 2020 research projects REPAiR and CINDERELLA, offer avenues for enhancing data availability, transparency, and spatial applicability of these indicators.

Some UM indicators in Group F are deficient across all four criteria, based on respondents' opinions. These indicators include "evapotranspiration," "carbon sinks," "waste management accessibility," and "waste management organization." Due to their specialized nature, these indicators are infrequently utilized in urban planning and are often perceived as challenging to use by planners. While integrating these indicators into urban planning is indeed complex, their potential for further exploration exists to enhance their integration possibilities.

4.3 Discussion: Exploring the implementation of UM indicators across stakeholder groups

From the study of two surveys in section 4.1 and 4.2, we can find not only the dissimilar perception of UM indicators between planners and stakeholders, but also the implementation obstacles of UM indicators experienced by planners. Although the indicators are being implemented in existing planning projects, still several challenges need to be addressed.

4.3.1 Challenges arising from knowledge diversity among stakeholders

The renowned assertion by Meadows (1998) that "we measure what we care about and we care about what we measure" holds true, especially in the realm of indicators and quantitative research. In the context of planning practice, the selection of indicators is closely intertwined with the concerns and perceived significance of stakeholders. The survey findings underscore that many stakeholders assign varying degrees of importance to the same UM indicators, thereby impeding efficient communication between different groups. An illustrative observation comes from an anonymous survey participant in China who highlighted the contrast between planners' multifaceted considerations, such as resource recycling and ecological benefits, and the government's often singular focus on immediate economic gains resulting from planning endeavors.

During the process of designing and selecting indicators, planners must navigate the challenge of introducing numerous professional concepts to decision-makers and the public. Concepts like "carbon sinks" and "thermal comfort," while pivotal in evaluating resource and energy flows, remain relatively novel in practical application (Yang et al., 2022). This unfamiliarity among decision-makers curtails their grasp of these concepts and hampers their recognition of the indicators' significance. To circumvent this situation, indicators that are specialized or newly introduced should be presented using more accessible language during their description and design. Incorporating concrete case studies can also aid in demystifying these concepts and enhancing their understanding among a broader audience.

4.3.2 Enhancing communication among different stakeholders

In contemporary planning projects, indicators serve as pivotal communication tools among diverse stakeholders (Anderson, 2013). These indicators hold a dual role: firstly, aiding planners in establishing quantifiable objectives within planning strategies and blueprints; secondly, pinpointing impacts and challenges in decision-making processes, thereby fostering heightened awareness among decision-makers of critical issues demanding resolution (Nordic Centre for Spatial Development, 2015). To ensure the effective implementation of indicators, robust communication channels must be established among various stakeholders.

One avenue for effective communication is the tailoring of indicators for their intended audience. Shields et al. (2002) advocate for indicators to be designed with the intended recipients in mind, which might necessitate data condensation (Refer to Fig. 4.8). In essence, the information contained within indicators requires skillful interpretation using appropriate language, facilitating seamless information transfer. While specialists like ecologists and industrial ecologists boast expertise in their respective domains, decision-makers require intelligible information to conceive actionable strategies. Overloading decision-makers with an excessive array of indicators can lead to a loss of efficiency and clarity (Bell & Morse, 2003). Therefore, UM indicators should be distilled into a simplified format that aligns with the needs of decision-makers, enabling them to comprehend and act upon the provided insights.

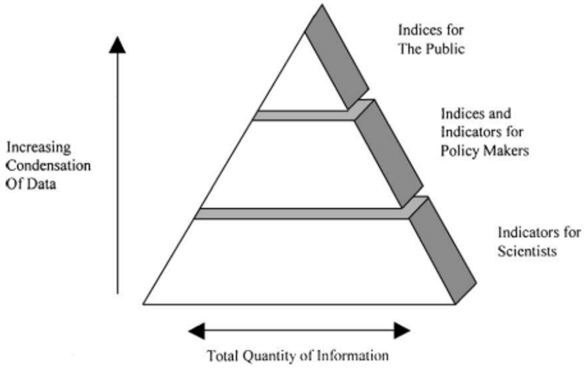

FIG. 4.8 Integrating UM indicators with different actors (Shields et al., 2002)

A complementary solution entails fostering more opportunities for interaction among diverse stakeholders within the planning process. Various EU projects, such as Urban-Wins and BRIDGE, have already employed workshops to engage an array of stakeholders in the selection of UM indicators (Chrysoulakis et al., 2013; Longato et al., 2019). To ensure more potent communication with decision-makers, the integration of indicators within the decision-making process itself is crucial. A noteworthy example is the Peri-urban Living Labs orchestrated by the REPAiR project, which leverages input from stakeholders spanning multiple domains to collaboratively design circular economy solutions for these regions (Amenta et al., 2019b). During these discussions, UM-related indicators evaluate each eco-innovative solution, providing insights for future strategies. This participatory approach ensures that indicators are deliberated upon by a diverse cohort of stakeholders, thereby enhancing their practical utility within projects.

4.3.3 Overcoming shortcomings of the indicators themselves

The survey on the practicability of UM indicators highlights the perceived hurdles associated with data availability and accessibility, as well as spatial and structural applicability within the context of urban planning. To address these challenges, several countermeasures can be implemented.

1 Data availability and accessibility

The broad spectrum of UM research, ranging from uncomplicated analyses to more resource-intensive investigations, necessitates an extensive corpus of comprehensive data for effective exploration of a city's metabolism (Currie & Musango, 2017). However, the availability of such data remains a persistent challenge, an issue underscored by numerous scholars (Barles, 2009; Blečić et al., 2014; Gonzalez-Garcia et al., 2018; Patrício et al., 2015; Schandl et al., 2020; Szabó, 2015; Vandevyvere & Stremke, 2012; Voskamp et al., 2018). Overcoming data access obstacles necessitates addressing the following concerns: (a) data confidentiality stemming from regulatory constraints; (b) data dispersion across various institutions; (c) data accessibility varying across different scales (e.g., regional, neighborhood); and (d) incorrect or incomplete data.

To bolster data quality and availability, several strategies can be adopted. Firstly, tapping into diverse yet reliable sources can provide a robust dataset (Blečić et al., 2014; Vandevyvere & Stremke, 2012), although this might entail additional time to collate scattered information from multiple entities. Secondly, bridging data gaps through cross-scale collection and comparison can mitigate deficiencies (Patrício et al., 2015). Often, data availability wanes with decreasing scale, while errors might escalate; reconciling these inconsistencies across different administrative levels holds potential (Patrício et al., 2015). Thirdly, generating high-resolution data through modeling techniques, especially in domains like water and energy, presents an avenue for exploration (Danius & Burström, 2001; Voskamp et al., 2018).

2 Spatial and structural applicability

The UM concept draws an analogy between a city and a human body, with the analysis of a city's metabolism mirroring the intricate nature of human physiology, if not surpassing it (Kennedy et al., 2007). The complexity inherent in this comparison poses challenges when attempting to study spatial and structural UM distribution (Kennedy et al., 2011). As elucidated in section 1.3, previous endeavors have endeavored to link UM with urban planning or design (Claudia Marcela Agudelo-Vera et al., 2012; Codoban & Kennedy, 2008; Montrucchio, 2012; Oswald et al., 2003). Despite this, the survey findings echo planners' reservations about effectively implementing numerous UM indicators with spatial and structural considerations.

To surmount these spatial and structural applicability hurdles, several approaches can be adopted during UM indicator selection and application. Firstly, UM indicators derived from grey-box or network models show promise in aligning with spatial and structural elements. Though time-intensive, these models offer insights into material quantities within nodes and flows, fostering stronger integration with planning objectives (Beloin-Saint-Pierre et al., 2017). Secondly, Life Cycle Assessment (LCA), as opposed to Material Flow Analysis (MFA), offers greater potential for spatial and structural integration of a city's metabolism (Newell & Cousins, 2014). LCA examines specific components like water, food, wood, waste, and energy individually, facilitating links to urban and rural concepts (Newell & Vos, 2011). Thirdly,

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visualization tools for UM indicators can provide visual maps depicting the interplay between a city's activities and its metabolism, a facet exemplified by decision-supporting tools in initiatives like BRIDGE and REPAiR (Amenta et al., 2019b; Perrotti, 2019). Lastly, introducing UM concepts to early-stage urban planning students can foster comprehension of interrelationships between subsystems and their spatial structures (Remøy et al., 2019).

4.4 Summary

This chapter delves into the practical application of Urban Metabolism (UM) indicators in urban planning, viewed through the lens of stakeholders' perspectives. The chapter offers insights into challenges, communication dynamics, and strategies to enhance the effective utilization of UM indicators in planning endeavors.

The chapter initiates by unraveling divergent viewpoints on UM indicators between urban planners and stakeholders. It draws from a survey involving governmental bodies, industries, research institutions, and civil society representatives. Stakeholders' positive attitudes towards UM indicators' significance are illuminated, coupled with distinct preferences and emphasis on specific indicators. The chapter underscores the need to augment stakeholders' awareness to ensure informed and integrated decision-making.

Shifting its focus to the domain of urban planning, the chapter navigates a survey conducted among urban planning professionals. This survey proves the feasibility and hurdles linked to the application of UM indicators. The findings spotlight challenges related to data accessibility, availability, and the spatial and structural applicability of these indicators. It unveils that only approximately 54% of respondents perceive UM indicators as meeting evaluation criteria, underscoring existing limitations. Considering these challenges, the chapter advocates for effective communication between stakeholders and planners. It emphasizes that UM indicators' acceptance hinges on tailoring their interpretation to various stakeholders. This involves simplifying complex concepts and utilizing relatable examples to facilitate comprehension, especially among decision-makers.

The chapter then delves into the pivotal role of communication in the planning process. It underscores the effectiveness of workshops and engagement platforms in fostering better understanding and collaboration between stakeholders and planners. A significant portion of the chapter is devoted to addressing data-related challenges. It explores strategies such as seeking diverse and reliable data sources, bridging data gaps through cross-scale comparisons, and utilizing visualization tools to enhance comprehension. Additionally, the chapter highlights the importance of LCA and grey-box models in aligning UM indicators with spatial and structural aspects, presenting opportunities for their practical integration.

In essence, Chapter 4 amplifies the challenges and prospects associated with implementing UM indicators from stakeholders' perspectives. It accentuates the imperative of fostering effective communication, interpreting indicators to cater to different stakeholders, and devising strategic data management approaches. Through this lens, the chapter underscores the journey towards harnessing the full potential of UM indicators in shaping sustainable and circular urban futures.

Sloterdijk, Amsterdam (Photo by Yan Song 2025)

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5 The Purposes and Applications of Urban Metabolism Indicators Across Different Scales

As stated in Section 1.5, a uniform approach for applying Urban Metabolism (UM) indicators across diverse scales—from metropolitan to neighborhood levels—is notably absent. Although several studies and projects have employed UM indicators to analyze material and/or energy flows within specific areas, the majority of these efforts have focused on a single scale or, at most, two scales (Lu et al., 2016; Tanguy et al., 2020). Consequently, a research gap persists regarding the comprehensive implementation of UM indicators across varying scales.

To address the challenge of implementing UM indicators across diverse scales, it is essential to explore the use of UM indicators in projects and applications at both individual and multiple scales. This chapter aims to bridge this gap by investigating the range of UM indicator scales and their proposed applications within selected UM-related projects, thus addressing the specific research question *SQ3: What are the different applications of UM indicators at various scales?*

Initially, Section 5.1 provides a delineation of the relevant scales for UM research, viewed through an urban lens. This foundation sets the stage for Section 5.2, which focuses on the Netherlands. The section curates 10 paradigmatic empirical and research projects for each scale within this context. Subsequently, an analysis was then conducted to scrutinize the UM indicators used in these projects across applications and dimensions. The investigation culminates in Section 5.4, which highlights the distinctions in UM indicators across multiple scales. Furthermore, this section explores the multifaceted functions these indicators play within the scope of correlated strategies.

5.1 UM across scales in the context of urban planning

Since its inception over 50 years ago, the concept of UM has become a key focus of research across a spectrum of scales, from anthroposphere metabolism to household metabolism, as depicted in Figure 5.1 (Zhang et al., 2015). However, in the context of urban planning, the applicability of UM scales for analyzing a city's metabolism is predominantly confined to the range extending from regional to neighborhood contexts (Codoban & Kennedy, 2008; Facchini et al., 2017; Kennedy et al., 2011). Consequently, the use of indicators to depict or assess UM necessitates an analysis across the following scales: beyond city scale, city scale, and neighborhood scale.

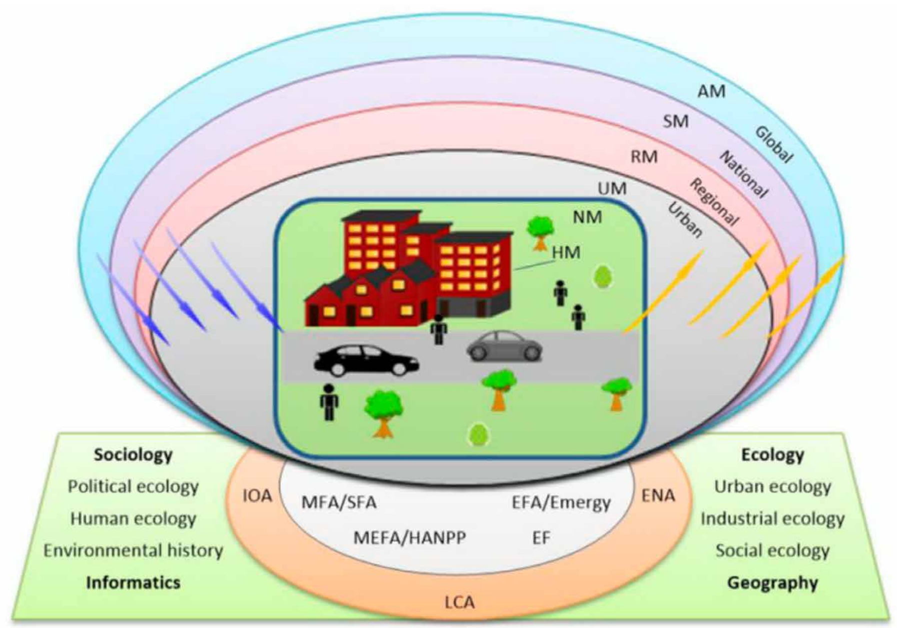

FIG. 5.1 Illustration of the diverse scales and disciplinary aspects essential for comprehensive urban metabolism studies (Zhang et al., 2015)

Notes: AM, anthroposphere metabolism; EF, ecological footprint; EFA, energy-flow analysis; ENA, ecological network analysis; HANPP, human appropriation of net primary production; HM, household metabolism; IOA, input–output analysis; LCA, life-cycle assessment; MEFA, material and energy flow analysis; MFA, material flow analysis; NM, neighbourhood metabolism; RM, regional metabolism; SFA, substance-flow analysis; SM, social metabolism; UM, urban metabolism.

5.1.1 Metropolitan scale

Research on metropolises and urban agglomerations, commonly referred to as metropolitan areas, has increasingly attracted scholarly attention considering its beyond city scale. These areas are central to the pursuit of sustainable development, posing challenges that include efficient resource utilization and socio-economic sustainability. Due to their substantial size and complexity, metropolitan areas often highlight the adverse effects of urbanization such as social inequalities, environmental degradation, elevated greenhouse gas emissions, and uneven resource allocation.

However, metropolitan areas also act as reservoirs for exemplary sustainable practices, providing valuable insights for replication (Facchini et al., 2017; Kennedy et al., 2014). Understanding these areas is crucial for the future initiatives of stakeholders including utility providers, urban planners, and policymakers (Kennedy et al., 2007). Therefore, exploring the complexity of UM within metropolitan areas is of paramount importance, tackling global environmental challenges and issues related to resource utilization efficiency and competition (Kennedy et al., 2015).

Conceptually, a metropolitan area consists of a densely populated urban core and its less populated peripheries, which together share industry, infrastructure, and housing (Squires, 2002). In many countries, these areas are vital centers for social, economic, and political institutions, evolving into crucial economic and political hubs (Muro et al., 2008). Numerous urban agglomerations have developed into complex metropolitan areas with multiple urban nodes. Notably, several nations, including China and the United States, utilize these metropolitan areas as experimental grounds to test future regional and urban development strategies (Caputo et al., 2016; Kennedy et al., 2015).

5.1.2 City scale

Originating from the concept, UM enables the investigation of a city’s functionality through the analysis of resource inputs and outputs. It also assesses how well a city coexists harmoniously with its surrounding environment (Dinarès, 2014). Initially, when the UM concept was introduced, research primarily focused on the urban scale, analyzing the metabolic processes of cities such as Hong Kong (Newcombe et al., 1978) and Brussels (Duvigneaud et al., 1977). However, as research expanded, the focus on a single city’s metabolism did not diminish; rather, there was a sustained interest in applying UM at the urban scale (Hoekman, 2015). To this day, this remains the dominant approach in UM research, with numerous significant global cities under scrutiny (Currie & Musango, 2017; Dinarès, 2014; Kennedy et al., 2007).

From an administrative perspective, the urban scale is the most pragmatic level for implementing effective actions. Typically, municipal administrations develop strategic plans at this scale. However, in terms of metabolic structure, the representation of metabolism at the urban scale often appears relatively incomplete. Many studies, frequently utilizing black- and grey-box methodologies, focus on intracity scenarios and impacts, yet often neglect to consider processes extending beyond the city limits (Beloin-Saint-Pierre et al., 2017). As a result, contemporary research into urban-scale metabolism has moved beyond traditional administrative city boundaries. Researchers, such as Barles (2009) and Voskamp et al. (2017), have broadened their analytical horizons to include not just the spatial and geographic dimensions of cities but also the regions influenced by the cities' material flows. Thus, the urban scale now centers on the impact of material flows rather than being restricted by administrative boundaries.

5.1.3 Neighborhood scale

The concept of neighborhood-level metabolism was first examined by Codoban and Kennedy (2008) in their seminal work, "Metabolism of Neighborhood," where they defined it as "a population-weighted fraction of a whole urban metabolism." Notably, this scale has seen the implementation of various developmental strategies incorporating pioneering technologies. Such strategies include the development of green buildings, climate-adaptive communities, integrated water systems, and designs that promote cycling and walking. Additionally, initiatives like neighborhood waste management and zero-carbon communities, though not explicitly termed 'metabolic', deeply integrate key metabolic components such as food, waste, water, and energy. This connection has led numerous researchers to focus on the community level to explore the impacts of new technologies on UM (Baccini & Brunner, 1991; Brunner, 2007). Investigating UM at the neighborhood scale is essential for creating sustainable and resilient communities (Codoban & Kennedy, 2008).

Highlighting the importance of this approach, Kennedy et al. (2011) emphasized the need for meticulous planning and design that tracks energy and material flows within communities. Thus, studying UM at the neighborhood level not only aligns with sustainable development goals but also meets the critical need for well-monitored energy and material dynamics within communities.

5.2 UM related projects in the Netherlands

With an increasingly in-depth exploration of integrating UM into urban planning, it is widely recognized that UM provides innovative insights for fostering more sustainable resource management, extending beyond the boundaries of cities and their surrounding areas (Pistoni & Bonin, 2017). A notable advancement in this direction was the Dutch government's 2016 launch of the "Government-wide Program for a Circular Economy", detailed in the document "A Circular Economy in the Netherlands by 2050". This initiative focuses on enhancing UM, especially in terms of raw materials, with the primary goal of developing a roadmap for an economy that is resilient and sustainable, serving both present and future generations (The Ministry of Infrastructure and the Environment & The Ministry of Economic Affairs, 2016).

The Dutch program builds on a solid base of local and regional initiatives that address urban development challenges through the lens of UM (See Fig 5.2). A key example is the collaboration for the sixth edition of the International Architecture Biennale Rotterdam (IABR), themed "Urban By Nature", which involved Rotterdam municipality, FABRIC, JCFO, and TNO (Gemeente Rotterdam et al., 2014). This partnership produced a detailed report that analyzed the metabolic intricacies of Rotterdam, significantly advancing the city's progress towards sustainable urban development. Currently, a growing number of Dutch public authorities are implementing urban experimental projects as benchmarks for energy transition and sustainability (Pistoni & Bonin, 2017). This collective effort has established the Netherlands as a leader in fusing the principles of UM with empirical urban planning projects, setting a notable global precedent.

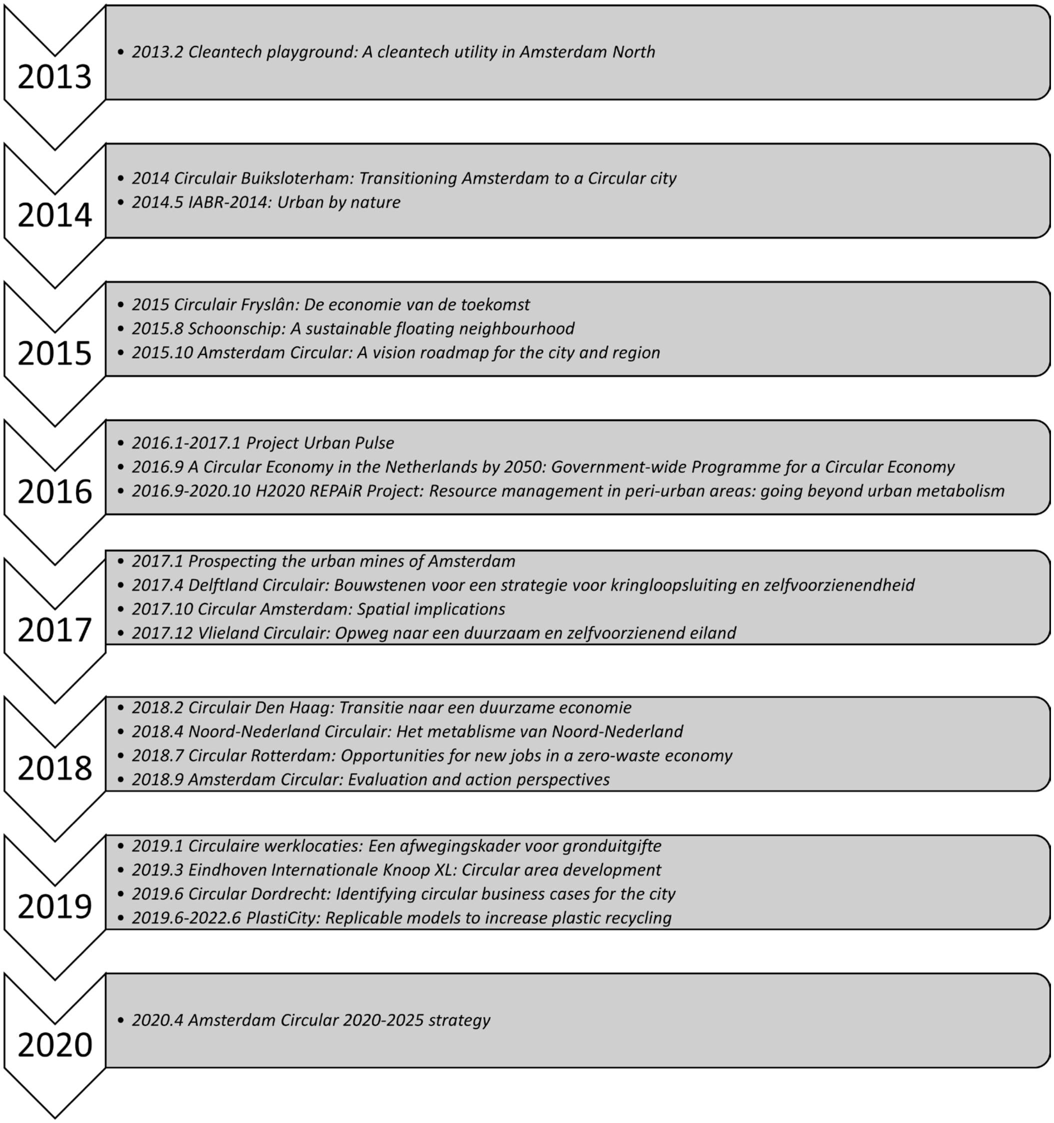

FIG. 5.2 Urban-metabolism-related projects in the Netherlands (until 2021)

This research examines a carefully curated collection of ten projects from the Netherlands that are deeply integrated with the concept of UM. These projects cover a range of scales, including metropolitan, urban, and neighborhood levels, with some initiatives demonstrating a cross-scale approach. Below is a list that highlights the UM indicators meticulously analyzed or effectively employed within these projects:

1 **A Circular Economy in the Netherlands by 2050 (Metropolitan Scale)**

This project encapsulates the government-wide program for a Circular Economy, launched in 2016 by the Ministry of Infrastructure and the Environment in conjunction with the Ministry of Economic Affairs. This comprehensive initiative delves into the utilization of raw materials, formulating a vision that outlines tangible objectives and unveils precise interventions within the developmental landscape (The Ministry of Infrastructure and the Environment & The Ministry of Economic Affairs, 2016). Notably, the program focuses on critical domains such as biomass and food, plastics, the manufacturing industry, the construction sector, and consumer goods, covering the entire national spectrum. At its core, this methodology utilizes a meticulous selection of UM indicators, strategically categorized under these five thematic pillars. This structuring of indicators serves as a navigational tool, guiding efforts towards achieving the program's strategic objectives and fostering a truly circular economy.

2 **IABR Rotterdam 2014 (Metropolitan and Urban Scale)**

This edition of the International Architecture Biennale Rotterdam, themed "Urban By Nature," represents a significant endeavor within the framework of UM. The Biennale has produced a comprehensive report that includes an in-depth analysis, strategically devised strategies, and thoughtfully crafted design propositions—all rooted in Rotterdam's metabolic dynamics (Gemeente Rotterdam et al., 2014). The project's foundation involves dissecting various flows—such as goods, people, waste, biota, energy, food, fresh water, sand, clay, and air—which have been methodically quantified, analyzed, and represented cartographically. Accompanying this are UM indicators, each carefully selected and evaluated for its potential to map each flow. This innovative approach offers a dynamic method for visualizing the city's metabolism, highlighting the complex interactions among different elements and processes.

3 **Circular Rotterdam (Metropolitan and Urban Scale)**

The City of Rotterdam has collaborated with Metabolic and Circle Economy on a pioneering project aimed at identifying new job opportunities within a zero-waste economy (Gladek, van Exter, et al., 2018). This initiative began with a thorough analysis of the current material and resource flows within the city, leading to the development of a comprehensive set of key performance indicators (KPIs) to monitor future progress. From this analysis, a series of interventions was proposed to facilitate Rotterdam's transition to a circular economy. The KPIs are structured around four primary sectors of the city's economy: agri-food and green flows, construction, consumer goods, and healthcare. These sectors were chosen because they are the largest sources of waste in Rotterdam. The KPIs serve to benchmark the current state of each sector and assess the city's progress towards circularity. While still in the early stages, the project holds significant potential to generate new employment opportunities in Rotterdam. The city, with its rich history of innovation and entrepreneurship, views this project as a continuation of its longstanding tradition. By moving towards a circular economy, Rotterdam aims to foster a more sustainable and prosperous future for its residents.

4 H2020 REPAiR Research Project (Metropolitan and Urban Scale)

The EU Horizon 2020 research venture, REPAiR (Resource Management In Peri-Urban Areas: Going Beyond Urban Metabolism), aims to provide local and regional authorities with an innovative, transdisciplinary open-source geo-design decision support framework. This framework has been implemented in living labs across six metropolitan areas, facilitating the application of geo-design to waste management and the evaluation of sustainability (Wandl et al., 2019). An open-source tool has been developed from this approach, designed to optimize geo-design capabilities specifically for waste management, while also assessing sustainability aspects. Central to the project is a catalogue of UM-related indicators that focus on waste management dynamics and sustainability assessments.

5 Circular Amsterdam (Urban Scale)

"Circular Amsterdam" represents a collaborative effort between Circle Economy, TNO, Fabric, and the City of Amsterdam. This project outlines an ambitious agenda to transform Amsterdam and its surrounding metropolitan area, recognized as a leader in circular economy practices (Circle Economy et al., 2015). At the heart of the project are four key UM-related indicators: value creation, job proliferation, material conservation, and CO_2 reduction. These indicators serve as the foundation for evaluating the effectiveness of various interventions across the city. Additionally, the project introduces a broader set of UM indicators, enhancing the toolkit available for assessing the circularity performance of Amsterdam and its wider metropolitan area.

6 Urban Pulse (Urban Scale)

The Urban Pulse initiative is motivated by the goal of advancing circular UM. This is achieved by deciphering the complex spatial and temporal dynamics of natural resource flows within the city of Amsterdam (Voskamp et al., 2017). A crucial element of this project is its integration of high-resolution, dynamic data with the AMS Institute data platform, facilitating the generation of critical insights.

These insights are vital for equipping planners and decision-makers with a deep understanding of Amsterdam's metabolic intricacies. Such knowledge forms the basis for developing technical and managerial strategies that support robust closed-loop resource systems. Within this framework, the UM indicators used are essential for defining both the cutting-edge status and the performance benchmarks of resource flows within Amsterdam's urban fabric.

7 Circulair Den Haag (Urban Scale)

Presented as a policy note by the City of The Hague, this document highlights the city's commitment to initiating a circular transition (Gemeente Den Haag, 2018). It outlines key developmental priorities with a focus on biomass, construction materials, and critical raw materials. Drawing parallels to the Circular Amsterdam project, this policy note employs a similar set of UM-related indicators: value creation, job expansion, material preservation, and CO_2 reduction. These indicators provide the evaluative framework for a series of actionable projects detailed within the document. By adhering to these indicators, the policy note not only charts the city's path towards circularity but also underscores the feasibility and potential impact of the proposed projects.

8 Circular Buiksloterham (Neighborhood Scale)

The Circular Buiksloterham project, led by Metabolic, explores the potential of the Buiksloterham neighborhood to serve as an exemplary model for circular city development within Amsterdam (Gladek et al., 2014). This initiative is grounded in the theoretical frameworks of circular cities and employs a strategic array of UM indicators to scrutinize the envisioned blueprint for the year 2034. These indicators are systematically categorized across themes such as energy, water, infrastructure, and mobility, acting as evaluative tools to assess the feasibility and alignment of the future plan with circular principles. The report transcends traditional urban planning by integrating UM theory with practical, future-oriented assessments. Ultimately, Circular Buiksloterham represents a paradigm shift towards not just constructing a neighborhood but fostering a pioneering narrative of circular city development that aligns with sustainable urban growth.

9 De Ceuvel (Neighborhood Scale)

De Ceuvel is a groundbreaking experimental project located in Amsterdam Noord, deeply embedded in UM principles (Pistoni & Bonin, 2017). As part of the "Cleantech Playground" initiative, De Ceuvel aims to establish a cleantech utility that catalyzes a circular and sustainable future (Metabolic Lab, 2013). This project strategically employs UM indicators as critical benchmarks throughout its development, which are artfully categorized into four domains: energy and materials, ecosystems and species, culture and economy, health and happiness. These categories guide the project's development towards comprehensive goals that extend beyond physical infrastructure. By incorporating these UM indicators into its strategy, De Ceuvel not only constructs a physical space but also cultivates a holistic ethos that resonates with the principles of sustainability and circularity.

10 Circulaire Werklocaties (Neighborhood Scale)

The "Circulaire Werklocaties" project, driven by a consortium including SADC, the City of Haarlemmermeer, and the Port of Amsterdam, epitomizes the concerted effort to transition towards a circular economy. This initiative is distinguished by the creation of circular workspaces, designed to herald a new era of sustainable urban development (Fleurke et al., 2019). An integral part of this ambitious project is the development of a robust land allocation assessment framework, which supports their comprehensive goal of achieving circularity. Central to the project's approach is its methodological rigor. The document outlines a detailed evaluation of various strategies, meticulously assessed through UM indicators. These indicators, thoughtfully organized into themes such as energy, materials, and water, provide critical insights into the feasibility and effectiveness of different strategies. The coherent application of these indicators aligns closely with the project's overarching goal— to cultivate circular economies that not only meet current challenges but also pave the way for a more sustainable future.

Collectively, these diverse Dutch projects illustrate the role of UM indicators as navigational tools, directing efforts towards sustainable and circular urban futures. By utilizing these indicators, these initiatives effectively bridge the gap between visionary principles and practical implementation, shaping urban environments that are resilient and geared towards circularity.

TOC

5.3 The UM indicators applied in the selected Dutch projects

This study explores the application of UM indicators across a variety of projects at different scales (see Appendix IV). UM indicators are broadly recognized as vital tools in urban planning, playing a crucial role in guiding development and measuring performance. Their widespread use highlights their importance in both project design and execution, serving a diverse array of functions:

- Prioritizing areas based on assessment outcomes.
- Identifying synergies among various regions.
- Measuring resource flows between cities and their hinterlands.
- Interpreting and aligning with planning ambitions.
- Enhancing the integration of UM in sustainability evaluations.
- Utilizing UM as a strategic compass in decision-making.
- Assessing the effectiveness of projects.
- Evaluating the performance of resources and energy.
- Developing comprehensive frameworks for urban development.
- Establishing benchmarks that span different areas.
- Promoting end-to-end sustainability in industrial chains.
- Implementing cutting-edge technologies in real-world applications.

Significantly, the effectiveness of UM indicators is scale-dependent, revealing varying impacts and insights at different urban scales (see Fig 5.3).

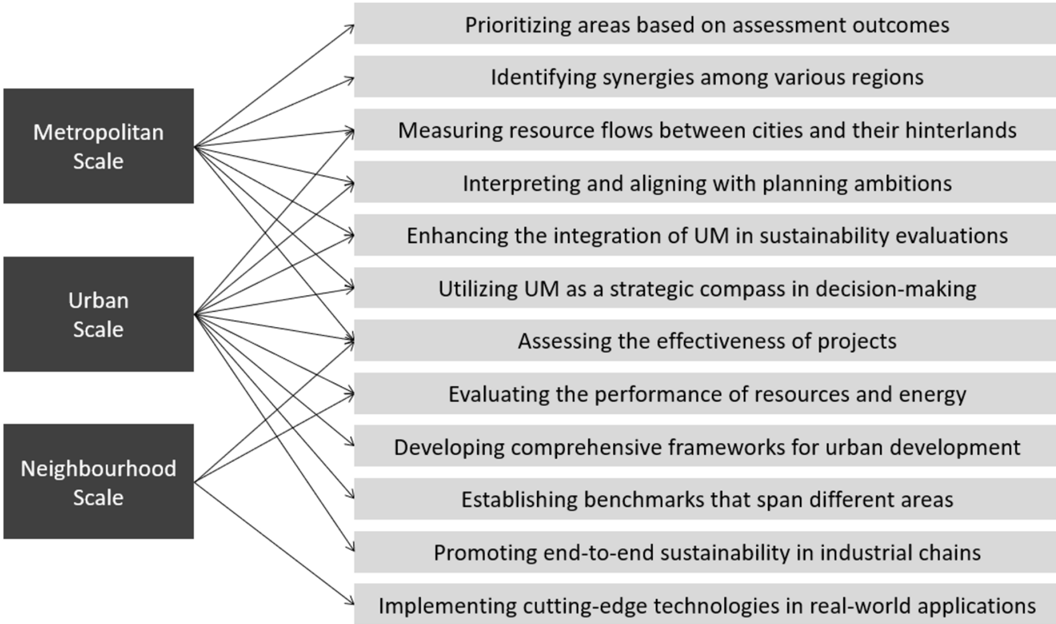

FIG. 5.3 Purposes of applying UM indicators at different scales

UM indicators, employed at the metropolitan scale, predominantly align with overarching development strategies, enhance regional synergies, and identify key focus areas. This scale emphasizes the direction and quantum of material flows rather than delving into technical intricacies or underlying impact factors. For instance, the Dutch government's "A Circular Economy in the Netherlands by 2050" project highlights five critical sectors crucial for transitioning to a circular future, integrating both qualitative and quantitative UM indicators to articulate a strategic vision for 2050 without prescribing detailed city-level procedures or tasks (The Ministry of Infrastructure and the Environment & The Ministry of Economic Affairs, 2016).

Cities such as Rotterdam, Amsterdam, and The Hague are frontrunners in developing circular economies and sustainable urban models. Reports like Circular Amsterdam dissect material flows and chart paths towards sustainability, employing a tripartite approach: analyzing current material flows, introducing innovative interventions, and outlining future visions. Here, UM indicators are pivotal in quantifying resource flows, facilitating inter-area comparisons, and fostering a sustainable industrial ecosystem. For instance, Circular Amsterdam utilizes UM indicators to quantify material flows through Material Flow Analysis (MFA) and evaluate project performance (Circle Economy et al., 2015). This urban scale thus becomes a fertile ground for catalyzing technical and managerial innovations, with projects like REPAiR and Urban Pulse strategically leveraging UM to guide decision-making and development pathways, thereby enabling comprehensive urban transformation (Geldermans et al., 2018; Voskamp et al., 2017).

At the neighborhood scale, UM indicators facilitate the pilot testing of novel technologies within real-world settings. Sustainable neighborhoods become test beds for innovations in energy distribution, waste management, and water conservation. Examples include Buiksloterham, Schiphol Area, and Schoonschip, which experiment with circular building practices, zero-emission mobility, and sustainable economies (Fleurke et al., 2019; Gladek et al., 2014). In these contexts, UM indicators are crucial for quantifying resource flows and assessing the performance of technologies, thus operationalizing the principles of UM.

Overall, the strategic use of UM indicators across different scales illustrates their versatility and critical role in crafting sustainable urban futures. By bridging the gap between visionary principles and concrete actions, UM indicators equip planners and policymakers with the necessary tools to shape resilient and sustainable urban environments, setting a global benchmark for urban development.

5.4 Exploring UM Indicator Applications in Dutch Projects

When considering the role of indicators as management tools, their direct linkage to policymaking and the formulation of development strategies is crucial. Urban planners can employ these indicators not only to measure project performance with greater precision but also to guide the development trajectories of projects. UM indicators are particularly valuable to local administrations as they facilitate the integration of diverse aspects into performance management, thereby improving decision-making processes and enhancing public awareness initiatives (Michael et al., 2014; Rahdari & Anvary Rostamy, 2015). However, the interpretation of the same indicator can vary significantly across different scales due to divergent access points, leading to unique applications. The subsequent sections will explore the specific applications of these indicators as demonstrated in selected Dutch case studies.

5.4.1 Planning actions in the selected Dutch cases

In UM practice, indicators are extensively utilized to support projects, primarily through assessing material and energy flows in alignment with public policy objectives (Kennedy et al., 2011). In the Dutch cases discussed in section 5.2, UM indicators play a critical role in shaping development strategies that incorporate metabolic thinking, grounded in the dynamics of existing resources. As highlighted in section 5.3, the diverse purposes of UM indicators across various scales lead to differing applications when integrating their analysis with practical projects.

1 A Circular Economy in the Netherlands by 2050

This program features a comprehensive suite of five national-level interventions, each designed to advance strategic goals around optimizing raw material use, fostering innovative substitution strategies, and transforming production methods. These interventions include:

- Regulatory Advancements: Developing legislation and regulations that foster a conducive environment for innovation, dynamic growth, and investment.
- Market Intelligence Empowerment: Creating a sophisticated market dynamic through targeted pricing incentives and regulations to boost demand, drive innovative business models, and strengthen international market standing.
- Circular Insight Advocacy: Promoting a thorough understanding of the socio-economic cost-benefit landscape, while actively supporting circular business models.
- Infrastructure Strengthening: Building a strong support infrastructure to guide societal decision-making and tailor innovations to align with the program's overarching goals.
- International Collaboration: Embracing a cooperative international approach to close supply chain loops, internalize ecological costs, and enhance supply security.

Together, these interventions are supported by a detailed analysis of existing barriers and opportunities, presenting a clear view of the current landscape. Ongoing initiatives are illustrated through case studies, leading to a roadmap of planned actions set to achieve the program's objectives. Central to this strategy are UM indicators, which are skillfully applied to assess the effectiveness of each intervention, allocate resources strategically, and identify key areas of focus.

2 IABR Rotterdam 2014

Based on an in-depth analysis of nine key resource flows, the report presents four strategic pathways to optimize resource utilization within Rotterdam and its surrounding metropolitan area:

- Resource Regeneration: Utilizing waste and surplus food as sources of raw materials to create a cycle of resource reclamation.
- Eco-Enrichment: Enhancing urban ecology by locally sourcing freshwater, sand, and clay, which supports the development of biotopes within the city.
- Energy Efficiency Valorization: Maximizing the potential of industrial by-products and electricity generation to improve energy efficiency and reduce waste.
- Technological Uplift: Improving the quality of goods, transport, and airflows through the adoption of Germany's "Industrie 4.0" program.

These strategies, outlined within the IABR Rotterdam framework, aim to address current challenges in resource circulation and are grounded in extensive analysis and mapping of diverse UM indicators. Built on well-defined principles, these pathways are supported by tangible design examples that serve as models. Importantly, the UM indicators in this report serve a dual purpose: they act as diagnostic tools to illuminate Rotterdam's current state and function as benchmarks to assess the impact of each strategic pathway.

3 Circular Rotterdam

Within this project, Rotterdam's journey toward circularity is analyzed through four key themes, all aligned with the vision of a waste-free, circular city. This approach is organized by a strategic hierarchy focusing on reduction, synergy, production and purchasing, and effective management, with carefully crafted interventions under each thematic area. For example, in the agri-food and green flow sectors of Rotterdam, a series of targeted actions include:

- Promoting Local Campaigns: Raising awareness at the local level to reduce food waste.
- Enhanced Food Preservation: Advocating for improved labeling strategies to optimize food storage and extend shelf life.
- Technological Solutions: Implementing discount apps and efficiency tools in restaurants and companies to reduce food waste.
- Localized Regulatory Measures: Developing regulations tailored to reduce retail food waste in the community.
- Bio Waste Collection: Launching door-to-door bio waste collection initiatives.

- Waste Valorization: Creating opportunities for the chemical processing of waste materials.
- Urban Agriculture Incentives: Offering incentives for low-impact urban agriculture, such as vertical farming.

The material flow analysis within each theme is conducted from multiple perspectives, with UM indicators applied to provide a comprehensive view of resource dynamics. Additionally, these UM indicators are used to evaluate the impact of proposed actions, offering a data-driven measure of their effectiveness. This evaluative approach, grounded in UM indicators, helps estimate the future trajectory of each initiative, enhancing the precision of the project's forward-looking strategy.

4 H2020 REPAiR research project

The EU Horizon 2020 project REPAiR is dedicated to creating an environment where public and private local stakeholders can simulate and assess projects, policies, and spatial plans to promote a circular economy. To achieve this transformative goal, REPAiR develops a suite of applications, including:

- Geodesign Decision Support Environment (GDSE): A dynamic platform designed to foster collaboration in resource management and support the shift to a circular economy. GDSE empowers stakeholders by providing an interactive space for engagement and co-creation.
- Peri-Urban Living Labs (PULLs): These living labs embrace a co-creation approach, serving as catalysts by involving researchers, experts, and stakeholders in shaping the project's direction and outcomes.
- Eco-Innovative Solutions: REPAiR promotes eco-innovative solutions tailored to address specific challenges within focal areas, recalibrating flow dynamics to achieve a more sustainable balance.
- Knowledge Transfer Nexus: Facilitating cross-contextual learning, REPAiR encourages knowledge exchange that spans diverse contexts and scenarios within the project.

The REPAiR project strongly integrates UM-related indicators to enhance its initiatives. The GDSE acts as a visual repository, offering insights into waste flows within case areas and providing sustainability analyses for a comprehensive view. Additionally, UM indicators play a key role in evaluating eco-innovative solutions, serving as benchmarks to measure the potential impact of each proposal. This coordinated use of UM indicators aligns with REPAiR's overarching mission to cultivate a circular economy.

5 Circular Amsterdam

This comprehensive report examines Amsterdam's circularity through two key value chains: the construction chain and the organic residual streams chain. By integrating strategies that address these flows, the report outlines spatial visions, identifies barriers, and pinpoints critical actions, while also assessing the potential economic and environmental impacts. Key recommendations and future directions include:

- Stakeholder Synergy: Highlighting the importance of collective action across government and market sectors, encouraging coordinated stakeholder involvement to drive change.
- Indicator Enrichment: Advocating for the development and refinement of indicators to provide more detailed insights into Amsterdam's circularity.
- Amplified Metabolic Insight: Calling for a deeper examination of the city's metabolic processes to enable more thorough and insightful analysis.
- Enhanced Transparency: Stressing the need for clear insights into resource flow demands to support informed decision-making.
- Demand-Supply Synchronization: Emphasizing active coordination to align supply and demand, facilitated by roles like chain directors.

The use of UM-related indicators in this report serves two main purposes: to provide a current view of Amsterdam's material flow landscape and to assess the transformative potential of various strategies for circularity. Several actionable steps for advancing the city's metabolic processes are also presented, including a virtual resource platform for accessible geo-data, a proposed circular bio-refinery free zone, and establishing a "launching customer" role for locally produced materials. Together, these initiatives offer proactive steps toward Amsterdam's circular future.

6 Urban Pulse

The Urban Pulse project has effectively utilized Material Flow Analysis (MFA) to explore the complexities of Amsterdam's UM, enhanced by space-time information analysis (Voskamp et al., 2018). The project's central aim is to identify UM-related data that can equip planners and designers with valuable insights for the efficient execution of urban projects. Within this scope, several strategic recommendations emerge:

- Eurostat Method Enhancement: Expanding the Eurostat method's application to achieve a more comprehensive UM analysis.
- Resource-Conscious Transition: Guiding decision-makers toward circularity in UM through resource-aware urban planning and design.

- Designer's Role: Emphasizing the significant role of designers as key contributors to advancing UM transitions.

This collaborative research project leverages the combined expertise of academic, societal, and industry partners to deepen the understanding of Amsterdam's resource flows through spatial and temporal dynamics. The indicators used in this project serve a dual purpose: to test the Eurostat method's robustness and to improve the precision of space-time information analysis. Ultimately, this initiative dissects UM to provide urban planners and designers with valuable insights, seamlessly integrating them into daily urban design practices.

7 Circulair Den Haag

The Circulair Den Haag project acts as a strategic guide, steering the city towards circularity within a vision of sustainable development. This initiative establishes a multi-layered policy framework that contextualizes its strategic goals and includes a set of immediately actionable projects and policies, prioritized across key focus areas. The action blueprint is structured around three core strategies:

- Sectoral Priority: Emphasizing key sectors—particularly households, construction, trade, and public administration—while fostering an environment that supports companies and start-ups.
- Material-Flow Centric Approach: Creating a strategic roadmap focused on critical material flows, maximizing the opportunities they present.
- Targeted Sectoral Actions: Implementing strategies for high-potential sectors. For the household sector, for instance, this includes promoting circular initiatives, raising citizen awareness about repair and reuse, establishing sharing platforms, and encouraging local recycling initiatives.

At the heart of the project's analysis are UM indicators, carefully examined to provide a clear view of Den Haag's current material flows. Insights gained through these indicators sharpen the project's strategic actions, ensuring they are both effective and impactful. The project's ambitions are closely aligned with these analyses, as demonstrated by a key target for 2025: to reuse 40% of discarded household raw materials and products within the region.

8 Circular Buiksloterham

The Circulair Buiksloterham project serves as a dynamic living laboratory, positioning Buiksloterham as a model for circular, intelligent, and bio-based development. It exemplifies the transformative path that other post-industrial neighborhoods can take towards circularity and sustainability. Building on the foundation of the Circular City Model (Gladek et al., 2014), the project presents an actionable blueprint with a comprehensive set of potential interventions:

- Systemic Interventions: Establishing inclusive governance structures to oversee the area's development and investing in urban sensing and open data infrastructure.
- Energy Self-Sufficiency: Aiming to make Buiksloterham fully energy self-sufficient through a 100% renewable energy supply. Planned measures include requiring new buildings to meet Passive House standards and reducing operational energy demands in existing industries.
- Innovative Water Management: Aspiring to make Buiksloterham the Netherlands' leading site for water innovation by developing advanced stormwater management systems, decentralized water collection, and natural buffering zones.
- Socially Valued Soil: Reimagining soil as a valuable social asset. Strategies include repurposing polluted land for temporary uses, implementing bioremediation, and elevating ground levels in key development areas.
- Progressive Mobility Plan: Reducing parking standards and expanding public transport infrastructure across water bodies.
- Closed Material Cycle: Creating a complete material lifecycle by designing new buildings for material recovery and reuse, along with launching material recovery and repair facilities.

This project offers practical, detailed actions aligned with the principles of metabolic thinking. The domains of energy, water, infrastructure, and mobility are highlighted as key areas for improvement, guided by the project's strategic report. Each action is paired with a specific, measurable goal, supported by indicators that not only confirm the feasibility of each initiative but also assist in prioritizing actions within the broader scope of the project.

9 De Ceuvel

De Ceuvel is an experimental community in Amsterdam Noord, representing a successful model of circular economy initiatives in the Netherlands. Designed as a creative and social enterprise hub, this innovative enclave is a collaborative effort between Delva Landscape Architects and the University of Ghent, integrating several strategic paradigms and dynamic initiatives:

- Energy Autonomy: Striving for complete energy independence through enhanced insulation and renewable heating solutions, thereby eliminating the need for a conventional gas connection.
- D-SARR System: At the heart of the project is the D-SARR system (Decentralized Sanitation and Resource Recovery System), a groundbreaking waste treatment and resource recovery unit that serves the entire De Ceuvel site. This innovative system combines waste processing with resource recovery, producing valuable biogas and nutrients for on-site use.
- Adaptive Technological Evolution: A core feature of the project is its commitment to continuous technological adaptation, with a flexible, evolving approach that ensures the project remains responsive to changing needs.

Central to De Ceuvel's approach are UM indicators, serving as essential benchmarks across efficiency, recovery, supply, and various performance metrics. These indicators play a dual role, acting as tools for evaluation and as guiding markers that clarify the financial aspects of the project's implementation.

10 Circulaire Werklocaties

The Circulaire Werklocaties project represents the transition from circularity concepts to practical implementations, creating adaptable and circular workspaces that foster a cohesive ecosystem where flexibility aligns with sustainability. This initiative encompasses diverse profiles, life stages, geographical locations, and an active knowledge-sharing community, weaving a vibrant tapestry of experiential learning. The project pursues several key objectives to advance the circularity agenda:

- Spatial Flexibility and Deliberation: Designed as a hub for various stakeholders, the project's primary goal is to create a flexible environment that encourages deliberation and choice.
- Foundation for Circular Values: This initiative aims to establish the essential conditions that support and nurture circular values.

- Strategic Development: By developing a carefully planned strategy within the chosen area, the project sets a blueprint for circular growth.
- Collaborative Refinement: In partnership with area developers and market entities, the project refines its approach to land allocation and methodology, fostering a collaborative pathway to circular goals.
- Concrete Policy Formation: A clear issuance policy, tailored for pilot locations, guides the project through specific conditions that align with its circular aspirations.

The project’s toolkit includes legislative guides, subsidy manuals, and circular issuance conditions—essential resources for integrating circularity into workplaces. Indicators play a crucial role, offering insights into current resource dynamics within these spaces. This analysis serves as a guiding light, informing future decisions, strategies, and policies to ensure they are firmly rooted in circular principles.

5.4.2 The interaction between UM indicators and their applications across various scales

As outlined in section 5.3, UM indicators are utilized for various purposes across the 10 selected Dutch cases. These projects produce diverse outcomes, each tailored to serve specific applications that strengthen UM’s effectiveness. These applications fall into four main categories: policy making, practical implementation, strategic planning, and technological advancement. Specifically, they include 1) targeted policy recommendations, 2) comprehensive legislative guides, 3) collaborative cooperation models, 4) innovative business models, 5) optimized industrial chains, 6) region-specific development plans, 7) spatial planning strategies, 8) technology refinement, and 9) holistic sustainability frameworks.

While these applications may impact various scales, the selected cases highlight the primary scale(s) where each application is most effectively implemented.

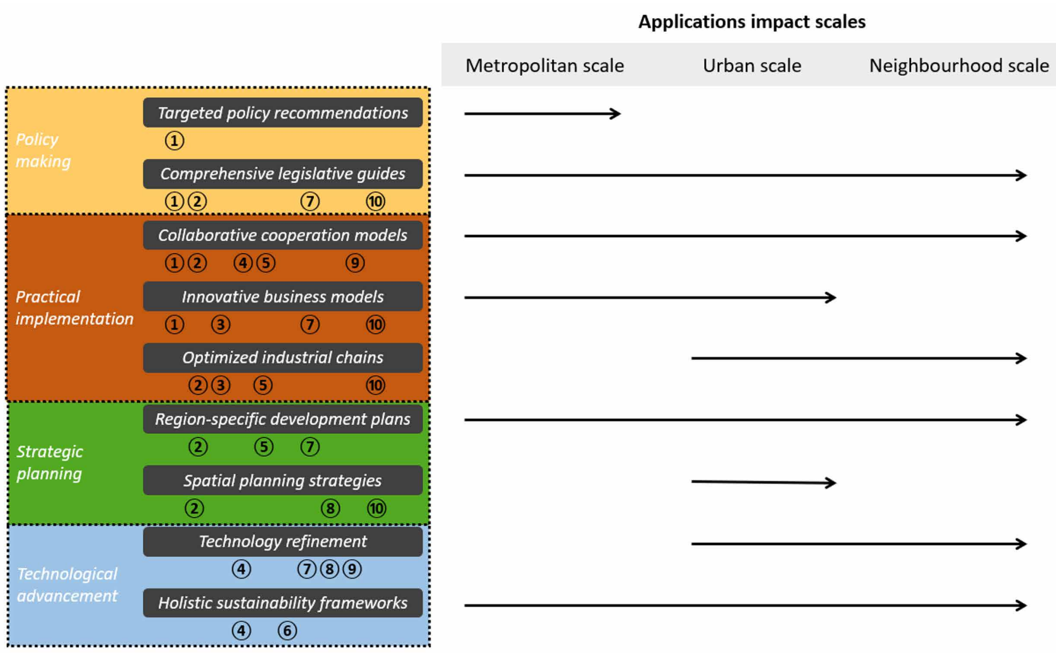

FIG. 5.4 Diverse applications from selected Dutch cases at various scales
(The numbers correspond to projects utilizing these applications, as listed in section 5.4.1. Arrows indicate the scale(s) of focus for each application.)

Policy making

Policy is essential in supporting the successful implementation of UM projects through regulatory measures. This support can be achieved through two main approaches: (i) the development of specific policies and (ii) the provision of legislative guidance to facilitate project execution. Tailored policies are typically established at the metropolitan level by national or regional authorities. For example, the program “A Circular Economy in the Netherlands by 2050” encourages governmental bodies to introduce initiatives that remove regulatory barriers to circular economies (The Ministry of Infrastructure and the Environment & The Ministry of Economic Affairs, 2016). This approach creates a favorable environment for innovation, investment, and progressive initiatives.

At the same time, implementing specific policies effectively requires comprehensive legislative guidance at all levels. The “Circulair Den Haag” project, for example, promotes collaboration between municipalities to advocate for regulatory amendments at the national level and fosters knowledge-sharing across cities and communities to balance costs (Gemeente Den Haag, 2018). Organizations must translate these policies into actionable strategies, enabling legislative implementations across various scales.

Practical implementation

In practical applications, three distinct forms emerge: (i) establishing cooperation models to engage relevant stakeholders, (ii) formulating sustainable business models to ensure a project's long-term viability, and (iii) creating robust industrial chains to facilitate the smooth flow of resources. The execution of UM projects naturally involves collaboration among multiple entities rather than a single organization. As discussed in Chapter 4, effective cooperation models are essential for engaging key stakeholders within projects. These models enhance communication, bridge perceptual gaps, and optimize project efficiency across all scales. For example, in the Horizon 2020 research project REPAiR, researchers, experts, and stakeholders participate in Peri-Urban Living Labs, employing a co-creation approach to address circular economy challenges across metropolitan, urban, and neighborhood scales (Amenta et al., 2019b).

The focus on business models primarily appears within projects at metropolitan and urban scales. The "Circular Rotterdam" project, for instance, explores new employment opportunities in a zero-waste economy by introducing incentive structures, innovative business models, and new economic evaluation methods at these levels (Gladek, Kennedy, et al., 2018). Additionally, close inter-sectoral collaboration and streamlined supply chains contribute to robust industrial chains, minimizing waste within these systems. A notable example is the partnership between AEB Amsterdam and Waternet, which resulted in an industrial cluster establishing a central bio-refinery hub to enhance energy circularity and material reuse (Circle Economy et al., 2015).

Strategic planning

Many projects also propose strategies that outline future development trajectories. These strategies include regional development plans with both short-term and long-term goals or introduce alternative future scenarios through innovative spatial planning. For instance, the "Circular Amsterdam" project presents a series of strategies focused on establishing a circular construction chain and an organic residual streams chain. These strategies are integrated into a roadmap that spans both the near term (1 year) and long term (20+ years) (Circle Economy et al., 2015). The scale of implementation ranges from metropolitan to neighborhood levels.

In contrast, the IABR Rotterdam project lays out four strategies designed to optimize resource flows within Rotterdam. This document not only details stages of development but also specifies potential locations, core technologies, and innovative planning interventions (Gemeente Rotterdam et al., 2014). In this way, these projects provide comprehensive outlooks that consider both temporal and spatial dimensions.

Technological advancements

Technological innovation in the selected projects emerges through two main avenues: the practical implementation and optimization of environmental technologies, and the development of a sustainability assessment framework grounded in material flow analysis. At smaller scales, these projects serve as experimental sites to test the viability of various technologies. For instance, Buiksloterham acts as a testbed for evaluating urine-separating toilet technology and its integration with resource recovery processes (Gladek et al., 2014). Similarly, the Schiphol Area serves as a pilot for the “Circulaire Werklocaties” initiative, focusing on enhancing circularity within office environments (Fleurke et al., 2019).

Additionally, many projects emphasize sustainability and intelligent urban metabolism as key developmental goals, making the evaluation of each project’s sustainability a recurring focus. In the REPAiR project, for example, a comprehensive sustainability framework is developed alongside the project’s objectives. This framework combines multiple methods to identify future strategies and scenarios for assessing life cycle impacts, thereby strengthening the sustainability assessment framework at metropolitan and urban scales (Taelman et al., 2018). Through these efforts, the projects advance both the practical adoption of advanced technologies and the establishment of effective sustainability assessment methodologies.

As illustrated in Figure 5.4, the diverse applications—spanning policy, practice, strategy, and technology—are implemented across various scales, including metropolitan, urban, and neighborhood contexts. These projects navigate multiple scales, highlighting their comprehensive nature. Effective implementation requires engaging a range of stakeholders while also considering the specific complexities of each scale. As a result, UM indicators play different roles tailored to these varying scales, guiding and supporting project execution across diverse contexts.

5.5 Interpretation of the findings

The importance of scale in urban planning cannot be overstated, as it directly influences the practical implementation of planning efforts. This chapter focuses on examining the role of scale within the context of UM indicators and their applications across a range of Dutch UM-related projects. The primary aim is to address SQ3: What are the different applications of UM indicators at various scales?

With an urban planning perspective, this chapter explores UM research scales—metropolitan, urban, and neighborhood—and uses this framework to select 10 representative Dutch projects from both empirical and research domains for detailed analysis. These projects serve as illustrative cases, revealing the diverse applications of UM indicators at different scales. The synthesis in Section 5.4 provides a comprehensive view of the varied roles played by UM indicators, woven into the domains of policy, strategy, practice, and technology. Within this broader perspective, several specific outcomes are highlighted for particular emphasis.

5.5.1 Applications across different scales

In the selected Dutch cases, diverse applications show distinct focal points across metropolitan, urban, and neighborhood scales, centering on the areas of policy, practice, strategy, and technology. These projects span a multi-tiered framework, requiring collaboration among various stakeholders and careful consideration of scale-specific nuances. As Peleman et al. (2019) highlight, a city's vitality is intricately linked to the flows from its hinterlands. This metabolic relationship, marked by synergies, cooperation, as well as power dynamics and conflicts (Tanguy et al., 2020), shapes contemporary urban planning, which often transcends administrative and geographic boundaries.

In analyzing urban flows, cities' increasing interconnectivity with the global market underscores the need to rely on resources beyond local contexts (Conke & Ferreira, 2015; Kaika, 2017). From a UM perspective, planning implementation moves beyond single-scale applications, evolving into a multi-scale endeavor that surpasses administrative limitations. This expansion presents challenges in deploying UM indicators, as the purpose of these indicators varies by scale. Identical indicators must be adapted and interpreted differently across scales. As a result, in cross-scale projects, the effectiveness and flexibility of indicator use at different scales become crucial, ultimately enhancing project implementation.

5.5.2 Promoting multifaceted approaches in project development

The Netherlands is at the forefront of circular economy adoption, leading with numerous scientific research and planning initiatives grounded in UM perspectives, spanning scales from metropolitan to neighborhood. Urban policymakers, managers, researchers, and planners work collaboratively to craft holistic, multi-dimensional strategies aimed at sustainability, with UM principles guiding their efforts. Although the selected projects begin with UM foundations, their applications go beyond mere material flow quantification, reaching into policy making, practical implementation, strategic planning, and technological advancement.

This multi-dimensional approach brings several benefits. First, decision-makers are equipped to harmonize various aspects of urban development, using UM indicator assessments to optimize material and energy flows for greater efficiency and effectiveness. Second, UM indicators provide a shared framework, enhancing cohesion and collaboration across diverse development efforts. This multifaceted approach highlights the transformative potential of UM thinking, propelling urban development toward a sustainable future on multiple fronts.

5.5.3 Diverse stakeholder perspectives on UM indicators

UM indicators serve multiple objectives, including regulation, goal setting, communication, and assessment. Their adaptability to diverse roles is essential, allowing them to meet various needs effectively. Decision-makers with different responsibilities navigate UM indicators based on their specific contexts. For example, an indicator might act as a regulatory tool in one instance, a goal-setting device in another, a communication tool in a third, and an assessment mechanism in yet another. This versatility highlights their importance in addressing a wide array of needs.

Clarity regarding the specific scale and purpose of UM indicators is crucial for effective stakeholder communication, enabling all parties to understand where and how these indicators apply. Additionally, stakeholders from different disciplines benefit from recognizing the symbiotic relationship between UM indicators and future developmental trajectories. This understanding allows them to offer valuable insights from their fields, supporting adjustments and optimizations.

For instance, during policy and regulatory formulation, informed decision-making relies on setting appropriate thresholds and developmental objectives, a process enhanced by thorough UM indicator assessments. The interaction between stakeholders, roles, and UM indicators creates a dynamic framework that integrates expertise to guide sustainable progress.

Shanghai Center, Shanghai (Photo by Yan Song 2024)

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6 Incorporating UM indicators into the strategic urban planning process

Indicator assessment in urban planning allows city planners, managers, and decision-makers to evaluate one or multiple aspects of the planning process (Science for Environment Policy, 2015). As discussed in Section 3.2, various organizations and research groups have proposed UM indicator(s); however, integrating these indicators into a cohesive framework is challenging due to differences in types, functions, and calculation methods. In different phases of strategic urban planning related to material flows, planners require diverse UM indicators to guide sustainable and resilient future planning. Consequently, it is essential to incorporate appropriate UM indicators into the relevant phases of the planning process.

This chapter addresses how to incorporate UM indicators into the strategic urban planning process to answer SQ5: How do the UM indicators contribute to strategic urban planning from the perspective of participant actors, focusing scales, and planning process? It begins by categorizing UM indicators into three types: thematic, performative, and systematic. Section 6.2 reviews four Dutch strategic urban planning cases, examining the UM indicators employed in each. Additional analysis is provided based on the four planning phases proposed by Cities Alliance, as discussed in Section 6.3. In Section 6.4, the application of these UM indicator types is further explored, demonstrating how to position the most suitable UM indicators in different planning phases.

6.1 UM indicator types

Building on Rosales (2011) research on using indicators to create sustainable cities, and incorporating UM characteristics, this study categorizes UM indicators into three types: thematic indicators, performative indicators, and systematic indicators. These three types are interconnected (see Fig 6.1), with each type serving distinct functions within the UM framework.

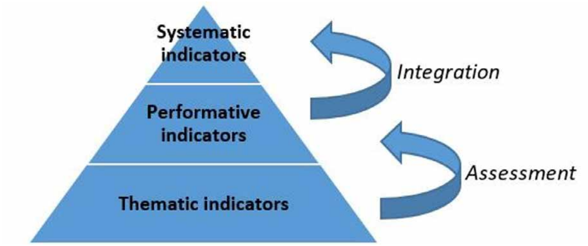

FIG. 6.1 Pyramid of three UM indicator types (by the author)

6.1.1 Thematic indicators

Thematic indicators describe or measure a specific metabolic aspect of a city, directly reflecting the current status of that aspect without necessarily aligning with a particular strategy (Westfall & de Villa, 2001). UM studies frequently use thematic indicators, particularly in material flow analysis or life cycle assessment, where they quantify flows such as water input or greenhouse gas emissions.

Calculating a thematic indicator typically involves minimal processing and unification of original data, without requiring complex formulas. Planners can source this data from statistical bureaus, companies, or local governments, or measure it directly in real life—though data collection can be time-intensive. Since thematic indicators objectively reflect a particular urban characteristic, they don't suggest a specific policy direction or application. Instead, they describe the current state of a specific characteristic and often serve as components within performative or systematic indicators.

Some researchers mistakenly label thematic indicators as mere "pure data" or "statistics" (Gonzalez-Garcia et al., 2018; Mori & Christodoulou, 2012; Newton, 2001). However, thematic indicators differ from raw data. As Newton (2001) points out, data typically appears as unprocessed statistics, often presented in tables and lacking clear interpretation, which can limit its usefulness for decision-makers. In contrast, a thematic indicator offers pre-processed data (though not strongly policy-directed), providing a more actionable result than raw data alone. Additionally, thresholds and targets for thematic indicators are established alongside their development, enhancing their utility in urban assessments.

6.1.2 Performative indicators

A performative indicator links a thematic indicator with policymaking, functioning as a "small model in its own right, implying elements of cause and effect, [...] and policy actions and outcomes" (Newton, 2001). This type of indicator is widely used by planners in their daily work and is commonly viewed as a fundamental function of indicators (Hiremath et al., 2013). With performative indicators, urban themes such as efficiency, resilience, and density can be assessed. By introducing a checklist across these areas, planners can evaluate urban planning performance. Performative indicators capture the degree of UM throughout different phases of the urban planning process by considering the components, processes, and outcomes of planning.

In the UM indicator type hierarchy, performative indicators hold a critical position. They build upon thematic indicators to enable deeper analysis and provide material for a more systematic study of a city's or region's metabolic performance. Unlike thematic indicators, performative indicators require mathematical analysis rather than direct measurement. They are calculated based on a pre-set model or policy expectations and are strongly policy-oriented (Pupphachai & Zuidema, 2017).

Despite focusing on a single urban aspect, performative indicators can vary widely, tailored to different users or policy objectives. Typically presented as single numbers or ratios, they facilitate comparisons over time and space, supporting normative recommendations and policy decisions (Newton, 2001). This comparability enables performance evaluation across cities or regions within a similar context, enhancing their utility in policy formulation.

6.1.3 Systematic indicators

Systematic indicators are instrumental in evaluating the overall performance of a city (Newton, 2001). Sometimes referred to as “indexes,” they occupy the top of the indicator pyramid. These indicators enable the establishment of linkages and causal relationships, allowing for a more comprehensive city evaluation. For UM assessments, several comprehensive systematic indicators can be synthesized to provide a general overview and enable comparisons across cities.

Like performative indicators, systematic indicators have specific calculation methods typically conducted by researchers or organizations. Presented as single numbers or ratios, they contextualize different themes and provide direction for policy-making by setting thresholds to quantify and rank analysis results. Decision-makers can then use these systematic indicator scores to inform their choices.

With a limited set of UM systematic indicators, urban economy, society, and material flows can be evaluated holistically. However, weighting in these calculations is often required, which can be controversial due to its potential subjectivity. Different weights can lead to varying outcomes, making it challenging to determine, for example, whether organic or construction waste should be given higher importance when evaluating urban waste output. To address this, researchers have developed the concept of “emergy,” which synthesizes various substances, circumventing the difficulty of standardizing different materials in cities (Huang & Hsu, 2003; Sun et al., 2016; Ulgiati et al., 1995). Emergy synthesis analysis, therefore, frequently relies on systematic indicators (Zhang et al., 2009a). Similarly, the MuSIASEM approach uses economic units as a surrogate metric to connect diverse substances (Chifari et al., 2017; Lu et al., 2016).

6.1.4 Comparison of three different types of indicators

Developing and implementing a unified framework is challenging without first distinguishing between the types of proposed indicators. Additionally, each type of indicator targets different groups within the urban planning process, with stakeholders selecting indicators based on their specific needs and understanding of the issues at hand. Since various stakeholders are engaged in different phases of urban planning, each phase often requires distinct types of indicators (see Section 6.3). Table 6.1 provides a comparison of these different indicator types.

TABLE 6.1 Comparison of three different UM indicator types

	Thematic Indicators	Performative Indicators	Systematic Indicators
Evaluation object	Specific and focusing on a particular aspect.	Specific and focusing on a particular aspect.	General and aiming to evaluate more content.
Starting point	Characteristics of the analysed aspect.	Performance of the analysed aspect.	Evaluation of the overall aspects.
Calculation	Rather simple statistics.	A particular data calculation method.	A particular data calculation methods and with a weight system to integrate various aspects.
Widely used approaches	Input-output analysis; material flow analysis; life cycle assessment	Input-output analysis; material flow analysis; life cycle assessment	Emergy synthesis analysis; Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)
Data requirements	Only data related to specific issues are needed, which are relatively low.	Need to combine all relevant data for the target, the information has a certain comprehensiveness.	Considerable data requirements based on the assessment target.

6.2 Urban metabolism indicators in current strategic urban planning

As noted in Section 6.2, the implementation of UM indicators varies across urban planning phases. Each phase encounters unique challenges, making it essential to select appropriate UM indicators to support decision-making. In urban planning projects related to UM, many city initiatives use strategic planning to construct a development vision and establish an integrated, long-term framework, as strategic urban planning addresses some of the limitations of conventional planning (Bolger & Doyon, 2019; United Nations Human Settlements Programme, 2009). Accordingly, this research uses strategic urban planning as a focal point to examine the application of different UM indicator types in urban planning within this section.

6.2.1 Why strategic urban planning?

Strategic planning is a process for developing a long-term roadmap with specific goals, objectives, and actions (DiNapoli, 2003). It guides development by enhancing action-orientation and supports a novel form of governance that incorporates the strategic priorities of various stakeholders (Bolger & Doyon, 2019; Healey, 2004; United Nations Human Settlements Programme, 2009). In strategic urban planning, an integrated, long-term vision is structured around a coherent and coordinated approach (Albrechts, 2017b).

Under neoliberal influences, conventional planning approaches like master and land-use planning are often criticized as ineffective, as they focus on maintaining the existing social order rather than challenging it (Albrechts & Balducci, 2013). In contrast, strategic urban planning is more flexible and adaptable (Hauser & Marjanovic, 2010), offering action-oriented solutions and a multi-level governance model that empowers cities or regions to work towards a more circular, sustainable, and resilient future. Many municipalities have adopted strategic planning for this purpose, including Amsterdam, Cape Town, Charlotte, Tel Aviv, and Seoul (Circle Economy et al., 2015; Climate-KIC, 2018; Gladek, Kennedy, et al., 2018).

Strategic planning takes various forms and produces different outputs. Although strategic plans differ in goals and focus areas, the planning process generally follows similar steps. The United Nations Human Settlements Programme outlines four essential questions for strategic urban planning: 1) Where are we now? 2) Where are we going? 3) How do we get there? and 4) How will we implement and track our progress?

Cities Alliance, a global partnership promoting urban development, provides guidance on strategic planning, summarizing the process into four phases: 1) Getting organized and situation analysis; 2) Visioning and setting strategic objectives; 3) Strategy formulation; and 4) Strategy implementation, monitoring, and evaluation (Davidson et al., 2016). These phases align with the UN-Habitat framework and are depicted in Fig 6.2. The strategic planning loop shown in Figure 6.3 covers the key steps at each phase across diverse strategic planning projects.

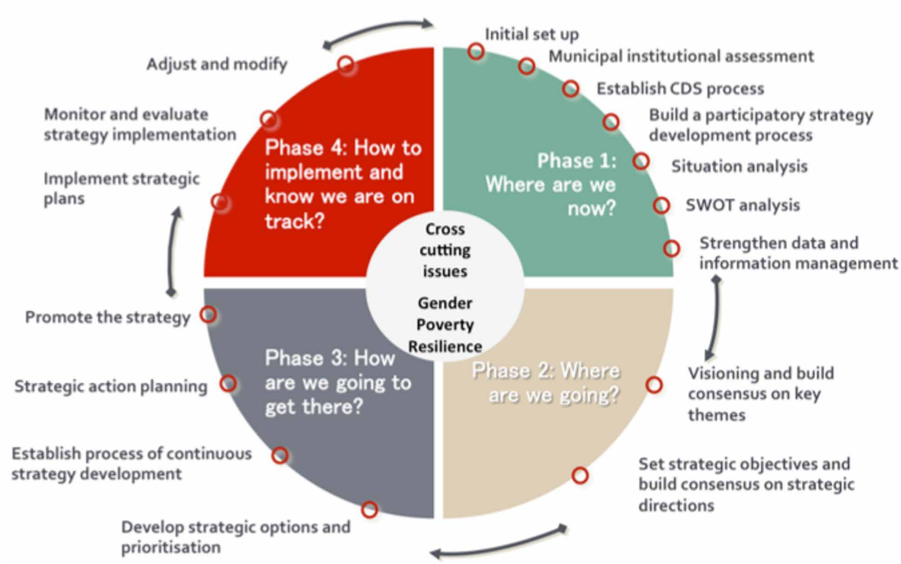

FIG. 6.2 Four phases of urban strategic planning (Davidson et al., 2016)

The following sections of this research focus on four Dutch strategic urban planning cases to illustrate how UM indicators are applied. While some strategic urban planning projects emphasize specific phases, others cover multiple phases (DiNapoli, 2003; Galan & Perrotti, 2019). Although the selected projects encompass various steps, this research emphasizes the primary phase for each project.

6.2.2 Phase 1 case study: Circular Rotterdam

An example of integrating various UM indicators in the first phase is the “Circular Rotterdam” project. As a baseline, this strategic project began by reviewing the current state of Rotterdam’s circular economy, analyzing the city’s material flows to understand its urban metabolism (Gladek, van Exter, et al., 2018). This report examines UM indicators related to food and agriculture, waste management, and energy to identify the best opportunities and assess the most significant losses in value for Rotterdam’s transition to a circular city.

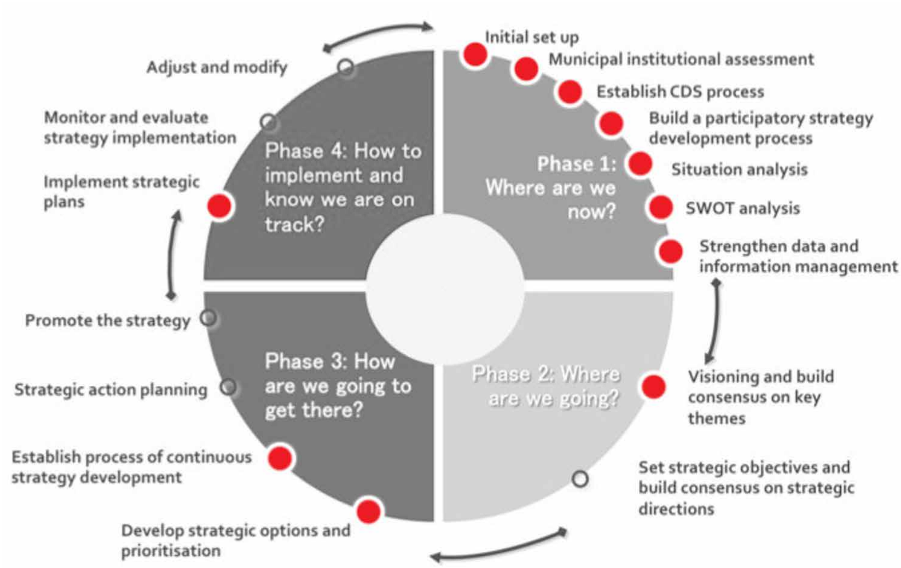

FIG. 6.3 Strategic planning steps in Circular Rotterdam (steps proposed in the document are marked red)

The UM indicators used in this phase were primarily thematic indicators, such as the amount of construction minerals, local crop production, and incineration with energy recovery. Additionally, the impact assessment incorporated performative indicators, including CO_2 intensity, embedded energy use, and social cohesion. With the insights gained from these indicators, the report outlines a vision for Rotterdam’s circular economy and provides strategic planning guidance for future developments.

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6.2.3 Phase 2 case study: Circular Amsterdam

In phase 2, the "Circular Amsterdam" project presents a vision and action agenda for Amsterdam and its metropolitan area by analyzing the opportunities and challenges of creating a circular economy in the city (Circle Economy et al., 2015). This action-oriented document focuses primarily on phase 2 of strategic planning. The report proposes two visions for a circular Amsterdam by optimizing the construction chain and organic residual streams, with UM indicators playing a crucial role in these proposals.

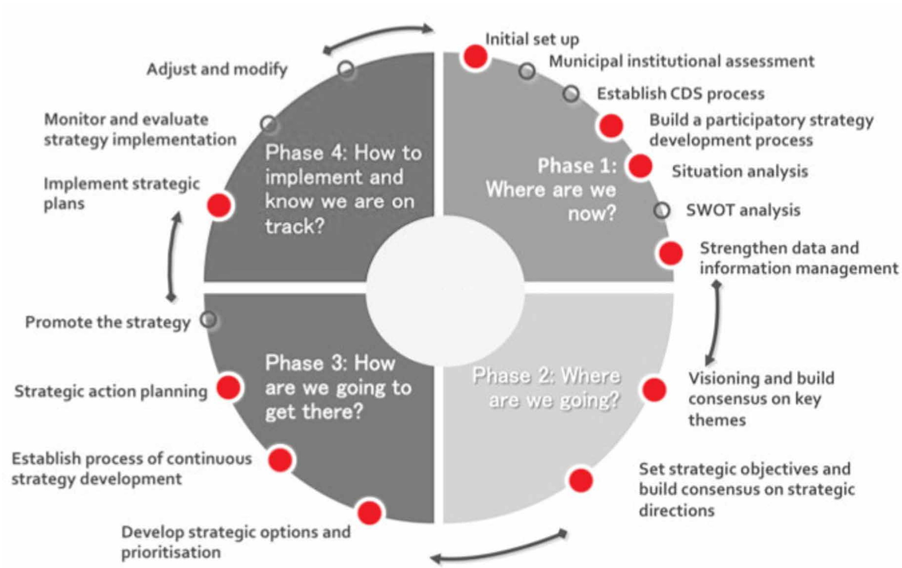


FIG. 6.4 Strategic planning steps in Circular Amsterdam (steps proposed in the document are marked red)

For example, four performative indicators—value creation, job growth, material savings, and CO_2 emissions—are used as assessment criteria to evaluate each strategy throughout the document. By applying these unified assessment criteria, decision-makers can make preliminary predictions of future scenarios, aiding in the adjustment of planning strategies. Additionally, these indicators allow various stakeholders to intuitively understand the impact of different strategies.

6.2.4 Phase 3 case study: Circulair Buiksloterham

"Circulair Buiksloterham" was one of the earliest circular economy-related area development projects in the Netherlands, serving as a pioneering test case for transitioning Amsterdam to a circular city (Metabolic Lab, 2013). Numerous UM indicators are integrated into the interventions, enabling detailed formulation and prioritization of sub-goals. For instance, UM indicators quantify the goals of each action, such as "reducing total projected energy demand by 75%."

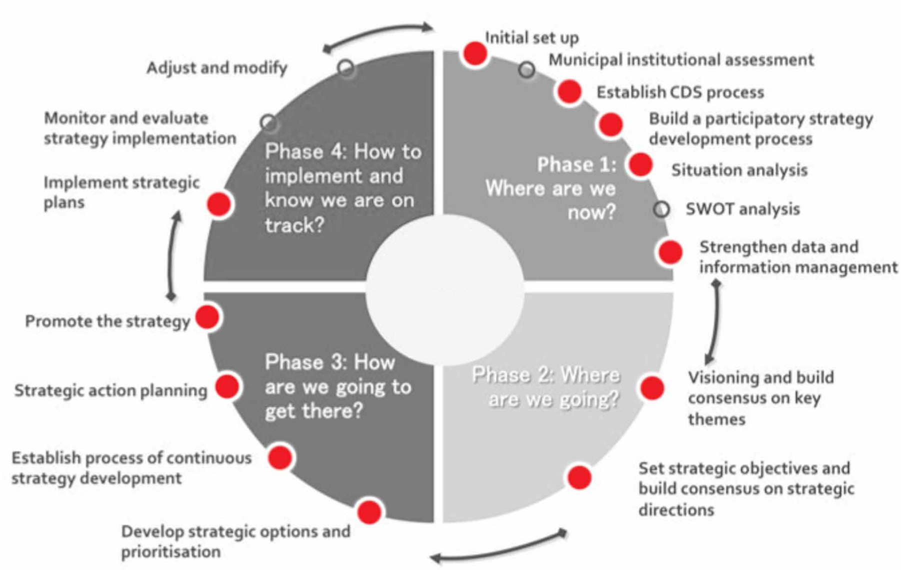


FIG. 6.5 Strategic planning steps in Circulair Buiksloterham (steps proposed in the document are marked red)

In the energy transition plan, current and projected energy demands are analyzed by sector. Based on this analysis, a targeted action plan is proposed to maximize progress in the energy circular transition.

6.2.5 Phase 4 case study: Amsterdam Circular 2020-2025 Strategy

UM indicators play a crucial role in the monitoring process of the "Amsterdam Circular 2020-2025 Strategy" (Circle Economy & City of Amsterdam, 2020). Indicators are incorporated into five key areas of monitoring: input, throughput, waste collection by public authorities, waste treatment processes of regional industries, and social foundation. These indicators evaluate resource flows and their quality in Amsterdam, offering insights into the general welfare of society.

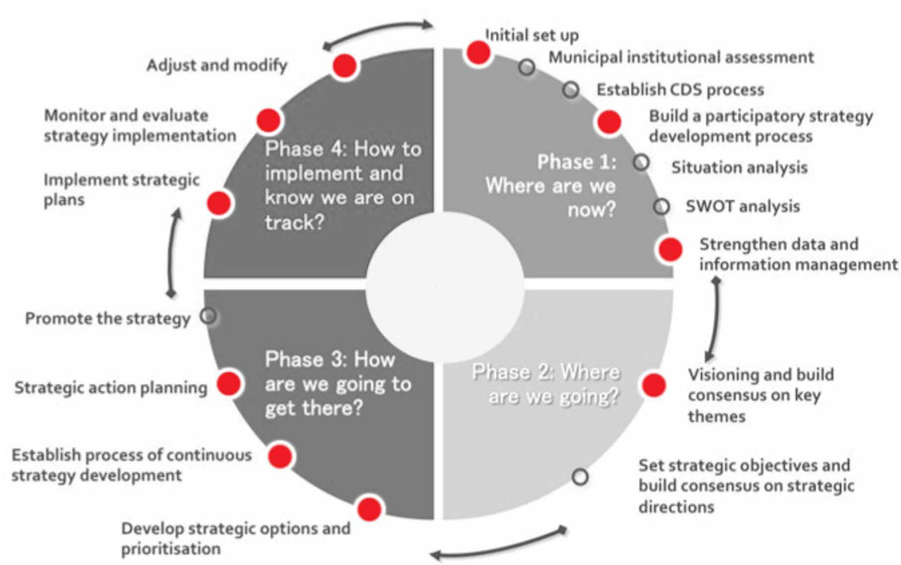


FIG. 6.6 Strategic planning steps in Amsterdam Circular 2020-2025 Strategy (steps proposed in the document are marked red)

The input and throughput analyses employ indicators from life cycle assessments, such as the volume of each flow and CO_2 emissions. Waste collection and treatment processes use UM indicators to assess performance. As an ongoing project, the indicator framework is continuously refined to better support strategy implementation, with improvements developed through workshops, data partnerships, and platforms.

6.3 Enhancing the application of UM indicators in strategic urban planning

The above section provides an overview of UM indicator integration in strategic planning projects from an indicator type perspective. As mentioned, strategic planning across distinct phases can incorporate UM indicators, and selecting appropriate indicators can enhance their role in supporting specific planning phases.

Each of the three types of UM indicators serves unique objectives and functions within strategic urban planning, making it essential to apply them appropriately. While the selected Dutch projects in the previous section have identified several UM indicators for various planning phases, there is still significant potential to expand their use. The following four sections examine the application of UM indicators in each planning phase and explore opportunities for improvement.

6.3.1 Getting organized and situation analysis

In the first phase of strategic planning, the goal is to establish a foundation for strategic proposals (Davidson et al., 2016). Effective strategic urban planning requires a contextual understanding of the prevailing discourse, power dynamics, and material interests (Albrechts, 2017b; Huxley & Yiftachel, 2000). To achieve this, planners gather as much information as possible about the focus area through municipal institutional assessments, situation analyses, or SWOT analyses.

During steps related to describing the status quo, thematic indicators can provide planners with objective data. UM indicators help characterize the current state of energy and resource use in urban development, identifying key areas of focus for strategic planning. Additionally, performative indicators assist in analyzing a city's performance and environmental impact, particularly within a SWOT analysis. Systematic indicators can serve as thresholds, indicating when the planning process is ready to advance to the next phase. Based on insights from selected planning cases, several recommendations can enhance the role of UM indicators in supporting the planning process:

Strengthening municipal institutional assessments with thematic and performative indicators

At this stage, it is important to clarify the institutional and organizational environment where strategic urban planning will take place (Davidson et al., 2016). This involves evaluating government and institutional structures, processes, capacities, and impacts. For example, the "Circular Rotterdam" project highlights the importance of involving multiple stakeholders, such as governments, companies, and civil society, and identifies organizations where actions can be implemented (Gladek, van Exter, et al., 2018). However, there is room for improvement in assessing the structures, processes, and capabilities of these organizations. Beyond identifying relevant actors, it is also essential to evaluate whether they can independently or collaboratively execute the tasks assigned. Thematic and performative indicators can help fill this assessment gap by providing rough estimates of organizational performance capacities, potentially reducing the need for stakeholder adjustments later in the planning process.

Integrating systematic indicators in the strategic planning framework

During the planning establishment phase, thematic and performative indicators serve as evidence to inform more feasible plans. The selected cases do not fully recognize the potential of systematic indicators in this phase, but these indicators could provide insights into future development through early-stage systematic analysis. They allow planners to adjust processes in coordination with the current statutory planning system (Davidson et al., 2016). By offering a broader perspective, systematic indicators reveal potential connections with other thematic plans.

Enhancing status quo assessments with performative indicators

In the situation analysis, planners focus on understanding the current context, setting realistic goals, identifying influential forces, and ensuring sustained planning actions (Albrechts, 2017b). Performative indicators are valuable for analyzing the quality of the present situation. For instance, the "Urban Metabolism Rotterdam" project provides an overview of Rotterdam's material flows using thematic indicators, but lacks information on the quality of these flows (Gemeente Rotterdam et al., 2014). In contrast, "Circular Rotterdam" analyzes not only Rotterdam's material flows in 2015 but also the quality and impacts of these flows, offering stakeholders a more intuitive understanding of the current situation (Gladek, van Exter, et al., 2018).

Increasing the use of systematic indicators in SWOT analysis

A SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) provides comprehensive decision support by linking indicators to specific objectives (Comino & Ferretti, 2016). Based on preceding steps like municipal institutional assessment and situation analysis, a SWOT analysis connects and guides the development of strategies and actions (Hauser & Marjanovic, 2010). In cases like "Circular Rotterdam," the analysis primarily relies on thematic and performative indicators to assess the status quo, but lacks a broader, systematic perspective (Gladek, van Exter, et al., 2018). Incorporating more systematic indicators would enhance the SWOT analysis by offering a more comprehensive view of strengths, weaknesses, opportunities, and threats.

6.3.2 Visioning and strategic objectives

The development of visioning and strategic objectives builds on an analysis of the current situation (Davidson et al., 2016). This phase establishes a vision for the city's utmost potential, setting objectives and directions supported by guidance for decision-making.

This phase consists of two main steps: (i) visioning and (ii) setting strategic objectives. UM indicators, particularly performative and systematic indicators, provide essential support for both steps. Phase 1 analysis offers valuable baseline information for developing performative indicators, which can help planners propose realistic, achievable visions. These indicators also align with each objective, allowing for the measurement of strategic planning performance. Reaching consensus among diverse stakeholders is crucial at this stage (Hauser & Marjanovic, 2010), and indicators facilitate interdisciplinary communication, uniting stakeholders and their interests. From UM indicators used in selected cases, two improvement suggestions for each step are summarized below:

Enhancing visioning with performative and systematic indicators

According to "Visioning as Participatory Planning Tool" by United Nations Human Settlements Programme (2012), visioning is a process that unites people in creating a shared vision for the future. In practice, discussions about future visions are often limited to strategic planners, even though diverse stakeholder participation is ideal. Albrechts (2017b) notes that strategic urban planning choices are typically inspired by broad, long-term visions rather than comprehensive analyses. While Phase 1 provides ample support from thematic indicators, stakeholders require more insight into the impacts of various plans, which performative and systematic indicators could provide. A good example is the “Circular Amsterdam” project, which not only presents projected changes in material flows within key industrial chains but also assesses anticipated impacts on value creation, job growth, material savings, and CO_2 emissions (Circle Economy et al., 2015). This project also envisions the future at a metropolitan scale, offering a systematic overview that stakeholders can interpret and apply to their specific contexts.

Using systematic indicators as facilitators in setting strategic objectives and consensus-building

Strategic objectives are vital in strategic urban planning, as they clarify preferred directions and establish decision criteria for evaluating strategies. Objectives translate questions and concerns into concise statements and, through indicators, define the urban issues to address in subsequent steps (Davidson et al., 2016). Many projects set strategic objectives to establish evaluation criteria for future initiatives (Circle Economy et al., 2015; Metabolic Lab, 2013). However, these objectives often focus on specific themes, such as material flows or policy, lacking a broader systematic analysis. Planners could enhance this step by incorporating systematic indicators to frame objectives and directions within a more comprehensive scope.

6.3.3 Strategy formulation

In phase 3, strategic planning focuses on turning the vision and objectives into concrete programs and projects (Davidson et al., 2016). This phase involves integrating legal, political, and financial frameworks, which requires policy and regulatory support as well as cooperation among various stakeholders.

The strategy formulation process consists of four key steps: (i) developing strategic options and prioritization, (ii) establishing a process for continuous strategy development, (iii) strategic action planning, and (iv) strategy promotion. Quantifiable information reflecting real-world conditions is essential for decision-making in operational strategic planning. In this phase, thematic and performative indicators are the most commonly used. Action planning can be associated with thematic indicators, enabling each link in the industry chain to set periodic goals and formulate plans. This coordinated approach helps each sector work toward the city’s overall goals. Meanwhile, performative indicators support prioritization among strategic options. The following suggestions outline ways to further enhance the use of UM indicators to better assist strategic urban planning:

Integrating systematic thinking in strategy prioritization

As United Nations Human Settlements Programme (2005) explains, strategic urban planning helps to “determine priorities, make wise choices, and allocate scarce resources to achieve agreed-upon objectives.” This step typically requires collaboration among stakeholders within a multi-criteria decision-making process (Davidson et al., 2016). Performative indicators are commonly used in this process, often combined with assessments such as cost-benefit analysis, environmental impact analysis, and social impact analysis (González et al., 2013; Pincetl et al., 2012; Pinho et al., 2013; Soria-Lara et al., 2016; Tjallingii, 1995). These indicators make it easier to identify critical areas or challenging industrial chains (D’Amico et al., 2020; Hoornweg et al., 2012). However, prioritizing with a systematic perspective is essential for a more comprehensive approach. For example, the “Circular Buiksloterham” project prioritizes interventions based on their potential impact, expanding its scope to cover Amsterdam and the entire metropolitan area (Metabolic Lab, 2013). Systematic indicators can guide broader decision-making, preventing a narrow focus on isolated issues.

Using performance indicators to establish continuous strategy development

This step focuses on developing human resources and institutional capacities for ongoing strategic urban planning (Davidson et al., 2016). Based on a municipal institutional analysis, planners refine the strategy development sequence by identifying each institution’s responsibilities and obligations (Hauser & Marjanovic, 2010). Performance indicators can assess each institution’s capabilities and efficiency, facilitating task allocation in strategic planning. In the “Circulair Buiksloterham” project, interviews and informal discussions were conducted to understand stakeholders’ interests and attitudes (Metabolic Lab, 2013). This approach allows continuous strategy development to better align with stakeholders’ needs. Future actions—such as area investment, conservation measures, and strategic infrastructure investments—can also be discussed in this step (Albrechts & Balducci, 2013; Healey, 2004). Performance indicators help ensure that diverse stakeholders communicate effectively.

Enhancing strategy promotion with UM indicators for stakeholder engagement

This step involves engaging various stakeholders with expertise related to the proposed plans (Davidson et al., 2016). It is crucial for building support for further collaboration, securing funding, and establishing effective connections between political authorities and implementation partners (Hillier, 2002; United Nations Human Settlements Programme, 2005). Currently, projects in this step focus on presenting stakeholders with the vision of the strategic plan's future goals and next steps for each institution. UM indicators could enhance communication by providing relevant data. Thematic indicators can illustrate city characteristics related to the strategies, allowing stakeholders to interpret results based on their expertise and interests. Performative indicators, in turn, can demonstrate the impact of strategies, fostering effective interdisciplinary discussions.

6.3.4 Strategy implementation, monitoring and evaluation

The objectives of phase 4 encompass managing the strategy implementation, operation, and monitoring. Strategic planning is recognized as an ongoing process that requires continual adjustments based on ground realities and environmental changes (Davidson et al., 2016; DiNapoli, 2003). In this phase, UM indicators are pivotal in several capacities. Planners utilize thematic indicators to develop legal frameworks and set developmental targets within the system, allowing companies or institutions to make necessary structural and technical adjustments. Performative indicators are crucial for evaluating and monitoring these strategies, enabling planners to modify plans based on real-time performance feedback. Systematic indicators are employed for a more comprehensive evaluation to adjust and re-prioritize coordination across different strategy components. These indicators also facilitate comparisons across different areas, helping to identify and replicate more successful cases.

Application of performance indicators by providing in-time performance assessment

Performative indicators are essential for implementing strategic plans by providing timely performance assessments. As noted by Metzger et al. (2020) and Soliman (2018), success in strategy formulation does not guarantee successful implementation, which is often complicated by dynamic and uncertain realities. Effective communication and coordination across various organizations are critical (Atkinson, 2006), necessitating real-time feedback on the steps being implemented. For example, in “Circular Amsterdam,” performative indicators have played a significant role, especially in the recently established monitoring processes, to assess and adjust strategies continuously (Circle Economy & City of Amsterdam, 2020; Circle Economy et al., 2015; City of Amsterdam et al., 2020).

The implementation of systematic monitoring and evaluation

In cases like “Circular Amsterdam,” performative indicators measure the effectiveness of strategic planning and monitoring (Circle Economy & City of Amsterdam, 2020). These include thematic indicators like input material amount and waste processing material amount, along with performative indicators such as CO2 impact and Environmental Cost Indicator (ECI) (City of Amsterdam et al., 2020). The integration of systematic indicators in monitoring offers a broader support system for planning adjustments and optimization, promoting a comprehensive feedback mechanism (Albrechts, 2017b).

Guidance for feasible adjustments by UM indicator analysis

The strategic planning process must remain relevant and adaptable by regularly re-evaluating actions in line with the actual situation (Davidson et al., 2016). Planners adjust plans based on performance assessments and stakeholder roles (Albrechts & Balducci, 2013)). Establishing thematic indicators ensures the operability of these adjustments, while systematic indicators provide benchmarks for progressing to the next planning phase. Regular assessments by these indicators enable decision-makers to determine the appropriate times for strategic plan adjustments or to commence a new iteration of the strategic plan.

6.3.5 Summary

To summarize, thematic indicators provide a clear and replicable framework for describing urban development processes. These indicators are instrumental in conducting situation analyses, SWOT analyses, and in setting specific, achievable objectives for strategic planning implementation (see Fig 6.7). Consequently, it is most effective for planners to employ thematic indicators in the initial phases of planning.

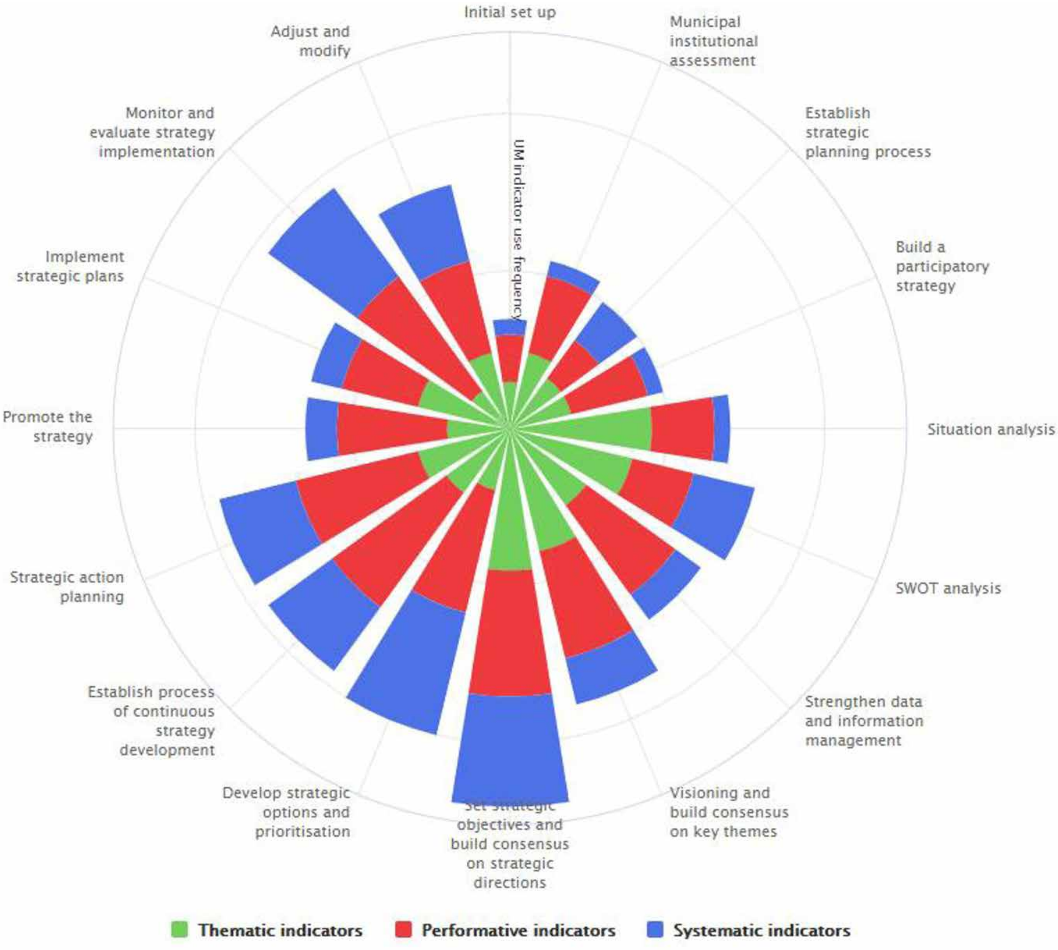


FIG. 6.7 The extent of UM indicators use in strategic urban planning from the perspective of indicator types (Vertical axis: the frequency of UM indicator uses in the selected cases)

Performative indicators, on the other hand, offer a quantitative evaluation of a city's current performance and facilitate the projection of strategic planning visions. Thus, these indicators are particularly valuable during the middle and late stages of the strategic planning process, where they play a crucial role in guiding implementation and adjustments.

Systematic indicators contribute to a more in-depth systematic evaluation, enabling periodic monitoring and comprehensive assessment of the impacts on the urban system. These indicators are typically utilized at the end of each planning phase to thoroughly assess the outcomes and inform the next phase of strategy development.

6.4 Different functions of UM indicators in the strategic urban planning process

Previous sections have analyzed several Dutch cases to explore the distinctions among UM indicator types across various phases of strategic urban planning. These discussions reveal that the differences in UM indicator types are not merely temporal but also functional within the planning process. Each type of indicator is tailored to specific phases and roles in strategic urban planning, illustrating their critical applications and contributions to both the development and implementation of planning strategies.

6.4.1 Thematic indicators in the urban planning process

Thematic indicators have played multiple roles in assisting urban planning. They provide the state-of-art of a city's metabolism and give a quantitative description of its development. In general, the thematic indicators have three functions in the urban planning process: early recognition for the management of a city, identification of crucial focus, and guiding local decision-making.

A. Early recognition for the management of a city

As Hendriks et al. (2000) state, the thematic indicators (especially material flow analysis indicators) can anticipate future environmental problems without relying on environmental stress signals in the longer term. Thus, it can be an ex-ante tool in urban planning with information on the city's in-situ. For instance, Hoornweg et al. (2012) liken the quantitative metabolism of a city to regular human body in the sense that the indicators can provide early warnings and help steer towards better health. Dissimilar environmental intervention and anthropogenic processes will lead to changes in the city's stock and resource flow, which needs these thematic indicators to identify future environmental problems.

B. Identification of crucial focus

Based on the analysis of each city's resource flows, the result can identify which departments or policies will meet the desirable aims best. Metabolic thematic indicators can help decision-makers allocate much-needed resources to the target group according to the analysis result (Chrysoulakis et al., 2013). "Circular Rotterdam" elaborates this identification function, in which Gladek, van Exter, et al. (2018) propose that the municipality can give priorities and accelerate procedures where possible, based on the analysis of materials within Rotterdam. For instance, based on the consumer goods flow analysis through indicators, three priorities in urban planning are identified, which are: reducing consumption of consumer goods, reusing waste at a high value, and selecting the proper infrastructure.

C. Guiding local decision-making

Planning is an evidence-based process, and municipalities should deliver evidence-based analyses to support their decision-making (Nadin, 2007). From this perspective, the UM thematic indicators provide a strong basis for decision-making through a city's quantitative description. Under the objective analysis of the state-of-the-art, the decision-maker can make more reasonable choices. The European FP7 Project BRIDGE (sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism) proposes a decision-support system (DSS) to integrate various components of UM into potential planning interventions (González et al., 2013). The UM thematic indicators play an essential role in computing performance for each planning alternative, such as CO_2 emission and heat (Chrysoulakis et al., 2013).

6.4.2 Performative indicators in the urban planning process

Metabolic performative indicators are applied to assess a city's progress performance or anticipate a new development strategy's performance. They also have various urban planning functions: priority setting in the decision-making process, the reflection of urban planning implementation, and facilitating effective communication (by comparative perspectives) in interdisciplinary discussion.

A. Priority setting in the decision-making process

After the indicators' performance assessment, decision-makers can use the result to examine the potential effectiveness of their policies, not only within the social or economic changes but also concerning the environmental impact (Hendriks et al., 2000). Additionally, Perrotti (2019) also brings up the possibility of indicator-based assessment of urban planning agendas for future strategic visions. Roy et al. (2014) conduct a research project on the spatial allocation of material flow analysis in Kildare County, Ireland. In this project, spatial allocation priorities are proposed based on the integrated scenario assessment through UM performative indicators, such as material intensity, energy efficiency, and waste recovery. Besides, this project advocates for a critical arena for decision-making policies at the local authority level through evidence-based resource planning.

B. Reflection of urban planning implementation

In practice, urban planning strategies will be subject to various changes. The performative indicators can highlight that the current policy is not yet in line with necessary addressing potential of environmental threats for long-term goals. They could advertise and assist the planners in redefining and optimising the urban planning strategies at an earlier stage. For instance, in the Mexico City project conducted by Rosales (2011), the water cycle's performance, energy, material, and waste is analysed in the form of indicators. The degree of resource efficiency and circularity of these resource flows, on the one hand, helps to identify development opportunities; on the other hand, it reflects the current situation of the implementation of planning. In this way, decision-makers can assess the performative indicators' feedback to adjust and optimise the plan in-time to align with actual development needs.

C. Effective communication in interdisciplinary discussion

The indicators provide us with a perspective to view the world, but also, they can serve this function in the interdisciplinary discussion among various stakeholders. Using graphics based on the performative indicators, planners can convey the results to the public and policymakers easier (Hendriks et al., 2000). The analyses provide a relatively objective basis for interdisciplinary discussions among stakeholders from various areas. Therefore, the indicators can support various stakeholders' studies to manage the city's process as communication channels to improve and smoothen information exchanges in the planning process.

6.4.3 Systematic indicators in the urban planning process

Systematic indicators assess the city as a complex system. The result shows the performance of one or two aspects of the city and provides a more systematic assessment. It isn't easy to summarise the operation of a whole city with several indicators or models in the urban system. Still, the systematic indicators become more accurate with the continuous development of technology, and the content covered by the indicators is also improving towards a more systematic assessment. Generally, the functions of systematic indicators are the following points: more effective urban planning and policymaking, comparison among different areas under the same context, and systematic monitoring of the management of a city.

A. More effective urban planning and policymaking

To conduct effective urban planning and policymaking, planners and decision-makers should preferably consider the entire system at multiple scales. Nowadays, cities are intermingled in trans-regional markets, and a better policy can be made only by a comprehensive analysis of the system (Conke & Ferreira, 2015). The UM systematic indicator can describe and analyse the total system under consideration. The policymakers can see the performance of various aspects of the city, not to overemphasise or neglect some elements.

B. Comparison among different areas under the same context

The systematic indicators provide a standard for comparing other cities or regions within the same framework. Stakeholders can analyse various cities' performance, which is convenient for urban managers to identify the best practices for learning. We can easier transfer different cities' experiences in the same context (Dąbrowski et al., 2019). The study by Kennedy et al. (2014) compares UM of several megacities under a systematic framework of metabolic indicators, which provides a standardised platform. As the research stated, with the help of pragmatic UM indicators, it allows for inter-city comparison to improve sustainable development in (mega)cities.

C. Systematic monitoring the management of a city

The systematic indicators propose guidelines to achieve the objectives of development strategies along with a monitoring process. The indicator analysis can characterise the urban system's operation and feedback. For instance, in "Amsterdam Circular Strategy 2020-2025", the monitoring of the transition to a circular economy is assessed by five significant parts: input, throughput, waste collection, waste industry, and social foundation (Circle Economy & City of Amsterdam, 2020). A systematic indicator framework helps monitor these five parts, which provides insight into various topics' performance improvements. It is worth mentioning that the indicator frameworks at the moment are being further developed and the city development process to adapt to the changes brought by the development of technology and society.

6.4.4 Different functions of UM indicators in strategic urban planning

Incorporating UM indicators within the urban planning process helps implement a more measurable and monitorable urban planning approach. Indicators provide a barometer of a city's development and performance from various aspects (Chao et al., 2020), including the metabolic study of a city (Chifari et al., 2017). Fig 6.8 summarises the functions of UM indicators from the perspective of three indicator types. It is not difficult to see that various UM indicators play different roles in strategic urban planning. But it also explains why many UM indicators are hard to combine into a unified framework.

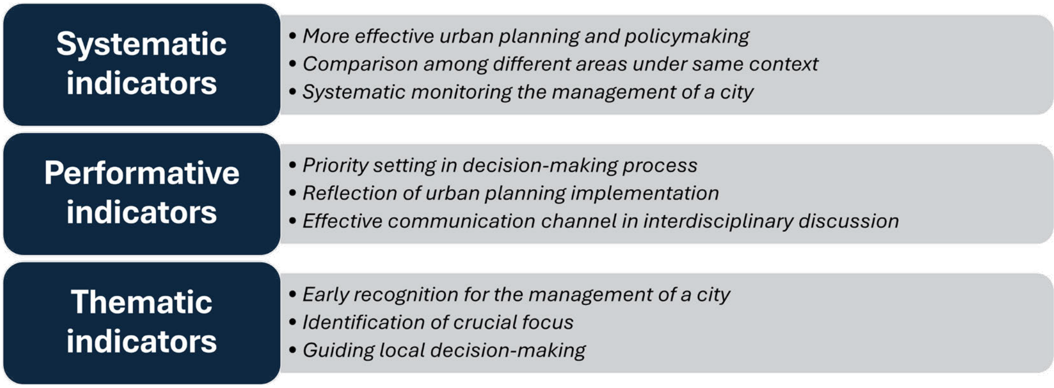


FIG. 6.8 Functions of UM indicators from the perspective of indicator types

6.5 Summary and discussion

This chapter presented three types of UM indicators and their incorporation in strategic planning. The study is based on the urban strategic planning framework by Cities Alliance and explored through several Dutch strategic planning cases. By analysing various UM indicator types and their application in strategic planning phases, this chapter answers how to use UM indicators in multiple phases during the urban strategic planning process. In addition to the outputs of the above study, there are still some aspects worth further discussion.

6.5.1 Optimizing UM indicator application at proper stages

We can see from the selected cases that the vital position of the UM indicators in strategic planning is generally recognised. However, we can still further enhance the use of these indicators to play their roles to a greater extent. Based on the findings in this chapter, this does not mean introducing all indicators excessively in every step of the process but to enhance the use of particular indicators at a specific stage. According to the project's time and capacity constraints, the extent of the use of different UM also needs to be balanced. The use of the various UM indicators presented in Fig 6.7 provides decision support for this process.

The thematic indicators are currently the indicators most used for quantifying the existing or the anticipating situation (Newton, 2001). When planners combine strategic planning with specific actions, they need to further develop these indicators for more practical support of this connection. Decision-makers can use performative indicators when it is necessary to provide decision-making reference, such as the step of municipal institution assessment, visioning and build consensus on critical themes, and establishing process of continuous strategy development (Albrechts, 2017b; Zengerling, 2019). The performative indicator's analysis results can also provide communication channels for people from various disciplines and play a non-negligible role in stakeholder communication. As for the systematic indicators, their use has not been fully appreciated, as we can see from the analysis. However, they can provide more comprehensive and systematic support for the formulation of policies, strategies and actions, which is also a meaningful way to implement system thinking (Maranghi et al., 2020; Savini et al., 2015). Early intervention in systematic considerations can also reduce the possibility of significant changes in the plan in the later stages.

6.5.2 Changes in focus at various stages of the projects

From the projects selected in section 6.2, we can see that not every project passes through every step of strategic urban planning. Most projects focus on a particular stage during the formulation process, which is also the stage where the project hopes to produce effort. However, this requires follow-up planning to ensure the full completion of strategic urban planning.

A good example is the "Circular Amsterdam" project. The document "Circular Amsterdam" proposed Amsterdam's vision and action plan and its metropolitan area in 2015. As stated in Section 6.2.3, the project mainly focuses on early-stage planning and offers the indicators to guide and assist further decision makings (Circle Economy et al., 2015). After five years, the project further advances and publishes the document "Amsterdam Circular 2020-2025 Strategy". This document focuses more on implementing the circularity actions and ensuring that the project can be completed as smooth as planned (Circle Economy & City of Amsterdam, 2020). Subsequently, "Amsterdam Circular Monitor" is proposed by a framework and initial insights to assist the implementation's measure (City of Amsterdam et al., 2020). Although the projects from Section 6.2 does not include all the steps in their plans, it is due to various points of concern selected according to the different stages of the projects. In practice, such disassembly is also necessary. Through this planning series, the strategies are broken down into small tasks that can be achieved and paid attention to in each time period.

6.5.3 Alternative and iterations of the plans along with the development

As aforementioned, strategic planning is not a once-and-for-all process. On the one hand, since the formulation of strategic planning often takes several months or even years, the combination of the current situation in the implementation phase could be lagged to a certain extent (Davidson et al., 2016). On the other hand, it is often different from the theory or expectation into practice (Milenković et al., 2021). Therefore, in the implementation phase of strategic planning, it is often necessary to constantly iterate or reserve alternatives.

Incorporated with UM indicators, such iteration and alternatives would require indicators to develop a series of analysis or more appropriate thresholds. For instance, in the Amsterdam Circular 2020-2025 Strategy, the monitoring is conducted by continuously developing universal indicators cooperated with other public authorities, knowledge institutions and the business community (Circular Economy & City of Amsterdam, 2020; City of Amsterdam et al., 2020). Changes in the planning will lead to changes in indicators, but indicators can also better assist in planning to make faster and more effective adjustments.

6.5.4 Challenges of incorporating UM indicators into strategic planning

From the strategic planning projects that this research studied, there are mainly three challenges in the incorporation process. Firstly, the determination of an efficient strategy relies heavily on a holistic and accurate analysis and understanding of the status quo. Therefore, the indicator selection should conform to the strategy's direction and choose the indicators that can reflect the city's development. Besides quantifying status, it also requires consultation with theme-related stakeholder groups and a more comprehensive public forum to obtain feedback that cannot interpret from the indicator analysis.

Secondly, the prioritisation of each strategy in the planning often needs to be considered. Indicators provide a baseline for strategic priorities. However, the decision-making of the prioritisation of the strategy comes to a dilemma. It will require prioritisation through a multi-criteria decision-making process rather than relying on only one or a few indicators. Simultaneously, the planning team and department should devise objective criteria to rate the strategy goals, followed by a holistic analysis.

Finally, we need to introduce system thinking into strategic planning. In many cases, strategic planning projects only use performance indicators to carry out performance assessment on a particular theme without systematic consideration. Such a lack of systematic thinking will encounter many difficulties in practice, which will lead the whole planning into a dilemma of balancing various purposes and have to adjust the planning goals. Therefore, strategic planning needs to base on a much broader vision. A city's strategic planning sometimes needs to take the metropolitan region as a whole (Farthing, 2004). It requires the flexible use of UM indicators to communicate among various stakeholders and explore UM indicators' adjustment at different planning scales.

Frankfurt (Photo by Yan Song 2025)

TOC

7 Developing an Integrative Framework for Urban Metabolism Indicator Selection in Strategic Urban Planning

In Chapters 4 to 6, three essential aspects of applying urban metabolism (UM) indicators were discussed: participating actors, focusing scales, and planning phases. While each aspect offers a unique perspective on UM, they fall short of capturing the full complexity of their joint functioning. Simply adding them up is not sufficient for a comprehensive understanding of how indicators support strategic urban planning. A more thoughtful selection of indicators across these three aspects will lead to better implementation. Therefore, this chapter presents the final product of this research: an integrative framework for selecting UM indicators in a strategic urban planning process. The findings from Chapters 4 to 6 are combined in this framework.

The framework comprises two instruments: (i) an abstracted timeline of iterations, serving as a guide that directs and concentrates the selection process of UM indicators; and (ii) a graph that integrates aspects of people, scale, and process, delineating the specific objectives the chosen indicators need to achieve, depending on the iteration on the timeline. These instruments empower a planning team to select and optimize UM indicators tailored for a particular strategic urban plan.

Furthermore, it guarantees the selection of indicators by stakeholders and their involvement throughout the planning process, accounting for scalar interrelations and contextual specificities.

The objective of this chapter is to address the sub-research question, *SQ6: How do UM indicators contribute to strategic urban planning?* Drawing on the analyses presented in the preceding chapters, Section 7.1 introduces a process for UM indicator development in strategic urban planning, focusing on the aspects of people, scale, and process. This process is represented by an abstracted timeline of iterations designed to guide and concentrate the selection process. Furthermore, in Section 7.2, specific objectives for selected indicators are delineated, grounded in an understanding of their roles and functions. Given that the analyses in the preceding chapters are confined to the Dutch context, Section 7.3 employs a non-Dutch empirical project, Circular Copenhagen, to examine whether UM indicators are utilized in similar ways in non-Dutch projects within comparable governance contexts.

7.1 An UM indicator development process in strategic urban planning

The timeline of iterations designed to guide and focus the selection process of UM indicators, presented in figure 7.1, which is grounded in the strategic urban planning model proposed by Coombes and Wong (1994) and further elaborated upon by Wong (2006). The entire process encompasses four major actions aimed at achieving the final selection of UM indicators: conceptual consolidation, analytical structuring metabolic model, identification of UM indicators, and monitoring and adjusting UM indicators (refer to Fig 7.1). These four actions need to be repeated and adjusted several rounds to improve the initial draft UM indicators to the final ones.

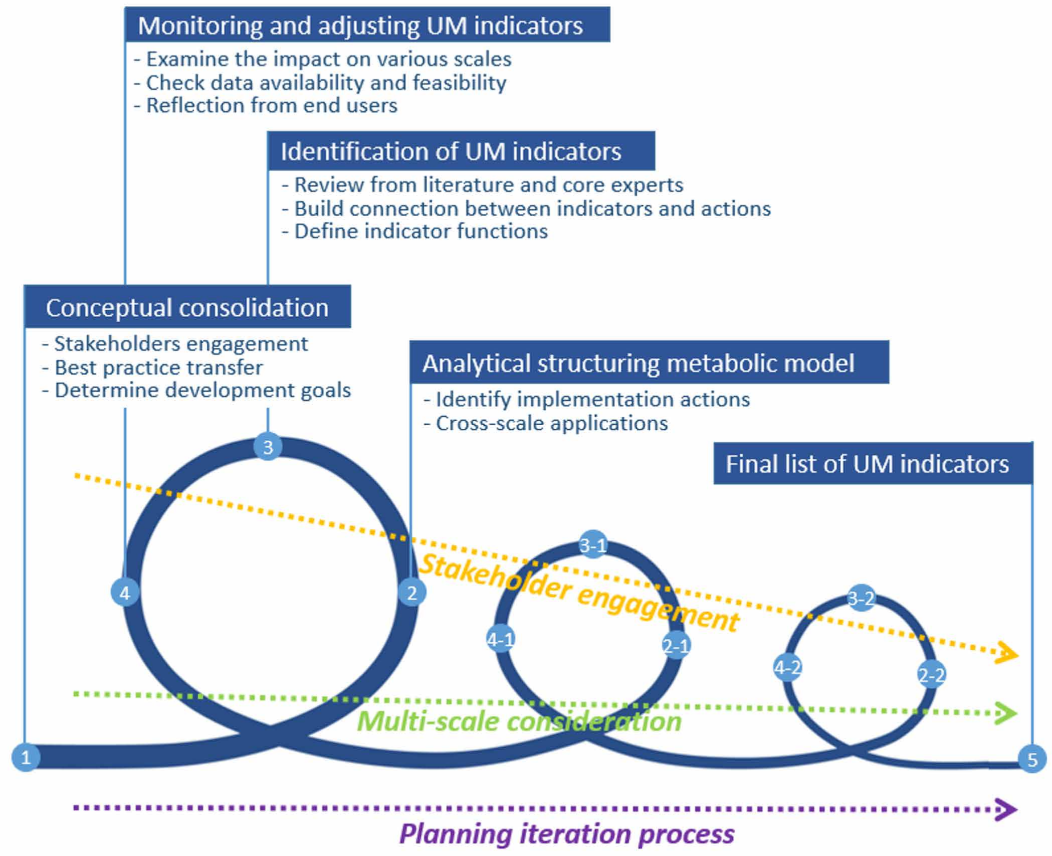


FIG. 7.1 UM indicator development process in strategic urban planning

In this process, stakeholder engagement plays a crucial role in facilitating selection and optimization. Participation spans from goal setting, choice of actions, implementation to evaluation and adjustment, as outlined by Zengerling (2019). In the selection process, it is imperative to enhance cooperative opportunities based on the interaction of participating actors and to balance the diverse demands of stakeholders (Montrucchio, 2012). Moreover, scales are considered regarding the project's implementation specificity. While cities' scales are closely interconnected from the perspective of urban flows, distinguishing or dividing each case's territories poses a challenge. Consequently, strategic urban planning projects often adopt a cross-scale perspective to maximize the effectiveness of indicator application across different scales.

7.1.1 Conceptual consolidation

Clarifying the basic concept is arguably an essential step in developing indicators, as emphasized by Coombes and Wong (1994). The indicators in the final output must gain widespread acceptance as policy-related information. People, scale, and process manifest differently in this step, with a general focus on aspects such as stakeholder engagement, best practice transfer, and the determination of development goals.

A. Stakeholder engagement

This step aims to elucidate the decision maker's issues, identify the focus area, relevant organizations, and anticipate future phases. Consequently, at the project's inception, engagement with diverse stakeholders is imperative. Stakeholder engagement can be executed at four levels: informing, consulting, involving, and co-creating (Azzizabalaga et al., 2018; Bammer, 2019). The selection of a specific method should consider various factors, including stakeholders' availability, capacity, and the extent of their participation in the project. Methods may include living labs, workshops, and interviews. It is important to note that higher levels of engagement entail greater process complexity and necessitate longer coordination times.

Engaging various stakeholders is crucial, including practitioners from local authorities, decision-makers, academics, and representatives of the public. As discussed in Section 4.3.1, the engagement of different groups yields varying effects on UM indicator selection. For instance, for policymakers, engagement can enhance their understanding of the policy operational environment and the subjective value and interest related to their field of work (Othman et al., 2013). Experts' opinions play a decisive role in establishing criteria and determining the significance of local issues, often proving more effective and valuable than literature reviews.

In the selection method, a commonly employed step involves obtaining relevant experts' indicators, which are then scored or classified by engaged stakeholders. This method has been applied in various projects, including the REPAiR project in the Afragola region, aimed at developing sustainability indicators (Mascarenhas et al., 2015; Taelman et al., 2018). The entire process can be managed through Delphi analysis, providing a normative approach to the development of UM indicators (Feil et al., 2015; Novakowski & Wellar, 2009; Shortall et al., 2015). Draft UM indicators may also be proposed from existing indicator sets of similar types of strategic urban planning projects. During this step, new indicators can be suggested, and inappropriate indicators should be eliminated with the consensus of stakeholders.

B. Best practice transfer

Indicators are widely applied in strategic urban planning to assess the current state and measure and monitor the components of strategies (Vázquez et al., 2014). A review of best practices enhances the understanding and anticipates the development direction of the project. For projects related to UM, it is important to compare UM indicators with the local situation, adjusting objectives within the framework of best practices to better align with local characteristics and stakeholder requirements.

In the practical process, transferring best practices presents specific challenges, stemming not only from differences in cities or regions but also from the diversity in knowledge and regulations. These challenges can be addressed through mechanisms such as living labs, expert discussions, and small-scale case studies (Dąbrowski et al., 2019; Hemphill et al., 2016; Shen et al., 2011). Interviews and discussions with policymakers and stakeholders aid in informing strategic urban planning, providing insight into the policy context and practical considerations.

For instance, in the REPAiR project, Amsterdam and Naples, as two pilot cases, initially conducted eco-innovation research and exploration through living labs. Subsequently, several cities applied their living lab experiences and sustainability indicator frameworks to complete the project more efficiently (Dąbrowski et al., 2019). These discussions not only inform the setting and formulation of indicators but also lend an empirical dimension. UM indicators play an important role in ensuring that urban planning and metabolism are integrated and aligned with best practices. However, such best practice transfer relies heavily on the substantial financial and organizational resources deployed, as well as detailed participant observation of the process, which can be a challenge for the project.

C. Determine development goals

Considering the entire process of strategic urban planning, establishing development goals at an early stage is crucial for better guiding strategy formulation. While these goals may be subject to appropriate adjustments during the implementation of strategic urban planning, their initial determination sets the development direction and forms the foundation of the project. In the context of indicators, they are widely utilized as criteria for assessing project performance (Milenković et al., 2021). Consequently, UM indicators associated with strategic goals should also be determined concurrently.

This process underscores the significance of understanding the concept of measurement (Othman et al., 2013). There exists a fundamental need to clarify and delimit the subjects of indicator measurement and how these subjects will be measured through the establishment of development goals. These goals are not merely a manifestation of the vision; they also need to be linked to concrete actions. Therefore, goals, actions, and indicators are three interrelated elements that must be considered simultaneously: goals guide the implementation of actions; the performance of these actions can be measured by indicators; and indicators serve as a tool to assess whether goals are on the right track. Consequently, this process holds great significance in the effective implementation of the project.

7.1.2 Analytical structuring metabolic model

This step aims to establish the structure and requirements that will guide the development and assessment of critical elements within the UM indicator set. It involves compiling a list of issues that need to be addressed through analysis (Othman et al., 2013). Additionally, the rationale for selecting UM indicators needs to be provided at this stage. Generally, the goals proposed in the previous step are translated into practical policy targets and development strategies, to align indicators to policies, making it feasible and practical.

A. Identify implementation actions

The goals are translated into more specific and practical actions in this step, encompassing policy, practice, strategy, and technology. As demonstrated in Section 5.4.3, actions can be categorized into four areas: policy, practice, strategy, and technology, taking the form of 1) specific policy, 2) legislative guide, 3) cooperation model, 4) regional development plan, 5) business model, 6) industrial chain, 7) technology optimization, 8) sustainability framework, and 9) spatial planning strategy. These actions constitute a well-considered plan, addressing aspects that must be resolved to achieve the goals and requiring a specific sequence of implementation (Bolger & Doyon, 2019). Various strategic urban planning projects, based on their goals, concentrate on critical aspects to refine each goal into specific plans.

B. Cross-scale applications

In this step, actions at different scales must be considered. Actions beyond the city-scale should prioritize focus locations, balance synergy among different areas, and establish regulations and legal support. In addition, burden shifting should also be considered. On the city scale, collaboration with enterprises and other organizations needs to be determined. Simultaneously, the definition and optimization of a performance evaluation framework, standards for comparison among different areas, decision-making tools, etc., are essential at this scale. On the neighborhood scale, the implementation of new technologies, specific locations, resolution of actual problems, acquisition of data, and other measures and countermeasures need to be discussed and addressed by various stakeholders. In general, each action must consider its application and impact at different scales.

7.1.3 Identification of UM indicators

Different UM indicators are developed to establish a (rather) comprehensive indicator framework in this process. Identifying these indicators involves considering various factors, such as the reflection of impact on different scales and meeting stakeholders' demands. It requires an exhaustive search for a wide range of potential indicators to address the issues outlined in the analytical framework (Chao et al., 2020; Coombes & Wong, 1994). This process primarily involves desktop and theoretical research. Expert opinions and experiences from literature should be taken into account, and the functions of UM indicators need to be determined simultaneously.

A. Review from literature and core experts

The selection process of appropriate indicators is determined by two main components: a literature review and the input from core experts and the local community. The literature review involves academic literature and an extensive review of related policy practices, necessitating a comprehensive search of statistical sources across relevant fields. This process helps identify information gaps that may impact the compilation of data sets (Othman et al., 2013).

Drawing from the stakeholder studies in Chapter 4, the opinions of core experts and the local community offer valuable recommendations that consider the specific circumstances. The local community provides professional and practical insights, particularly in areas such as local policies, regulations, and procedures. They also bring experience in data acquisition possibilities.

B. Build the connection between indicators and actions

The choice of indicators must consider the specific content of actions. On one hand, the selected UM indicators serve to reflect the performance of each action. On the other hand, they can also function as standards for performance evaluation. For example, when a city aims to achieve a goal of “reducing industrial CO_2 emissions,” it needs to be measured by relevant indicators (such as the annual CO_2 emissions of different industries, etc.). However, for evaluation purposes, it is crucial to establish a threshold in conjunction with the actual situation, avoiding setting standards that are either too high or too low. In short, indicators reflect the performance of actions, and actions, in turn, can shape the direction of development through the indicators.

C. Define indicator functions

As discussed in Section 7.1, UM indicators can serve as communication tools, aid in goal setting, establish a regulation basis, and act as assessment criteria. Therefore, during the process of indicator development, it is crucial to clarify their roles. These roles help determine when indicators are most efficiently employed throughout the planning period. For instance, consideration should be given to whether thematic indicators (describing flows) and/or performative indicators (evaluating performance) are needed. Elements that can reflect the flows and be linked to indicators are defined in this way, facilitating the study of spatial structural applicability.

7.1.4 Monitoring and adjusting UM indicators

The development of indicators is an iterative process and not a one-time endeavor. Particularly in the UM domain, where various departments are involved in the focus area, planners encounter challenges related to scale, data, and stakeholders (DiNapoli, 2003). As discussed in Section 6.3.5, the monitoring and adjustment of indicators through multiple iterations are essential to support the comprehensive implementation of strategic urban planning. Several aspects should be considered to facilitate the monitoring of UM indicators.

A. Examine the impact on various scales

UM is a multi-scale topic, and its indicators exhibit different meanings and characteristics under various scales. Section 5.4.2 explores the relationship between indicators, applications, and scales. It is essential to utilize applications that align with the scale according to UM indicators to achieve the goals of strategic urban planning. Systematic indicators are often applied to comprehensively assess the planning process, as discussed in Section 6.3. Therefore, at this stage, it is crucial to examine the impact of these applications on policy, practice, strategy, and technology and propose suggestions for reference. For instance, at a larger scale (e.g., beyond the city scale), planners can investigate whether the indicators reflect legislative guidance, cooperation models among various areas, regional development plans, etc. Subsequently, adjustments to the connotation of the indicators and corresponding applications can be made.

B. Check data availability and feasibility

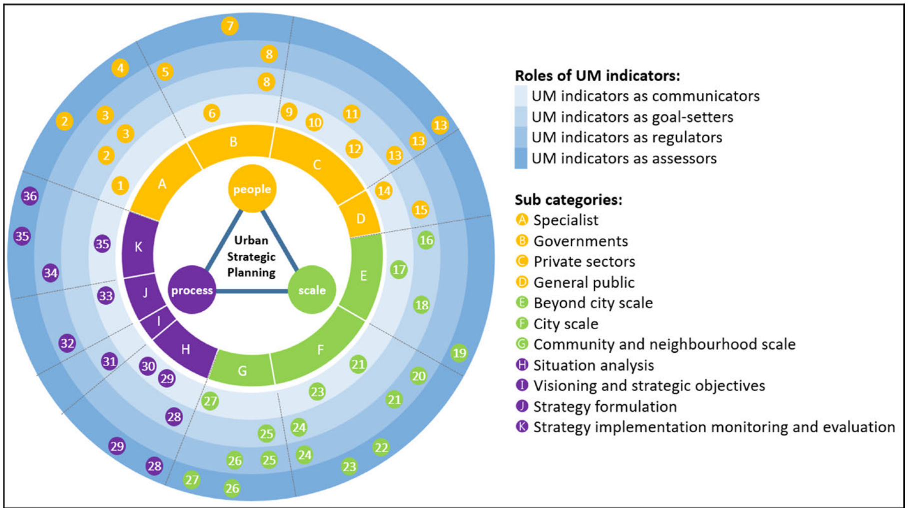
The proposed indicators must not only be methodologically sound and aligned with policy needs but also capable of practical data collection and analysis. In the actual application stage, a common challenge is the availability, accessibility, and feasibility of data (Barles, 2009; Vandevyvere & Stremke, 2012; Voskamp et al., 2018). Consequently, indicators need to undergo testing, adjustment, and revision based on the quality of the available data. As discussed in Section 4.3.3, various countermeasures can be implemented when facing data acquisition challenges, including selecting from reliable sources, cross-scale data collection, and employing high-resolution data based on modeling techniques. Additionally, it is essential to check spatial and structural applicability, and countermeasures such as visualization tools, advanced LCA accounting, and utilizing network models can offer suitable solutions.

C. Reflections from end-users

As discussed in Section 4.1, end-users within the UM framework play a crucial role in addressing urban resource problems and decision-making. Typically, these end-users are stakeholders and decision-makers in strategic urban planning (González et al., 2013). In practical terms, they are directly involved in the implementation of various policies and the outcomes of indicator assessments. Feedback from their perspectives is often a vital source in the iteration of UM indicator development and the monitoring loop of strategic urban planning. In addition, the public and various stakeholders can highlight existing problems and propose feasible solutions based on the current plan's implementation. Therefore, these reflections serve as valuable inputs for adjusting indicators and actions in the subsequent development iteration.

7.2 Selecting UM indicators by understanding their roles and functions

UM indicators are widely utilized in Dutch projects to quantify various city flows and evaluate the performance of strategic urban planning. Establishing refined objectives assists select UM indicators that better align with the specific demands of the strategic urban plan. This research proposes a graph (see Fig 7.2) that integrates aspects of people, scale, and process to specify the objectives that selected indicators need to achieve, depending on the iteration on the timeline. In this graph, the four roles of UM indicators are further refined into detailed objectives related to people, scale, and process. Planners can align these refined UM indicator roles with strategic planning goals, enhancing stakeholder engagement and cross-scale evaluation throughout the planning phases. The outer blue rings represent the general roles of UM indicators, and the dots on the rings symbolize the objectives that UM indicators can achieve under each category. Section 7.2.1 and 7.2.2 will describe this graph in more detail based on the roles and functions of UM indicators.



1	To coordinate the barriers between specialists' knowledge	13	To assist in making practical actions	25	To refine a business model
2	To analyze long-term effects	14	To reflect the response of the public	26	To evaluate the experiment site
3	To define measurable and more innovative goals	15	To make balanced goals	27	To assist knowledge transfer of best practice
4	To present a comprehensive image of the aspects for evaluation	16	To assist in making actions from the upper organization	28	To identify crucial problems
5	Early warning for taking actions	17	To coordinate wide scale to practical scale	29	To make a comparison under the same context
6	Communication channel	18	To prioritize focus area	30	To make effective communication
7	To make a comparison between cities possible	19	To study synergy among different area	31	To assist in setting strategic goals
8	To conduct actions related to impacts	20	To formulate a legislative guide	32	To guide the decision-making process
9	Communication channel	21	To formulate cooperation	33	To regulate different aspects in the same context
10	To help stakeholders understand the plans	22	To quantify material flows	34	To systematically monitor strategic urban planning
11	To highlight problems	23	To assist knowledge transfer of best practice	35	To reflect the implementation of the planning project
12	To counterbalance those who undermine the sustainability	24	To conduct a step-by-step goals and actions	36	To provide early recognition of the city

FIG. 7.2 The roles of UM indicators from the aspects of people, scale, and process

7.2.1 Which roles can UM indicators play in strategic urban planning?

Generally, UM indicators can contribute to strategic urban planning by regulating policies, setting development goals, facilitating stakeholder communication, and assessing the plan's performance. Accordingly, they can play in strategic urban planning:

As communicators

As highlighted in Chapter 4, improving effective communication among various stakeholders is a pressing challenge. In this context, UM indicators can serve as communicators to foster cooperation. These indicators are designed to assess the performance of either a business model or an industrial chain. For example, in the Buiksloterham project, the development process is conducted online concurrently with project assessments, enhancing traction and transparency for the public (Gladek et al., 2014).

Different stakeholders can connect to leverage their knowledge by interpreting indicators and understanding the impact of their actions. UM indicators play a crucial role in quantifying flows within the production chain, facilitating actions such as adding, cutting, optimizing, closing, or integrating different flows to enhance circularity. This approach makes it easier for stakeholders to align their specialties within the industrial chain. Given that each stakeholder has a unique understanding of a project based on their expertise, indicators contribute to making communication more objective and effective.

As goal-setters

UM indicators can be considered as goal-setters in development strategies, offering staged and quantifiable targets for both spatial characteristics and planning timelines. For example, in the Amsterdam Circular 2020-2025 Strategy, actions are categorized into long-, medium-, and short-term with the assistance of indicators (Circle Economy & City of Amsterdam, 2020). This approach enables the creation of a roadmap outlining different actions to be taken at various stages of the project.

Moreover, based on these gradual goals, UM indicators serve as early warning systems for potential problems or issues. UM's capacity to quantify flows and link material flows to spatial patterns allows for the formulation of suitable strategies for different areas. Consequently, UM indicators provide quantifiable goals for each phase of project development, assisting different areas in creating development plans that align more closely with their unique characteristics.

As regulators

UM indicators, as regulators, are crucial from the perspective of policymaking. They play a significant role in improving implementation by assisting in the establishment of specific policies and legislative guides. In cases where existing policies, based on laws and regulations, may lead to unforeseen consequences due to changes in market conditions, UM indicators serve as criteria to regulate the threshold of actions.

For example, in "A Circular Economy in the Netherlands by 2050," UM indicators are applied to gradually scale up standards towards circularity. Additionally, an assessment framework based on these indicators, especially benchmarking indicators, is proposed to select priority value chains (The Ministry of Infrastructure and the Environment & The Ministry of Economic Affairs, 2016). Furthermore, assessing pilot cases using UM indicators facilitates the establishment of sound thresholds for new policymaking. Drawing from existing successful experiences, regulations and/or adjustments to laws can be made to form the basis for incentives.

As assessors

A substantial sustainability framework has been implemented in various cases (Chao et al., 2020; Mega & Pedersen, 1998). UM indicators can serve as assessors to evaluate the performance of these frameworks. For example, in Circular Rotterdam, interventions in the material flows of Rotterdam are analyzed using indicators. This analysis provides decision-makers with a more objective evaluation of envisioned interventions, assisting in prioritizing or refining recommendations (Gladek, van Exter, et al., 2018). Using common indicators, comparative studies can determine best practices, offering valuable insights for future projects.

The indicators provide a fair measure for achieving goals, allowing for comparisons between different areas. However, UM indicators need a suitable method for assessing results, necessitating optimization of the assessment process itself. Projects like Urban Pulse have enhanced methods for UM indicators to improve their performance in assessment processes (Voskamp et al., 2017).

7.2.2 The detailed functions of UM indicators

1 Involvement of various participating actors

With the resurgence of strategic urban planning and an increasing collaboration with industrial and civil society partners, urban planners must engage with various groups to drive the planning process forward (Özdemir & Tasan-Kok, 2017; Sehested, 2009). To ensure accurate and effective knowledge transfer in dialogues with distinct groups, diverse communication approaches are essential (Dąbrowski et al., 2019).

Strategic urban planning necessitates the involvement of a wide range of actors in the process. This includes not only public governmental partners but also sector departments (umbrella organizations), research organizations, trade unions, associations of entrepreneurs, civic associations, consumer organizations, and various private companies (Albrechts, 2006). Enhancing cooperative opportunities based on the interaction of participating actors and balancing the diverse demands of stakeholders are vital aspects of this process (Montrucchio, 2012). Indicators can be applied to facilitate the process, especially in strategic urban planning related to physical substances and conditions (Gao et al., 2017).

This section focuses on four perspectives of participating actor groups that urban planners typically need to integrate into strategic urban planning: specialists, governments, private sectors, and the general public.

Planners and specialists

Urban planners and specialists must acknowledge their different interests and perspectives. Generally, specialists focus on data, resources, and obstacles, while urban planners are more concerned with the future and possibilities (Dick et al., 2018). Specialists often interpret urban development through their professional knowledge, and planners must integrate these diverse interpretations to ensure that planning goals align with effective communication (Tjallingii, 1996). In this process, indicators play a crucial role as a means of communication and expression.

Specialists’ knowledge has its limits, and there is a disciplinary bias in the planning process (Perrotti, 2019). Combining different indicators or indicator groups can present a more accurate and objective situation, mitigating bias. By interpreting the same indicators through different specialists, urban planners can gain a more comprehensive understanding of specific domains. With the knowledge of planners, planning and professional knowledge can be transparently and transdisciplinarily combined, bridging the gaps between specialists' knowledge.

In strategic urban planning, an urban planner is not only a specialist solving immediate problems but also needs to consider the long-term effects of solutions and ensure the implementation steps over time (Albrechts, 2006; Nordic Centre for Spatial Development, 2015). It is impractical to simply shut down a factory or develop a new industry solely based on a strategic plan. A comprehensive analysis of the action's impact, alternatives, and the timetable for realization is necessary. Interpreting UM indicators with multiple specialists allows planners to define more innovative and measurable goals in development strategies and plans.

Planners and governments

In general, indicators serve as benchmarks, offering early warnings to inform alternative considerations. They enable both qualitative and quantitative measurements, guiding decisions by providing an evidence base (Nordic Centre for Spatial Development, 2015). Development trends can be more easily communicated among governments and other groups (Newton, 2001), creating accessible connections and facilitating communication through shared metrics.

From a knowledge transfer perspective, urban planners can assist governments in identifying barriers hindering the transferability of innovative solutions between different regions using indicators (Dąbrowski et al., 2019). Indicators enhance cities' performance comparability, enabling regions and cities with similar issues to compare achievements and share solutions (Nordic Centre for Spatial Development, 2015). By systematically comparing key UM indicators across projects, urban planners can analyze best practice cases and propose strategic development recommendations to governments more in line with local characteristics.

Indicators also play a crucial role in identifying impacts and challenges associated with policymaking. They represent degrees of causal relationships, guiding decision-making in benchmark setup (Pineo et al., 2020). Urban planners can use indicators to analyze the status quo, advising policymakers on the most challenging issues.

Planners and private sectors

The circular economy is considered a promising concept for society and industry (Maranghi et al., 2020). Many UM-related strategic plans include a long-term vision, incorporating a circular economy-based strategy in the city's industry plans. Therefore, in UM-related plans, planners need to coordinate with stakeholders from relevant private sectors. Indicators play a crucial role in communication and tuning of goals, creating synergies.

Different private sectors interpret strategic plan goals differently and focus on decisions and implementations related to their industries. Private sectors influence the urban system through consumption and production (Kalmykova et al., 2016). Involving stakeholders and providing tangible information through UM indicators is vital to help them understand and contribute to the process. Indicators can highlight problems and areas needing improvement, counterbalancing efforts undermining sustainable development. They can be used to re-interpret the strategic plan, making it more accessible for stakeholders to understand and promote (Gann et al., 2003).

Stakeholders, with practical experience in issue-specific tasks in industries such as waste or energy, can provide valuable feedback on the impact of planning results. Their feedback helps planners formulate and optimize strategic urban planning, linking indicators with plan actions. Indicators provide an informed and methodical way to present both sound and undesirable practices (Newton, 2001). Planners can correlate indicators to plan appropriate actions and make corresponding adjustments.

Planners and the general public

In recent years, an increasing number of citizens actively participate in bottom-up urban planning. Conversely, many strategic plans now consider public participation an essential element of the planning process. Public participation is advocated by numerous projects to promote sustainable development (Gatta et al., 2017; Yung & Chan, 2012). Özdemir and Tasan-Kok (2017) suggest that urban planners should provide the public with tools to express their interests, and using indicators can better reflect public feedback. By analyzing (development) plans with indicators, urban planners can adjust and visualize details more easily according to public input.

Another challenge in public participation is ensuring that the general public understands the message well enough to act accordingly. Urban planners must find a balance between providing too much and too little information and complexity (Soria-Lara et al., 2016). In this regard, indicator analysis can display expected results and impacts, simplify complex problems and visually illustrating the planning's impact for the public. This helps the public understand the planning content and propose corresponding suggestions for change.

To obtain representative and reliable information, citizens can contribute valuable local data. Urban planners can make more adaptive decisions to optimize strategic urban planning toward sustainability and resilience based on these practical local inputs during the decision-making process (Davidson et al., 2016; Talen, 2011). In the communication between planners and the public, appropriate entry points should stimulate discussion. Indicator analysis for proposed plans allows the public to intuitively compare similarities and differences and choose a relatively better option. Indicators can also show the expected impact and further obtain the public's feedback on the cases.

Integrating various actor groups

In strategic urban planning, it is common to involve various groups in the decision-making process, including specialists, governments, private sectors, and the general public. Participation occurs throughout the entire process, from goal-setting and choosing actions to implementation, evaluation, and adjustment (Zengerling, 2019). The involvement of diverse actors enhances the comprehensiveness and operability of plans, but it also introduces complexity and, at times, incompatibility in the process. However, the application of indicators can help establish connections among different groups, integrating diverse opinions within the same context. Indicators play a crucial role in defining goals and ensuring that plans are implemented in a controlled manner, aligning with the specialization of various participating actors.

2 Application at multiple scales

Scale is a crucial aspect to consider in strategic urban planning, and UM is a concept that involves multi-scale synthesis. Research and planning projects often explore possibilities at various scales, and UM indicators serve different functions at different scales. As noted by O'Sullivan et al. (2014), the city and region may be more appropriate scales to address environmental and ecological challenges, while other scales are relevant during the project's operational phase. Strategic urban planning is not limited to a specific scale or group of stakeholders. Therefore, it is essential to understand the functional use of indicators at different scales to efficiently develop indicators in a multi-scale context.

Beyond city scale

In general, UM studies analyze impacts on a larger scale beyond cities or regions. As Bai (2007) stated, larger scales can better describe changes in the urban structure, land use transition, consumption patterns, and impacts on the hinterland. Some driving forces operate at a larger scale, such as the greenhouse gas composition of the atmosphere and financial systems (Wilbanks & Kates, 1999). Therefore, UM indicators have two major functions above the city scale. On the one hand, the indicators can inform specific policies that serve the strategies from the previous stage according to the plan's impact. On the other hand, the indicators can assist in coordinating from the national to local level with the implementation of plans. The indicators can be used for cross-scale communication. The results expressed in the indicators are used to facilitate policymakers in participating in planning projects.

On this scale, indicators can quantify the resource flows in the region and guide urban planners in prioritizing focus areas based on the assessment results. From a larger perspective, it helps make the problem more concrete, translating strategic urban planning goals into achievable levels. Through the indicators, planners can study the interactions among different areas and their hinterlands. Resource flows between cities are no longer limited to a single area, so we can systematically evaluate resource and energy performance (or overall environmental performance). By studying and analyzing on this larger scale, UM in environmental assessment can help avoid problem shifting.

City scale

The city scale is commonly the focus of strategic urban planning. This is a typical entry point for planners and industrial ecologists when addressing various problems related to UM. On this scale, UM indicators can support legislative guidance for planning policies and assist in making specific planning strategies. Additionally, UM indicators can help coordinate stakeholders, fine-tune their cooperation or business models, and improve the sustainability framework from a systems perspective. Many measures and concerns converge at the city scale. One reason is that, generally speaking, enough data are available at this scale, largely determining the effectiveness and integrality of the application of UM indicators (Athanassiadis et al., 2017).

At the city scale, UM indicators can assist strategic urban planning by quantifying resource flows, helping better characterize the physical state of the city. Cities typically have better spatial organization, which often aids in the availability and accessibility of data. Hence, the performance evaluation of resources can be more easily conducted, providing criteria for comparison among different cities. Best practices from different cities can also be shared, supporting peer-to-peer knowledge transfer.

Indicators can be used to set up a process for evaluation during decision-making (and potentially after realization). Actions can be implemented step by step through the evaluative guidance of UM indicators. In this way, they provide both long-term planning benchmarks and evaluation criteria. For industries, the indicators can align industry development with planning goals and requirements.

Community and neighborhood scale

Local governments can effectively drive transitions toward circularity and sustainability in urban planning (Ghisellini et al., 2016). At this scale, UM indicators support the refinement of various business and industrial models, as well as assist in optimizing technological solutions. Some pilot cases can be implemented as experimental sites to test the practicability of proposed technologies (Metabolic & CleanTech Delta, 2019; Metabolic Lab, 2013). UM indicators can be applied to assess their performance in practice. Through indicators, “best practices” for future projects can be identified by analyzing the performance of new technology. Changes in resources and energy can be detected in these pilot cases to help adjust the specific content of strategic urban planning. The indicators offer a fair measure for success, enabling the comparison of different pilot cases.

Strategic urban planning not only requires the participation of various stakeholders but also needs to consider the specificity of the project’s implementation at different scales. Although this study divides the scale into three parts, in practice, cities’ scales are tightly connected from the perspective of urban flows. Therefore, it is challenging to distinguish or divide each case’s territories. Consequently, strategic urban planning projects tend to use a cross-scale perspective to maximize the effectiveness of indicator application at different scales.

3 Different phase in strategic urban planning process

As discussed in Chapter 6, UM indicators serve distinct functions during various phases of the strategic urban planning process. These indicators play a crucial role in aiding planners and decision-makers by facilitating an understanding of the existing situation, establishing development goals, formulating the plan’s implementation, and evaluating and revising the project. According to Davidson et al. (2016), strategic urban planning unfolds in four key phases: situation analysis, envisioning and setting strategic objectives, strategy formulation, and strategy implementation, monitoring, and evaluation. Subsequent sections of this study will delve into the specific functional applications of UM indicators within each of these delineated phases.

Situation analysis

At the onset of urban planning, planners must possess a comprehensive understanding of the prevailing characteristics within the focus area. This entails a thorough analysis of the area's existing challenges and a precise depiction of its status. UM indicators serve as invaluable tools in presenting the status quo both quantitatively and qualitatively, allowing for a nuanced characterization of the prevailing situation, particularly in relation to targeted issues (Chifari et al., 2017; Kalmykova et al., 2016). The landscape of the area can be delineated by different resource flows, and the intricate relationship between cities and their hinterlands can be scrutinized through indicator analysis (Bahers et al., 2020). Consequently, indicators are essential in identifying crucial focal points within the area by facilitating comparisons across various flows.

For effective peer-to-peer learning between different territories, it is imperative to align their contextual settings. UM indicators prove instrumental in enabling meaningful and equitable comparisons. As highlighted by Newman (1999), UM has the potential to offer practical guidance for sustainability by facilitating comparisons between the target area and a reference area from multiple perspectives. Such comparisons can extend beyond cities and include benchmarking against national or EU-level targets, ensuring alignment with established criteria (Paiho et al., 2020).

In addressing the persistent science-practice communication gap, as evidenced in stakeholder analysis in Chapter 4, UM indicators play a crucial role. This communication gap often stems from conflicting goals and incomplete perspectives on problems among different stakeholders. Therefore, adopting quantifiable or graphical methods becomes essential for translating goals and issues effectively. UM indicators support this interpretation process by quantifying goals, fostering effective communication, and facilitating interdisciplinary discussions, wherein stakeholders can share their insights and experiences targeting the same set of indicators.

Envisioning and setting strategic objectives

During the envisioning process, a collaborative effort involving various stakeholders is undertaken to cultivate a shared vision for the area, accompanied by a set of strategic objectives (Davidson et al., 2016; United Nations Human Settlements Programme, 2009). A critical prerequisite for this process is the availability of robust baseline information to ensure its successful and efficient execution. As discussed in section 6.3.3, stakeholders engage in discussions regarding the challenges faced by the focus area, drawing insights from the analysis facilitated by UM indicators.

Through these deliberations, consensus emerges, allowing stakeholders to compare their envisioned future with the current status quo. UM indicators are important in guiding strategic decisions and prioritization based on the insights of specialists. This, in turn, steers the development of objectives in a direction that is both visionary and feasible.

Strategic formulation

In the strategy formulation phase, planners face the task of breaking down strategic objectives into distinct projects and actions, operationalizing the visions and goals established in the previous phase (Davidson et al., 2016). UM indicators continue to be instrumental during this stage. The outcomes of indicator assessments serve as a guiding foundation, harmonizing the interests of diverse stakeholders and informing decision-making processes. Using indicators as criteria, the legal and political framework can be delineated to govern projects effectively. UM indicators act as connectors, ensuring the coherence of strategies and objectives across different projects and actions. Additionally, these indicators serve as assessment criteria, aiding in the prioritization of various projects and actions.

Stakeholder engagement is crucial during this process, where diverse groups contribute their perspectives to propose feasible urban strategy implementation plans and alternative options (Taleghani et al., 2020). Public feedback on strategic urban planning is also sought during this period. As in previous phases, indicators prove invaluable in facilitating communication and discussions among groups. By quantifying demands and their impact on the area, indicators inform decision-making and guide the exploration of alternative solutions. This inclusive approach bridges long-term perspectives with short-term actions, fostering a holistic urban strategy.

Strategy implementation, monitoring and evaluation

Numerous research projects have underscored the pivotal role of indicators in monitoring the implementation process of urban plans (Circle Economy & City of Amsterdam, 2020; Nordic Centre for Spatial Development, 2015; Sustainable Cities International, 2012). UM indicators, reflecting changes in environmental mediums and anthropogenic processes, serve as crucial tools. Real-time assessments through indicators allow for the early detection of potential future issues, enabling planners to make timely optimization and adjustment plans. Decision-makers, by recognizing patterns in the resource inflow and outflow of the focus area, can align policies with overarching strategies.

Alberti (1996) highlighted the function of indicators in systematically monitoring urban environmental changes. Simplifying large amounts of information into indicators enhances stakeholders' ability to comprehend complex systems, connecting simple measures to intricate environmental phenomena. Projects incorporating real-time flow monitoring, as seen in Maranghi et al. (2020), demonstrate the digitization potential of monitoring aided by indicators. This digitization facilitates planners and policymakers in optimizing current strategic directions or selecting more suitable alternatives in response to ongoing developments.

In strategic urban planning implementation, indicators play a crucial role in providing performance reviews through the establishment of targets or thresholds. UM indicators offer timely feedback on plan performance and its impact at a larger scale. As discussed in section 6.3.5, indicators enable swift adjustments to the plan's implementation, ensuring alignment with reality and the success of proposed urban strategies. Furthermore, indicators foster performance comparability among diverse regions and cities facing similar challenges, promoting the exchange of solutions and knowledge transfer (Dąbrowski et al., 2019; Nordic Centre for Spatial Development, 2015).

7.3 Testing the integrative framework as an analytical tool: Circular Copenhagen

To study the validity of UM indicators from a broader perspective, an additional non-Dutch project (Circular Copenhagen) is selected in this section. The proposed roles of UM indicators, i.e., communicators, goal-setters, regulators, and assessors (cf. section 7.2), are examined in this case, and the potential functions of UM indicators are discussed.

The Danish Ministry of Environment and Food, in collaboration with the Danish Ministry of Industry, Business and Financial Affairs, has launched a Circular Economy (CE) strategy based on recommendations from an Advisory Board for Circular Economy (Copenhagen Municipality, 2019). Mirroring this initiative, the Netherlands and Denmark exhibit similarities not only in governance structures and the current state of UM but also in their proposed strategies for CE. Both countries emphasize strengthening enterprises as drivers for circular transition, supporting CE through data and digitalization, and extracting more value from buildings and biomass.

This shared strategic direction has manifested in various city and regional projects aligned with the Danish government's approach. Notable examples include Circular Copenhagen and CE in Odense, reflecting the influence of the Danish strategy on practical implementations at the local level (Copenhagen Municipality, 2019; Lanau & Liu, 2020), that makes it a good validation case to test the integrative framework in this chapter.

7.3.1 Introduction of Circular Copenhagen

Circular Copenhagen is a city development plan with politically adopted resource and waste management objectives towards a circular economy for the period 2019-2024 (Copenhagen Municipality, 2019). To support this initiative, the city of Copenhagen runs an innovation platform with the aim of developing circular economy solutions for pending city challenges. Various stakeholders from industry and academia are engaged to advance the circular economy in Copenhagen on multiple scales.

The plan document, titled “Circular Copenhagen: Resource and Waste Management Plan 2024,” comprises six themes with concrete measures that will be useful throughout the entire planning process, up to realization. Selected UM indicators are applied in this strategic plan to assist in the implementation of the project. Therefore, this section will analyze their roles from the perspectives of communicators, goal-setters, regulators, and assessors, and highlight the functions in Fig. 7.2 that UM indicators play in Circular Copenhagen.

7.3.2 Role 1: communicators

In Circular Copenhagen, UM indicators play the role of communicators in three ways: first, for communication purposes and to discuss various stakeholders’ demands; second, for coordination with other planning policies; and third, to pursue synergy with related cities and regions. Various stakeholders participate in this strategic plan, including industry, academia, governments, and citizens. Workshops are organized, involving relevant stakeholders, where indicators are applied to present the circularity status quo of Copenhagen and contribute to a better understanding of resources. For instance, in Measures Topic 4 (Copenhagen promoting circular economy), indicators are used as a supporting tool to understand waste prevention and management for children and young people. Considering this, UM indicators assist in understanding plans, effective communication among various stakeholders, and knowledge transfer of best practices, representing Functions 1, 6, 9, 10, 14, 23, and 27.

UM indicators, such as CO2 emissions and the amount of waste, are applied in both Circular Copenhagen and other environmental plans in Copenhagen. The resource and waste management system interacts with other municipal focus areas, such as transportation, energy, and soil management. Therefore, the indicators serve as a common denominator among different plans to compare effects, reduce conflicts, and comply with an integrated vision (Functions 29 and 30). In particular, Circular Copenhagen supports the vision proposed by the CPH 2025 Climate Plan, ensuring a carbon-neutral Copenhagen by 2025 through the same indicator target goals (Copenhagen Municipality, 2012).

Copenhagen is the core of Hovedstadsområdet (Copenhagen Metropolitan Area, CMA). Within the context of CMA, the development of Copenhagen needs to be effectively coordinated with the surrounding areas that jointly form CMA. Circular Copenhagen also considers waste management at a regional and national level (Functions 17 and 21). Resource flows are organized and planned regionally to optimize Copenhagen and its hinterlands together. Additionally, the performance of Copenhagen and other cities in CMA is compared by indicators, such as the amount of waste per capita, to adjust the plan more in line with the actual situation in CMA

7.3.3 Role 2: goal-setters

In Circular Copenhagen, indicators play a crucial role in setting goals for strategic urban planning, leveraging their measurable and fast-feedback characteristics. They assist in establishing phased and long-term goals for specific strategic actions and objectives.

Circular Copenhagen utilizes indicators to address three concrete targets for 2024: (i) achieving a 70% recycling rate for household waste and light industrial and commercial waste, (ii) reducing 59,000 tons of CO2, and (iii) reusing 6,000 tons of material in municipal swap and reuse facilities (Copenhagen Municipality, 2019). Together, these targets support Copenhagen's vision to Co-Create Copenhagen and achieve carbon neutrality by 2025 (Functions 3, 15, and 31). The implementation of each research topic and city project is aligned with these three overarching targets (Functions 13, 16, and 24).

In addition to setting the overall goals of Circular Copenhagen, UM indicators are employed to establish specific project goals and actions. For instance, in Topic 2 (Development of existing and future collection schemes), Circular Copenhagen sets three objectives with UM indicators to guide the process: (i) a 3% increase in the collection of household waste for recycling, (ii) approximately 2,250 tons CO_2 reduction, and (iii) approximately 800 tons of general waste for reuse. These objectives involve the implementation of small measures in various areas (Functions 13 and 24). The overarching goals of Circular Copenhagen are systematically broken down into the goals of each sub-project to ensure a coordinated and efficient operation.

7.3.4 Role 3: regulators

Considering legislative regulations, Circular Copenhagen is intricately connected to existing plans and regulations for the city, such as the Municipal Plan 2015 (Functions 8 and 13). Beyond this scope, the Danish Environmental Protection Agency has formulated the national waste management plan, reflecting EU targets for Denmark in the context of the circular economy. The energy and resource recycling regulations outlined in Circular Copenhagen align not only with these national goals but also with EU regulations. Comprehensive regulations are established for various themes, including building, waste, and heat (Function 32).

For example, the Copenhagen government published the Resource and Waste Management Plan 2018, serving as a knowledge basis to promote better waste sorting practices in citizens' daily lives. The waste sorting regulations utilize data as a motivator for automatic registration, providing clear results for citizens to help them realize their circularity goals (Functions 3 and 13). In addition, companies are obligated to manage their waste in compliance with the Statutory Order on waste (Copenhagen Municipality, 2019) (Function 21).

7.3.5 Role 4: assessors

Assessment is a fundamental function of UM indicators in urban resource management. In Circular Copenhagen, these indicators play a crucial role in evaluating the current situation, the performance of each project, and the overall impact on a larger scale.

Circular Copenhagen builds upon the foundation of the previous Resource and Waste Management Plan from 2010 to 2018 (Copenhagen Municipality, 2019), significantly improving upon it. For example, the recycling rate, which was 27%, has increased to 45%. The new actions in Circular Copenhagen are developed based on the achievements and advancements of previous initiatives, including technological developments for the optimal treatment of resources (Functions 2 and 13).

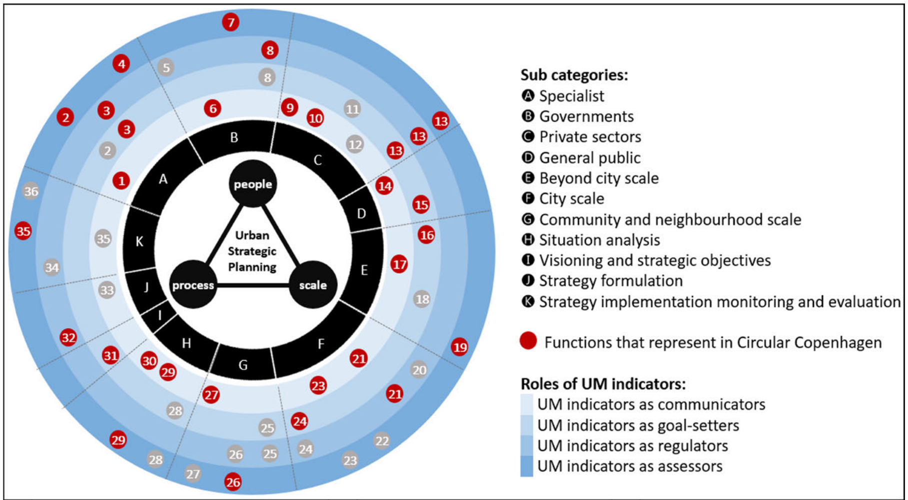
To assess performance, Circular Copenhagen employs several interlinked measures contributing to the objectives of the entire urban strategic plan (Functions 4, 19, and 29). In Topic 5 (Increased recycling of industrial and commercial waste), UM indicators are applied to establish objectives, such as a 15% increase in the collection of industrial and commercial waste for recycling (approximately 25,700 tons of waste). This will be assessed annually to measure completion and adjust future schedules. Additionally, the total cost, which includes investments and operational costs during the planning period, is presented using economy-related indicators specific to Circular Copenhagen Topic 5.

Circular Copenhagen utilizes UM indicators, including CO_2 reduction and the amount of waste for reuse, to evaluate the performance of each project and align them with policies at the national or regional scale, such as the CPH 2025 Climate Plan (The City of Copenhagen, 2012). This approach allows policies at different scales to be connected through the assessment results of indicators, enabling a multi-criteria assessment (Functions 7, 26, and 35).

7.3.6 Summary of the validation case

While Circular Copenhagen is not directly comparable to a strategic urban planning process in the Dutch context, the role of UM indicators is crucial, as analyzed in this section, particularly concerning the four aspects outlined in section 7.2.1—namely, as communicators, goal-setters, regulators, and assessors. In Circular Copenhagen, UM indicators are applied across six resource and water management topics, building on previous regulations and policies.

The analysis above reveals the various functions of UM indicators in Circular Copenhagen, as depicted in Fig 7.3. The figure illustrates that UM indicators serve multiple functions in this project, such as defining measurable and innovative goals (Function 3) and assisting in practical actions (Function 13). However, some functions, like counterbalancing those undermining sustainability (Function 12) or refining a business model (Function 25), are not explicitly reflected in this project. Nonetheless, the overall contribution of UM indicators in Circular Copenhagen is evident across participating actors, focusing scales, and planning phases.



1	To coordinate the barriers between specialists' knowledge	13	To assist in making practical actions	25	To refine a business model
2	To analyze long-term effects	14	To reflect the response of the public	26	To evaluate the experiment site
3	To define measurable and more innovative goals	15	To make balanced goals	27	To assist knowledge transfer of best practice
4	To present a comprehensive image of the aspects for evaluation	16	To assist in making actions from the upper organization	28	To identify crucial problems
5	Early warning for taking actions	17	To coordinate wide scale to practical scale	29	To make a comparison under the same context
6	Communication channel	18	To prioritize focus area	30	To make effective communication
7	To make a comparison between cities possible	19	To study synergy among different area	31	To assist in setting strategic goals
8	To conduct actions related to impacts	20	To formulate a legislative guide	32	To guide the decision-making process
9	Communication channel	21	To formulate cooperation	33	To regulate different aspects in the same context
10	To help stakeholders understand the plans	22	To quantify material flows	34	To systematically monitor strategic urban planning
11	To highlight problems	23	To assist knowledge transfer of best practice	35	To reflect the implementation of the planning project
12	To counterbalance those who undermine the sustainability	24	To conduct step-by-step goals and actions	36	To provide early recognition of the city

FIG. 7.3 The functions of UM indicators in Circular Copenhagen (functions in red are reflected in the project)

Apple Developer Academy, Naples (Photo by Yan Song 2019)

8 Synthesis and Outlook

8.1 Introduction

This study investigates and develops a framework for selecting Urban Metabolism (UM) indicators to support strategic urban planning for urban planners. The framework integrates three critical dimensions: participating actors, focusing scales, and planning phases. By conducting multi-faceted analysis, the research provides insights into the application of UM indicators in the planning process. This includes identifying trends in UM research and currently utilized indicators, assessing gaps in their implementation by stakeholders and planners, examining the various roles of UM indicators across different scales, and determining appropriate planning phases for their application in strategic urban planning.

This chapter presents the discussion, conclusion, and recommendations based on the findings from the preceding chapters. Each sub-research question is addressed to respond to the overarching research question, followed by reflections from both theoretical and practical perspectives. The discussion encompasses limitations inherent in the theoretical foundation of UM research and practical challenges associated with implementing UM indicators in strategic urban planning. To overcome these challenges, recommendations for future research are proposed, aiming to advance theoretical development and practical application of UM research.

8.2 Answers to research questions

— Main Research Question: How can urban metabolism indicators support strategic urban planning process from the perspectives of actors, areas, and flows?

This research is motivated by three key challenges: (i) divergent preferences among stakeholders and planners regarding UM indicators, leading to differing opinions on their selection; (ii) inefficiencies in the application of UM indicators across varying spatial scales; and (iii) the underutilization of UM in strategic urban planning processes.

The study finds that UM indicators can effectively support strategic urban planning by addressing these challenges through three perspectives. From the actor perspective, UM indicators facilitate stakeholder engagement by enhancing communication and aligning objectives. From the area perspective, they address cross-scale dynamics and provide focused insights tailored to specific spatial contexts. From the flows perspective, UM indicators offer tools for analyzing and managing resource flows, enabling planners to set development goals, regulate policies, and assess plan performance.

The findings further emphasize that the selection of UM indicators must be tailored to the specificities of each planning project. Planners must ensure that these indicators align with the priorities of stakeholders, address relevant spatial and material flows, and are applied at appropriate phases of the planning process. By integrating these perspectives, UM indicators can serve as a comprehensive tool to enhance the strategic urban planning process and contribute to more sustainable urban development.

8.2.1 Current UM research trends and indicators

— SQ1: What are the current research trends in UM and which indicators can be used and adapted to describe UM?

In chapter 3, a CIMO (Context-Indicator-Mechanism-Outcome) approach is employed to analyze current literature on UM-related topics. The review encompasses articles published within the past decade, focusing on the development and evaluation of UM. To provide a comprehensive overview of research trends, this study selects UM research topics, analytical models, and methods as entry points.

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Regarding research topics, current UM literature focuses on the following six domains: (1) ecosystem health, (2) energy, (3) environmental technology, (4) urban planning, (5) waste management, and (6) water technology. Each domain serves distinct purposes for applying indicators, summarized as: (1) developing new indicators, (2) establishing indicator frameworks, (3) testing indicators in empirical cases, (4) utilizing indicators as decision-making support, and (5) addressing the importance of specific indicators.

From the perspective of analytical models, three primary models are commonly utilized to describe a city's UM: the black-box model, the grey-box model, and the network model (Beloin-Saint-Pierre et al., 2017; Zhang, 2013). Historically, prior to 2010s, the black-box model was prevalent, particularly in methodologies such as input-output analysis, material flow analysis, and ecological footprint analysis. The grey-box model integrates top-down and bottom-up data collection methods, exemplified in approaches like life cycle assessment (LCA, LCC, S-LCA), emergy synthesis analysis, and material flow analysis (MFA). The network model represents the latest development in systematic UM analysis, relying on bottom-up (or a combination of bottom-up and top-down) data as proxies for these processes. Each model type has its own set of advantages and disadvantages, which must be considered during UM analysis.

Regarding analytical methods, a variety of alternatives have been employed across the field. Commonly utilized methods include material flow analysis, life cycle assessment, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism, and Emergy assessment. The selection of a particular method is typically determined by the research objectives of each individual project.

In this research, 38 indicators were extracted from the literature review (See Table 8.1). They were categorized into three levels following an in-depth literature review procedure, aiming to furnish a practical UM indicator set for urban planning. The three major categories encompass the Environment, Resource flow, and City development, delineating the physical basis, flow dynamics, and impact on cities. This classification facilitates a deeper understanding for planners, while offering decision-making support for urban planning and development processes.

TABLE 8.1 The categorized urban metabolism indicator set

Category	Theme	Indicator
Environment	Water condition	Precipitation
		Evapotranspiration
		Infiltration rate
		Surface run-off
	Air quality	Air temperature
		Air pollutant concentration
		Exceedance
	Carbon	Carbon sinks
	Thermal	Heat island effects
		Heat balance
		Thermal comfort
Resource flow	Resource input	Biomass
		Minerals
		Water
		Fossil fuels
		Renewable energy
		Waste
		Others
	Resource output	Solid waste
		Wastewater
		Gas emission
		Electricity
		Industrial products
	Stored resource	Construction
		Water storage
		Stored industrial products
City development	Population growth	Population characteristic ratio change
		Demographic composition change
	Economy development	GDP
		Employment condition
		Effects on local economy
	Land-use transition	New urbanized area
		Land-use transformation
	Transportation changes	Transportation construction growth
		Public transportation accessibility
		Transportation method change
	Waste management	Waste management accessibility
		Waste management organization

8.2.2 Perspective from participating actors

— **SQ2: What countermeasures can be employed to bridge the gap in implementing UM indicators by stakeholders and planners?**

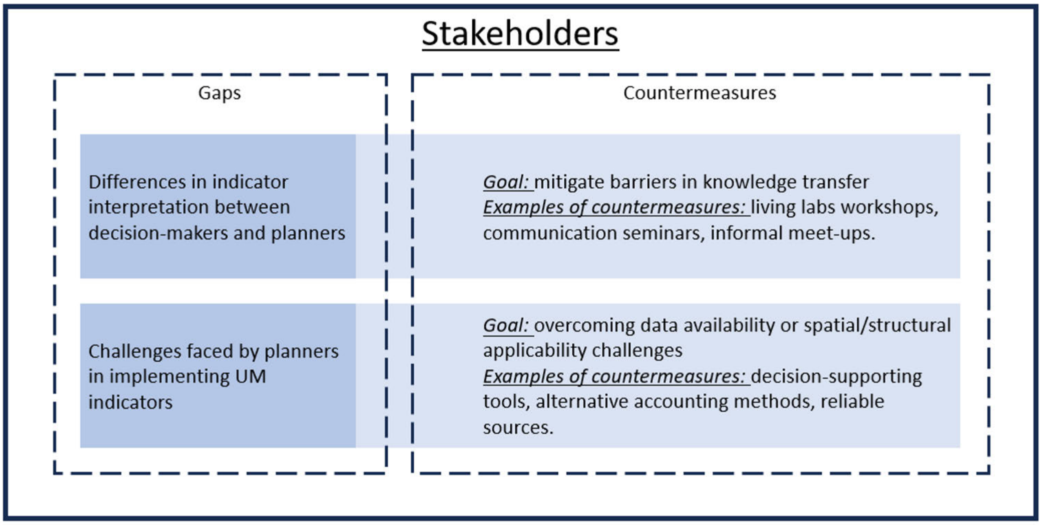

FIG. 8.1 The gaps and countermeasures from stakeholder perspective

The obstacles encountered in applying UM indicators primarily stem from two factors: cognitive differences among different stakeholders and implementation challenges for planners. Chapter 4 investigates the drivers behind these factors to enhance the applicability of UM indicators. The first obstacle discerned arises from differences in indicator interpretation between decision-makers and planners. Their divergent perspectives result in varying views on the significance of UM indicators, leading to differences in emphasis on key indicator selection and prioritization. The second obstacle pertains to the challenges faced by planners in implementing UM indicators. This difficulty varies across indicators but is predominantly attributed to factors such as insufficient availability of data and challenges in relating available data to spatial elements.

To explore the divergent perspectives of decision-makers and planners, this research conducted a survey to assess their attitudes toward UM indicators. The survey revealed that stakeholders from government, industry, research and education, and civil society place differing emphasis on various aspects of UM indicators and their significance. Take material flow aspect as an example, research and education stakeholders exhibit heightened concern for indicators linked to resource input, reflecting their emphasis on innovative approaches to address urban consumption patterns in city development. Industry stakeholders attribute relatively higher focus on resource output, e.g., solid waste, which may be attributed to the prevalent adoption of circular economy concepts, prompting stakeholders to prioritize efficient waste management strategies within urban contexts. To mitigate barriers in knowledge transfer, various forms and methods, such as living lab workshops, communication seminars and informal meetups, could be employed. All stakeholders need to recognize these discrepancies and work toward establishing a common understanding of UM indicators within a given project.

Another survey was conducted to examine the criteria for required UM indicator selection from the perspective of urban planners. Five key criteria are defined, which are (i) relevance; (ii) uniqueness and precision; (iii) communication and accessibility; (iv) data availability and accessibility; and (v) spatial/structural applicability. Respondents in this survey highlighted certain challenges in meeting implementation criteria, making widespread adoption of UM indicators difficult. Specifically, “Data availability and accessibility” and “spatial/structural applicability” were identified as the most challenging criteria for many indicators. More than half of the respondents regard these criteria are hard for UM indicators to achieve. Consequently, a range of countermeasures, such as utilizing decision-supporting tools, exploring alternative accounting methods, or obtaining data from reliable sources, need to be employed to address these difficulties.

8.2.3 Perspective from focusing scales

— **SQ3: What are the different applications of UM indicators at various scales?**

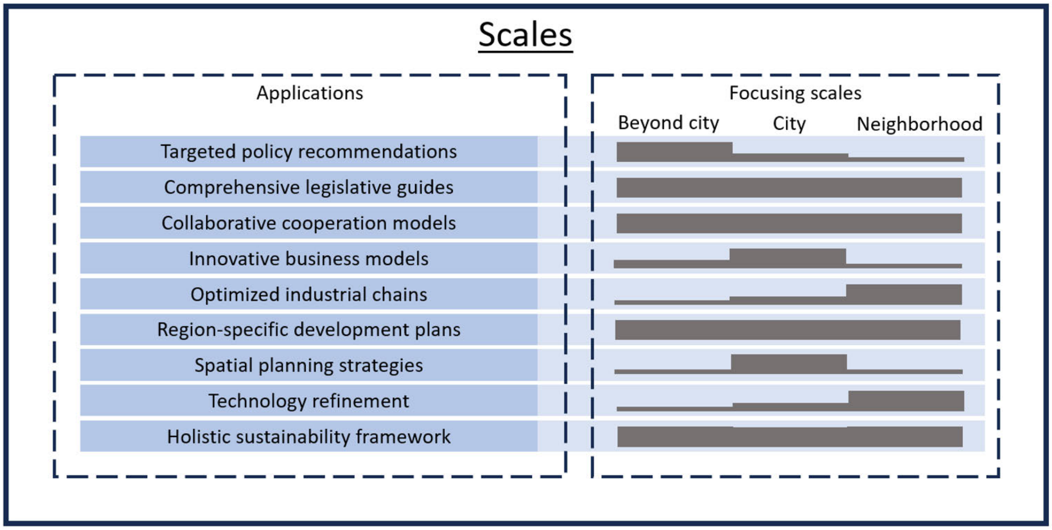

FIG. 8.2 The applications and their focusing scales

The significance of scale in urban planning cannot be overstated, as it shapes the tangible implementation of planning endeavors. Chapter 5 is dedicated to examining the dimensions of scale within the context of UM indicators and their projected applications across a spectrum of Dutch UM-related projects. Drawing on the delineation of relevant scales in UM research, this study focuses on the Netherlands and selects 10 representative practical and research projects as case studies. UM indicators employed in these projects are analyzed across various applications, providing insights for planners to evaluate their projects.

From the perspective of policy making, it is mainly developed at the metropolitan level by national or regional authorities. For example, initiatives such as “Circular Dutch Economy by 2050” aim to remove regulatory barriers that hinder the circular economy and create an environment conducive to innovation and investment within metropolitan areas. Furthermore, effective policy implementation requires comprehensive legislative guidance at all levels. Projects such as “Circulair Den Haag” advocate cooperation among cities to modify national regulations, promote knowledge sharing and ensure coordination at different scales. Therefore,

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organizations involved in unified management programs must become adept at translating policies into workable strategies that facilitate their implementation at all administrative levels. This highlights the importance of considering scale in policy development to effectively address the complexity of UM projects.

As for practical implementation, it is affected by scales by establishing collaborative models that engage stakeholders at different scales, such as the co-creation approach adopted in projects such as REPAiR, which involves metropolitan, urban and community levels of stakeholders. Furthermore, a scale-specific focus on business model innovation, particularly evident in metropolitan and city-scale projects like Circular Rotterdam, introduces novel incentive structures and economic evaluation methods to ensure project sustainability. In addition, scale considerations play a crucial role in fostering strong industrial chains, as exemplified by the partnership between AEB Amsterdam and Waternet to establish a central biorefinery hub to enhance energy recycling and material reuse properties, thereby minimizing waste generation and optimizing resource flow efficiency. These aspects emphasize the importance of scale in developing practical implementation strategies for UM projects.

Concerning strategic planning, scale has a significant impact on UM projects, as evidenced by the different scopes and approaches adopted at different scales. Projects like Circular Amsterdam outline strategies that span short and long-term horizons, propose circular construction and organic residual flows, interconnected in a roadmap vision that addresses the metropolitan to the community level. In contrast, initiatives such as the IABR Rotterdam project focus on optimizing the flow of resources within Rotterdam, with strategies developed that not only cover development stages but also identify potential locations, core technologies and innovative planning interventions. These examples highlight the importance of considering scale in strategic planning as it determines the scope, depth and focus of future development trajectories, ensuring a comprehensive outlook covering both temporal and spatial dimensions.

For technological advancements, scale affects the actual implementation of environmental technologies and the establishment of sustainability assessment frameworks. On a smaller scale, projects serve as experimental sites for testing the feasibility of various technologies, such as urine separation toilet technology in Buiksloterham and circulation enhancement technology for business office environments in the Schiphol area. Furthermore, sustainability and smart UM are core development objectives of many projects, leading to the implementation of comprehensive sustainability frameworks, such as the REPAiR project. These frameworks use multiple methodologies to assess life cycle impacts and identify future strategies, thereby enhancing sustainability assessments at metropolitan and city scales. The diverse applications of technological advances in UM projects, across metropolitan, urban and community settings, emphasize the comprehensive nature of these initiatives and the need to work with various stakeholders and consider scale-specific complexities to execute them effectively.

Project implementation of UM indicators not only necessitates the involvement of various stakeholders but also requires consideration of the project's particularity at different scales. From a UM perspective, project implementation transcends singular scales and constitutes a multi-scale endeavor extending beyond administrative boundaries. In cross-scale projects, the effectiveness and feasibility of indicator application at different scales must be considered to better support project implementation.

8.2.4 Perspective from planning process

— **SQ4: How can UM indicators be effectively utilized across different phases of the strategic urban planning process?**

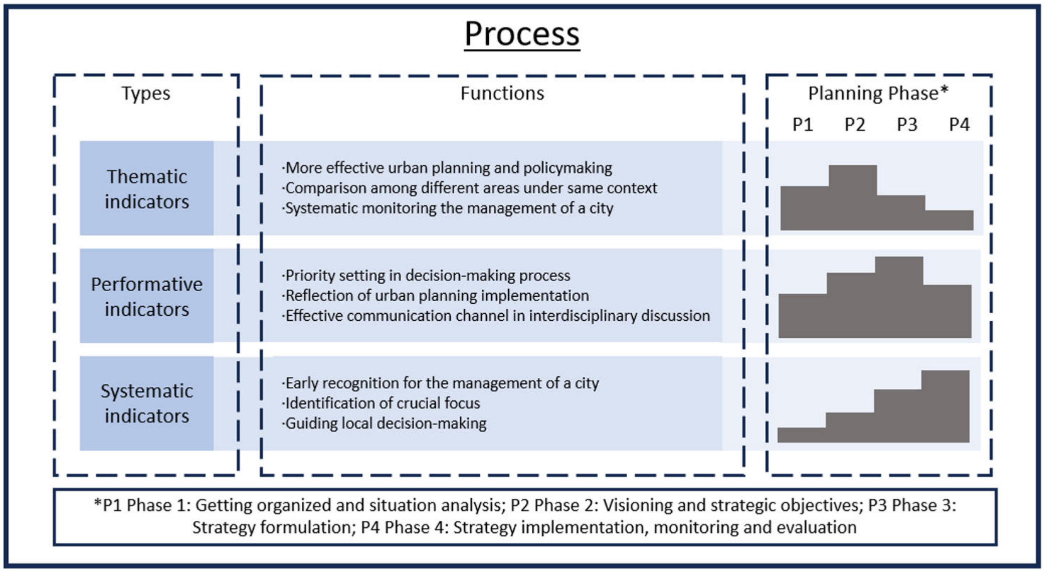

FIG. 8.3 Types of indicators, their functions and planning phases

In various phases of strategic urban planning concerning material flows, planners rely on a range of UM indicators to guide them towards a sustainable and/or resilient future. Hence, it is imperative to incorporate appropriate UM indicators into the appropriate phases of the planning process. Chapter 6 categorizes UM indicators into three types: thematic indicators, performative indicators, and systematic indicators. These categories determine the suitable timing for each indicator's application in the planning phases. Drawing on four case studies related to four planning phases, this research explores the application timing of UM indicators based on their types.

Thematic UM indicators are an integral part of the strategic urban planning process, providing multifaceted support and insights for effective decision-making and urban management. These indicators quantitatively describe a city's development trajectory, helping planners identify potential challenges early, identify key focus areas and guide local decision-making. Thematic indicators, derived primarily from material flow analysis, can serve as proactive tools for urban planning, allowing one to predict future environmental problems without relying solely on stress signals. Similar to monitoring vital signs, they provide early warning and facilitate a shift to healthier environmental states. In addition, by analyzing the flow of resources in a city, thematic indicators help identify specific sectors or policies that are likely to achieve desired goals, thereby enabling efficient allocation of resources. For example, initiatives such as Circular Rotterdam identify key priorities in city planning by prioritizing and expediting processes based on material analysis. Additionally, thematic indicators provide a quantitative snapshot of urban conditions, supporting evidence-based decision-making processes. Projects such as the European FP7 project BRIDGE integrate these indicators into decision support systems, facilitating the assessment of planning alternatives by including indicators such as CO_2 emissions and heat. In essence, thematic UM indicators are valuable tools for strategic urban planning, contributing to proactive urban management, effective resource allocation and evidence-based decision-making.

For performative UM indicators, they play a vital role in different phases of the strategic urban planning process, serving various functions that contribute to informed decision-making and effective urban development strategies. First, these indicators provide decision-makers with a comprehensive assessment of the potential social, economic, and environmental impacts of policies, thereby enabling the setting of priorities in the decision-making process. Through indicator-based assessments, local authorities can determine spatial allocation priorities. Second, performance indicators serve as a barometer of the implementation of city plans by highlighting the discrepancy between current policies and long-term environmental goals. By analyzing the resource cycle, decision makers can evaluate the consistency of plan implementation with sustainable development goals, so that plans can be improved and optimized in a timely manner to meet changing development needs. Finally, these indicators facilitate effective communication in interdisciplinary discussions by providing a visual perspective of urban dynamics. Planners can leverage graphical representations based on these indicators to clearly communicate results to the public and policymakers, promoting productive interdisciplinary dialogue between stakeholders from different fields. Overall, performance UM indicators are a valuable tool for strategic urban planning, helping to make informed decisions, promote alignment with the Sustainable Development Goals, and enhance collaboration among stakeholders to achieve better outcomes through effective urban development.

Systematic UM indicators are an important part of the strategic urban planning process, allowing for a comprehensive assessment of cities as complex systems and facilitating informed decision-making at all stages. First, these indicators contribute to more effective urban planning and policy development by providing a holistic analysis of the entire urban system. In the contemporary urban environment, where cities are interconnected in cross-regional markets, systemic indicators enable policymakers to gain insight into all aspects of city performance, ensuring balanced priorities without losing sight of essential elements. Second, system indicators serve as standardized indicators for comparing different areas within the same context, allowing stakeholders to analyze the performance of different cities and identify best practices for learning and adaptation. They facilitate meaningful inter-city comparisons and thus contribute to the sustainable development of urban areas. Finally, system indicators provide basic guidance for achieving strategic development goals, thus enabling continuous monitoring of urban management. Initiatives such as the Amsterdam Circular 2020-2025 Strategy assess the transition to a circular economy through a systematic indicator framework, providing valuable insights into performance improvements in all aspects of the city. It is crucial to recognize that indicator frameworks continue to evolve to adapt to technological and social changes, ensuring their relevance in the dynamic landscape of urban development.

8.2.5 UM indicator selection framework in strategic urban planning

— **SQ5: How do the UM indicators contribute to strategic urban planning?**

Chapter 7 culminates in the presentation of this research's final product: an integrative framework for selecting UM indicators in a strategic urban planning process. This framework synthesizes the findings from Chapters 4 to 6 into two graphical representations. It comprises two instruments: (i) an abstracted timeline of iterations guiding and focusing the selection process of UM indicators, and (ii) a graph that brings together aspects of people, scale, and process to specify the objectives that selected indicators need to achieve, contingent on the iteration on the timeline. These instruments enable a planning team to select and optimize UM indicators suitable for a specific strategic urban plan, ensuring stakeholder selection and adequate involvement throughout the planning process while considering scalar interrelations and contextual specificities. Although the analysis in previous chapters is focused on the Dutch context, this research also examines a non-Dutch empirical project, Circular Copenhagen, to ascertain whether UM indicators are similarly used in non-Dutch projects within a comparable governance context.

For the process of UM indicator selection, the entire strategic urban planning process involves four major actions: conceptual consolidation, analytical structuring of metabolic models, identification of UMIs, and monitoring and adjusting UM indicators. These actions necessitate multiple rounds of iteration and adjustment to refine initial draft UMIs into final selections. Stakeholder engagement and cross-scale considerations are pivotal and must be integrated throughout the entire process.

UM indicators play a crucial role in strategic urban planning at all stages of the planning process. First, they facilitate conceptual integration by clarifying basic concepts and ensuring that policy-relevant information is widely accepted. This involves engaging stakeholders at different levels and disciplines to promote understanding and consensus on key issues and development goals. Stakeholder engagement is a platform for identifying focus areas, anticipating future phases, and incorporating diverse perspectives into the planning process. Furthermore, the UM indicators facilitate the transfer of best practices by comparing local conditions to established benchmarks, adjusting targets accordingly, and informing decision-making through expert discussions and empirical insights.

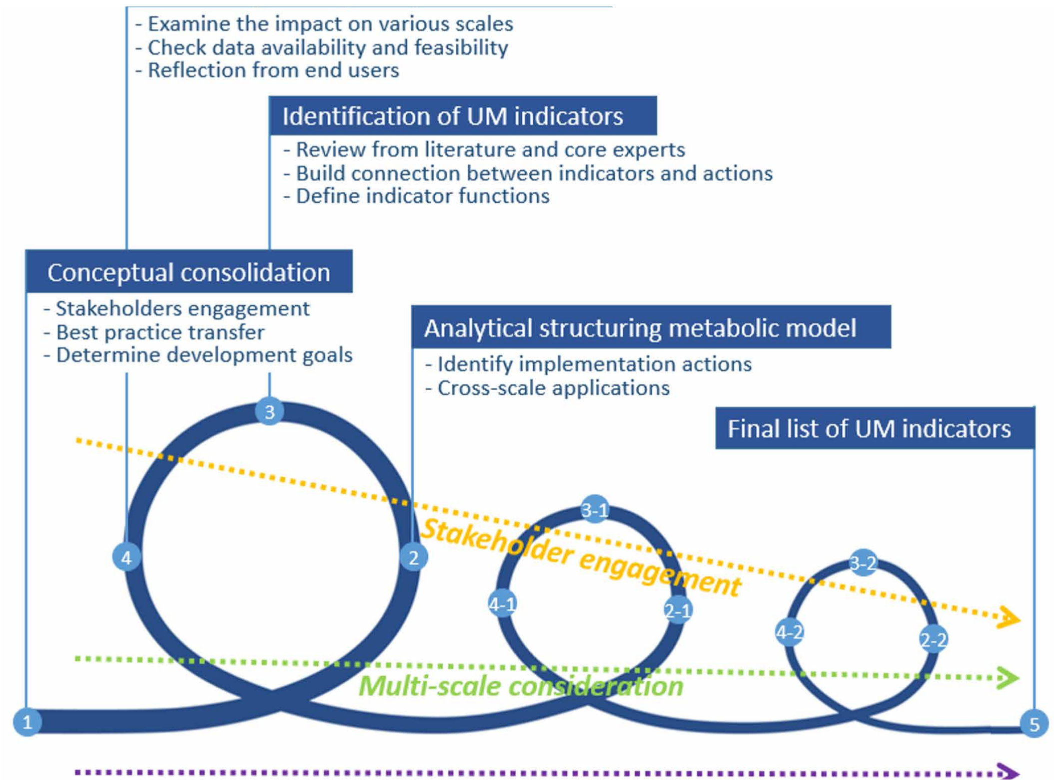

FIG. 8.4 UM indicator development process in strategic urban planning

Furthermore, these indicators help define development goals by linking them to specific actions and providing a framework for assessing program performance. Within the analytical structure of metabolic models, indicators help identify key issues, translate goals into practical actions, and ensure cross-scale applicability to different urban environments. Through systematic monitoring and adjustment, indicators enable planners to address challenges related to scale, data availability, and stakeholder feedback, thereby supporting the iterative refinement of strategic urban planning initiatives.

Furthermore, UM indicators do more than just measure and evaluate; they serve as communication tools, help set goals, establish the basis for regulation, and serve as evaluation criteria throughout the planning process. By combining indicators with actions and targets, planners can effectively guide the implementation of strategies, measure progress and evaluate the effectiveness of interventions. Overall, UM indicators provide a comprehensive framework for understanding urban systems, guiding decision-making, and promoting sustainable development in urban areas.

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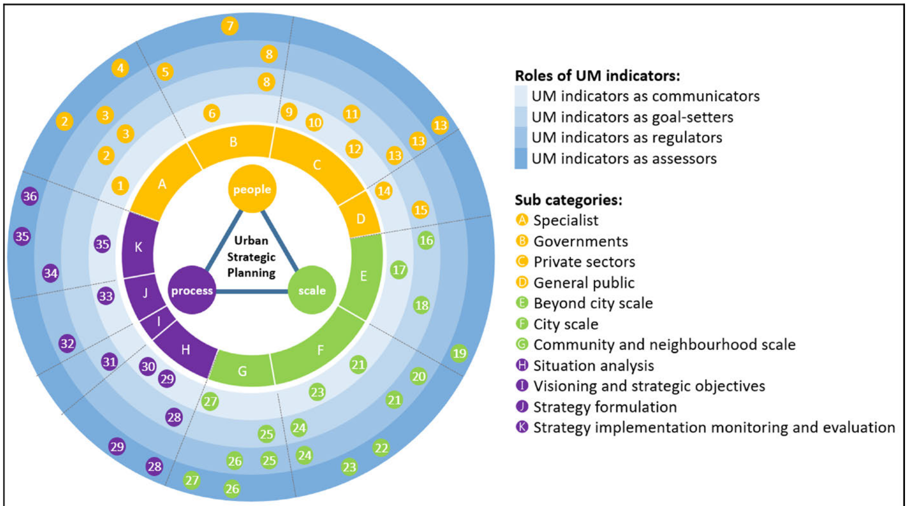

1	To coordinate the barriers between specialists' knowledge	13	To assist in making practical actions	25	To refine a business model
2	To analyze long-term effects	14	To reflect the response of the public	26	To evaluate the experiment site
3	To define measurable and more innovative goals	15	To make balanced goals	27	To assist knowledge transfer of best practice
4	To present a comprehensive image of the aspects for evaluation	16	To assist in making actions from the upper organization	28	To identify crucial problems
5	Early warning for taking actions	17	To coordinate wide scale to practical scale	29	To make a comparison under the same context
6	Communication channel	18	To prioritize focus area	30	To make effective communication
7	To make a comparison between cities possible	19	To study synergy among different area	31	To assist in setting strategic goals
8	To conduct actions related to impacts	20	To formulate a legislative guide	32	To guide the decision-making process
9	Communication channel	21	To formulate cooperation	33	To regulate different aspects in the same context
10	To help stakeholders understand the plans	22	To quantify material flows	34	To systematically monitor strategic urban planning
11	To highlight problems	23	To assist knowledge transfer of best practice	35	To reflect the implementation of the planning project
12	To counterbalance those who undermine the sustainability	24	To conduct a step-by-step goals and actions	36	To provide early recognition of the city

FIG. 8.5 The roles of UM indicators from the aspects of people, scale, and process

To understand the roles and functions of UM indicators, this research integrates aspects of people, scale, and process to specify the objectives that selected indicators must achieve, contingent on the iteration on the timeline. Planners can incorporate strategic planning goals and refine UM indicator roles to better engage stakeholders and facilitate cross-scale evaluation throughout the planning phases.

UM indicators play a key role in strategic urban planning, serving multiple functions that contribute to the effectiveness and success of planning initiatives. They contribute to strategic urban planning in the following ways:

Communicators: UM indicators promote effective communication among stakeholders by quantifying flows within the industry chain and evaluating project performance. They foster collaboration by providing stakeholders with a common language to explain and understand the impact of their actions. This communication enhances transparency and collaboration, as exemplified by projects such as the Buiksloterham project.

Goal-setters: UM indicators help set development goals by providing phased and quantifiable goals for spatial characteristics and planning timelines. They assist in classifying actions into long-term, medium-term and short-term objectives, as shown in the Amsterdam Circular Strategy 2020-2025. Additionally, UM metrics can serve as an early warning system for potential problems and provide quantifiable goals for each stage of project development.

Regulators: UM indicators are important in policy development by assisting in the development of specific policy and legislative guidance. They help regulate actions based on thresholds set by evaluation metrics. For example, in " Circular Dutch Economy by 2050", the UM indicator is used to gradually improve circular standards. Furthermore, pilot cases assessed using UM indicators help establish reasonable thresholds for new policy development.

Assessors: UM indicators act as assessors to evaluate the performance of sustainability frameworks and interventions. They provide decision-makers with an objective assessment of intended interventions, helping to prioritize or refine recommendations. UM metrics enable comparative studies to identify best practices, providing valuable insights for future projects.

In addition to these roles, UM indicators integrate various actor groups involved in strategic urban planning, such as experts, government, the private sector, and the public. They facilitate knowledge transfer, communication, and collaboration between these groups, ensuring that planning objectives are aligned with effective communication and the diverse interests of stakeholders. In addition, UM indicators are applicable to multiple scales, including extra-urban scale, urban scale, and community/neighborhood scale. They help quantify resource flows, guide decision-making, and evaluate plan implementation at different scales, thereby enhancing the comprehensiveness and operability of plans. Finally, UM indicators have various functions throughout the strategic urban planning process, including situation analysis, envisioning and setting strategic goals, strategy formulation, and strategy implementation, monitoring, and evaluation. They provide valuable insights and guidance at every stage, promoting informed decision-making, stakeholder engagement and program optimization. Overall, UM indicators play a multifaceted role in strategic urban planning and contribute to the development of sustainable, resilient and inclusive cities.

8.3 Limitations

This section addresses the theoretical and practical limitations of this research, highlighting areas for further study. Theoretical limitations stem from the predominant use of MFA as the accounting method UM indicators, with less focus on alternative methods such as EmA or LCA. Practical limitations arise from the research's focus on Dutch case studies, with limited exploration of UM indicator applications in differing international contexts. These limitations emphasize the need for future research to refine UM methods and expand their applicability globally.

8.3.1 Theoretical limitations

Material Flow Analysis vs other accounting methods

As discussed in Chapter 2, accounting for UM extends beyond Material Flow Analysis (MFA) to include methods such as EmA, LCA, and Carbon Footprint Analysis. However, the UM indicators analyzed in this research are predominantly based on MFA, which remains the most commonly utilized method.

The widespread use of MFA in UM and circular economy studies can be attributed to several factors. First, MFA is highly practical due to its feasibility and the availability of established specifications and standards, such as those provided by Eurostat. Additionally, MFA indicators are generally more accessible and easier for the public to understand. In contrast, EmA, while offering functional-level indicators, presents challenges in data collection, as it requires extensive bottom-up data that is often difficult to acquire at national or regional scales. Furthermore, incomplete resource flow data can lead to inconsistencies and divergent results in analyses.

Despite its popularity, MFA has inherent limitations. Emerging trends in UM research emphasize the integration of EmA with planning processes to achieve more precise quantitative assessments of urban metabolism. However, due to this research's focus on MFA, such approaches are not explored in detail. Similarly, while some scholars, such as Patrício et al. (2015) and Voskamp et al. (2017), have worked to improve the accuracy of MFA statistics and evaluation methods, this study does not delve deeply into these advancements. Nevertheless, accurate evaluation remains crucial for the effective application of indicators in urban planning, underscoring the need for future research to refine UM measurement methodologies and provide robust data to support indicator-based planning processes.

Hybrid or multi-method approaches

Another theoretical limitation in this research is its limited exploration of hybrid or multi-method approaches in UM analysis. While MFA is the primary method employed in this study, emerging research trends advocate for the integration of multiple methodologies to capture the complexity of urban systems more comprehensively. For example, combining MFA with methods such as EmA or LCA can provide a more nuanced understanding of resource flows and their broader environmental and socio-economic impacts. These hybrid approaches enable the examination of dynamic interrelations between energy, materials, and ecological systems across scales and phases, offering a richer analysis than single-method approaches.

Despite recognizing the potential of these multi-method strategies, this research does not delve deeply into how they could be operationalized in the selection and application of UM indicators. For instance, EmA could complement MFA by providing insights into the energy value embedded in resource flows, which could be particularly valuable for long-term strategic planning. Similarly, LCA could help assess the environmental impacts of specific urban policies or interventions across their lifecycle, bridging the gap between short-term actions and long-term sustainability goals.

By not fully addressing the integration of these methodologies, the research potentially limits the theoretical framework's ability to account for complex, overlapping urban processes. Future studies could explore how hybrid methods can improve the accuracy, relevance, and applicability of UM indicators in diverse contexts, thus enhancing their utility for planners in addressing sustainability and resilience challenges in urban systems. Integrating these approaches would provide a more robust foundation for UM research and expand its theoretical and practical contributions to strategic urban planning.

Simplification of stakeholder perspectives

A notable theoretical limitation of this research lies in the simplified treatment of stakeholder perspectives in the application of UM indicators. While the study effectively categorizes stakeholders—such as government bodies, industries, research institutions, and civil society—it does not sufficiently explore the nuanced and often conflicting priorities these groups may hold, especially in varying cultural, economic, and political contexts. Stakeholder engagement is a critical component of strategic urban planning, as the successful integration of UM indicators relies on a shared understanding and alignment of objectives across diverse groups.

This limitation is particularly evident in the research's primary focus on European contexts, where participatory governance and collaborative decision-making are more established. For instance, in the Dutch and Danish case studies, the research assumes a relatively balanced power dynamic among stakeholders, with planners facilitating dialogue and collaboration. However, in contexts with more hierarchical governance structures, such as those found in parts of Asia, Africa, or Latin America, stakeholder involvement might be constrained by top-down decision-making processes (Cui et al., 2019; Enserink & Koppenjan, 2007). Such differences can significantly influence how UM indicators are prioritized, interpreted, and applied in planning processes.

Additionally, the research does not delve deeply into the variability of stakeholder priorities within specific contexts. For example, industry actors might emphasize economic efficiency and resource optimization, while civil society groups may prioritize social equity and environmental justice. Without a more detailed exploration of these conflicting priorities, the theoretical framework risks oversimplifying the dynamics of stakeholder engagement and undervaluing the negotiation processes required to achieve consensus on UM indicator selection and application.

To address this limitation, future research could develop a more comprehensive framework that incorporates a wider range of governance structures and stakeholder dynamics. Such an approach would enhance the transferability of UM indicators across diverse urban planning contexts and ensure their relevance to the unique challenges faced by different regions and stakeholders.

8.3.2 Practical limitations

Application across scales and cross-scale integration

A practical limitation in this research lies in the application of UM indicators across overlapping or intermediate scales and the challenges of cross-scale integration. While the study effectively categorizes scales into “beyond city,” “city,” and “neighborhood,” the dynamics of intermediate scales, such as metropolitan regions or peri-urban zones, remain underexplored. These areas often exhibit unique characteristics, such as fragmented governance, varied land-use patterns, and mixed urban-rural interfaces, which complicate the straightforward application of UM indicators.

Intermediate scales, such as metropolitan regions, frequently involve multiple administrative jurisdictions, making it difficult to align priorities and data collection efforts across stakeholders. Similarly, peri-urban zones, where urban and rural systems interact, require indicators that can address the complexities of resource flows and ecological impacts spanning both environments. The lack of practical guidance on how to adapt UM indicators for these contexts limits their effectiveness, particularly in addressing the interconnected challenges of resource allocation, land use, and infrastructure development that are typical in such zones.

Additionally, cross-scale integration is critical for ensuring coherence between local, regional, and national planning objectives. For example, a UM indicator applied at the neighborhood level may yield results that are incompatible or inconsistent with regional indicators if data collection methods, objectives, or definitions are not harmonized. This inconsistency can create gaps in planning, where local initiatives fail to align with broader strategic goals.

Future research should focus on developing methodologies and frameworks that enable the seamless integration of UM indicators across scales, with particular attention to intermediate and transitional zones. This could include creating standard protocols for cross-scale data harmonization, fostering multi-jurisdictional collaboration, and designing adaptable indicators capable of addressing the specific challenges of overlapping urban systems. By addressing this limitation, planners could more effectively apply UM indicators to support cohesive, multi-scale urban strategies.

Knowledge transfer and context-specific adaptation

A practical limitation in this research lies in the limited exploration of knowledge transfer and context-specific adaptation of UM indicators across diverse socio-political and cultural settings. While the study offers insights from Dutch and Danish contexts, it does not provide detailed strategies for tailoring UM indicators to governance systems and planning processes that differ significantly from those in Europe. This limitation is particularly relevant when considering regions with varying levels of institutional capacity, regulatory frameworks, and stakeholder dynamics.

For example, European contexts often emphasize participatory governance and multi-stakeholder collaboration, where UM indicators are used to balance economic, environmental, and social priorities. However, in countries with more centralized governance structures, such as China, UM indicators might serve a different purpose, often functioning as assessment criteria driven by government mandates rather than as tools for participatory decision-making (State Environmental Protection Admiunistration of China & The World Bank, 2007). Similarly, in decentralized systems like those in India, where planning responsibilities are distributed across multiple local governments, the use of UM indicators may require extensive coordination and adaptation to align with local needs and capacities (Alizadeh, 2021; Jadhav & Choudhury, 2022).

The lack of practical guidance for adapting UM indicators to these varied contexts limits their global applicability. For instance, strategies for knowledge transfer, such as capacity-building programs, localized indicator development, and stakeholder engagement tailored to specific governance structures, are underdeveloped in the current framework. Additionally, challenges such as data availability, differing policy priorities, and cultural attitudes toward resource management need to be considered when adapting indicators to new contexts.

Future research should focus on creating adaptive frameworks for UM indicator implementation that account for regional and cultural differences. This could include piloting UM frameworks in non-European contexts, analyzing the outcomes, and identifying best practices for scaling and transferability. Such efforts would enhance the practical relevance of UM indicators in supporting global urban sustainability goals.

Data availability and quality issues

A critical practical limitation in the application of UM indicators lies in data availability and quality. While the research acknowledges challenges related to data collection, particularly for advanced accounting methods like EmA or LCA, it does not extensively address how planners and researchers can work with incomplete or fragmented datasets. In real-world scenarios, the lack of reliable, consistent, and high-quality data often hampers the effective implementation of UM indicators, especially in regions with limited data collection infrastructure or weak institutional capacity.

The reliance on MFA, for instance, is facilitated by standardized data protocols such as those provided by Eurostat (Voskamp et al., 2017). However, even these protocols require comprehensive datasets that are not always available, particularly in less developed regions or at more granular scales like neighborhoods or small cities. Furthermore, advanced methodologies such as EmA require extensive bottom-up data that is often difficult to obtain, especially for large-scale national or regional applications. Data gaps in resource flows or inconsistencies between datasets can lead to inaccurate analyses, reducing the reliability of UM indicators in guiding decision-making processes.

The research framework does not fully explore practical strategies for addressing these limitations. For example, leveraging proxy data, integrating satellite imagery and remote sensing, or employing data interpolation techniques could mitigate some of these challenges. Similarly, establishing partnerships between academia, industry, and government institutions to improve data-sharing frameworks and build robust databases could significantly enhance data availability.

Future research should focus on developing methods for working with incomplete datasets, ensuring that UM indicators remain applicable even in data-constrained environments. This would not only broaden the practical relevance of the framework but also make it more adaptable to diverse urban contexts where data quality and availability remain persistent challenges.

8.4 Recommendations

This section outlines key areas where improvements are needed to enhance the integration of UM indicators into strategic urban planning. It emphasizes the importance of strengthening data collection and management systems to provide a robust foundation for indicator-driven planning. Furthermore, it highlights the need to tailor UM indicators to local contexts, ensuring their relevance and effectiveness across diverse urban settings. The section also discusses the value of adopting iterative planning processes that incorporate real-time adjustments based on reflective evaluations, enabling planners to respond proactively to dynamic urban challenges. Lastly, recommendations for future research identify opportunities to expand the scope and utility of UM indicators, including cross-regional studies, multi-method integration, and the incorporation of circular economy principles at broader scales. Together, these insights provide a pathway to refine urban planning practices and ensure that UM indicators support more sustainable and inclusive urban development.

8.4.1 Recommendations for planners

This research introduces a novel approach for urban planners to enhance their understanding of the integration of UM within strategic urban planning processes. This integration is facilitated by engaging relevant stakeholders, addressing multiple spatial and temporal scales, and employing indicators tailored to specific planning phases. The UM indicator framework serves as a comprehensive support tool for strategic urban planning, illustrating how diverse elements of UM can be effectively incorporated into planning initiatives. The findings of this study highlight three key areas for future exploration:

Strengthening data collection and management systems

One of the critical recommendations for urban planners is to strengthen data collection and management systems to support the effective application of Urban Metabolism (UM) indicators. Reliable and high-quality data is the foundation for understanding resource flows, monitoring urban dynamics, and evaluating sustainability efforts. However, current practices often face challenges related to incomplete, inconsistent, or inaccessible datasets, which limit the applicability and accuracy of UM indicators in strategic urban planning.

To address these issues, planners should advocate for the adoption of advanced technologies that enhance data collection and monitoring capabilities. Tools such as Geographic Information Systems (GIS), remote sensing, and Internet of Things (IoT) devices can provide real-time insights into material and energy flows within urban systems. These technologies enable planners to gather granular and large-scale data efficiently, which is crucial for multi-scale urban planning.

Furthermore, establishing collaborative data repositories is essential for improving data accessibility and consistency. By working with academic institutions, government agencies, and private organizations, planners can contribute to shared databases that pool resources and knowledge. Such repositories can standardize data formats, reduce duplication of effort, and ensure that relevant datasets are readily available for UM indicator applications.

Additionally, planners should prioritize data quality by implementing validation protocols and cross-referencing data sources to minimize errors and inconsistencies. Integrating these efforts into urban planning processes not only strengthens the reliability of UM indicators but also supports evidence-based decision-making and promotes transparency.

In summary, enhancing data collection and management systems equips planners with the tools and resources needed to apply UM indicators effectively. This approach ensures that strategic urban planning processes are informed by accurate, timely, and comprehensive data, ultimately contributing to more sustainable and resilient urban development.

Tailoring UM indicators to local contexts

While standardization is valuable for facilitating comparability and knowledge sharing, a one-size-fits-all approach to UM indicators may overlook the unique challenges and priorities faced by individual urban areas. Customizing indicators to reflect local realities ensures their relevance and effectiveness in addressing context-specific urban dynamics.

Local tailoring begins with a comprehensive understanding of the urban context, including its demographic, economic, environmental, and institutional characteristics. Planners should engage with a diverse range of local stakeholders—such as community groups, businesses, and local government officials—to identify pressing urban challenges and opportunities. For example, in regions with significant informal settlements, indicators might need to focus on resource access and equity, while in rapidly urbanizing cities, indicators may prioritize infrastructure capacity and land-use efficiency.

Additionally, tailoring UM indicators involves considering the availability and reliability of local data. Planners should select indicators that align with existing data collection systems to ensure feasibility, or they should establish mechanisms for generating new, context-specific data where gaps exist. This includes integrating traditional knowledge and localized practices, particularly in regions where formal datasets may be limited.

Another crucial aspect of local adaptation is ensuring cultural and political alignment. For instance, indicators must resonate with local governance priorities and be framed in ways that are accessible to local decision-makers and the public. This enhances stakeholder buy-in and ensures that the selected indicators drive actionable and impactful urban planning interventions.

By tailoring UM indicators to local contexts, planners can address the unique challenges of individual urban systems while aligning with global sustainability objectives, ultimately fostering more inclusive and effective planning outcomes.

Adjusting actions in real-time based on planning reflections

Urban systems are dynamic and often subject to unforeseen changes, such as economic shifts, technological advancements, or environmental challenges. To remain responsive and effective, planners must adopt an iterative approach that incorporates continuous feedback and reflection, allowing for timely adjustments to strategies and interventions.

Reflection involves evaluating the progress and performance of planning actions against defined objectives, using insights derived from UM indicators. These indicators can provide quantifiable evidence of whether strategies are meeting their intended goals or if unintended consequences are emerging. For example, if material flow data indicates inefficiencies or imbalances in resource use during the implementation phase, planners can recalibrate their actions to address these issues promptly

To facilitate this process, planners should establish mechanisms for systematic feedback at regular intervals. Tools such as stakeholder consultations, participatory workshops, and periodic progress reports can provide valuable insights into how planning actions are being received and whether adjustments are needed. Furthermore, integrating digital tools and platforms that enable real-time monitoring of UM indicators can enhance the speed and accuracy of feedback.

By embedding reflection and adjustment into the planning process, urban planning becomes more adaptive and resilient. This approach not only ensures that plans remain aligned with overarching sustainability goals but also enables planners to respond proactively to emerging challenges and evolving stakeholder needs. Ultimately, these iterative and reflective practice positions planners to navigate complex urban challenges more effectively and deliver more impactful outcomes.

8.4.2 Recommendations for future research

This research provides a comprehensive overview of utilizing UM indicators to support strategic urban planning from a multidimensional perspective. Building upon the current stages of progress, several critical directions for future development are identified:

Developing cross-regional comparative studies

While the current research provides valuable insights through case studies in the Netherlands and Denmark, it remains largely Eurocentric. Extending this focus to other regions—particularly those in the Global South—can help uncover new dynamics and challenges that affect the selection, adaptation, and application of UM indicators.

In rapidly urbanizing regions such as Asia, Africa, and Latin America, urban systems face distinct pressures, including informal settlements, resource scarcity, and varying levels of institutional capacity. Comparative studies can examine how these factors influence the implementation of UM indicators and identify best practices that account for unique local conditions. For instance, in cities with limited data availability, research could explore how proxy data or community-driven monitoring can be incorporated into UM frameworks. Similarly, in regions with decentralized governance structures, studies could investigate how UM indicators can facilitate coordination among multiple jurisdictions and stakeholders.

Cross-regional research also provides an opportunity to examine the role of cultural and political differences in shaping the use of UM indicators. For example, while participatory governance is emphasized in European contexts, top-down approaches dominate in many Asian countries. Understanding how these governance models affect indicator selection and implementation can enhance the transferability and adaptability of UM methodologies globally.

By expanding the geographical scope of UM research, cross-regional comparative studies can contribute to a more comprehensive understanding of how UM indicators function in diverse settings. This, in turn, will strengthen the global applicability of UM frameworks and promote more inclusive and context-sensitive urban planning practices.

Incorporating circular economy principles beyond cities

Much of the current research on UM focuses on cities as discrete systems, the interconnected nature of urban, peri-urban, and rural areas necessitates a more holistic approach to circularity. Expanding the application of CE principles beyond the city scale can address resource flows, waste management, and economic interdependencies that extend across regional and even national boundaries.

Urban areas do not operate in isolation; they rely on surrounding regions for resources, labor, and waste absorption. Research into how CE principles can be applied across these interconnected systems would help planners optimize resource efficiency and minimize environmental impacts on a larger scale. For example, regional studies could explore how waste output from urban centers might serve as inputs for peri-urban agricultural or industrial systems, fostering closed-loop processes. This would align with CE principles by reducing waste, lowering resource extraction, and enhancing sustainability across the entire urban-rural continuum.

Future studies could also investigate governance and policy mechanisms required to facilitate CE integration across regions. This includes developing frameworks for collaboration among municipalities, industries, and communities within a region, as well as exploring financial incentives or regulatory tools that promote circular practices. Additionally, understanding how UM indicators can be adapted to measure circularity at regional and national levels would support more robust monitoring and evaluation of CE initiatives.

By extending CE principles beyond individual cities, research can provide a blueprint for sustainable development that accounts for the full complexity of resource flows and interactions within and between regions. This broader perspective is essential for achieving sustainability goals at national and global scales.

Exploring multi-method integration in UM research

Future research should focus on integrating multiple accounting methods to enhance the robustness and comprehensiveness of UM studies. While MFA remains a dominant and practical tool due to its standardized approach and data availability, it does not capture the full complexity of urban systems. Combining MFA with other methods, such as EmA, LCA, and Carbon Footprint Analysis, offers an opportunity to address these gaps and provide a more holistic understanding of resource flows, environmental impacts, and socio-economic interactions.

For instance, MFA excels in quantifying material inputs and outputs within an urban system, but it may lack the capacity to evaluate energy efficiency or ecological impacts in depth. EmA can complement MFA by assessing the energy value embedded in resource flows and providing a clearer picture of the sustainability of urban systems. Similarly, LCA offers insights into the environmental impacts of products and processes throughout their lifecycle, bridging the gap between resource use and long-term consequences of urban planning decisions.

The integration of these methods requires the development of hybrid frameworks that capitalize on the strengths of each approach. This involves designing methodologies that align data inputs, harmonize terminologies, and address inconsistencies between methods. Future studies could also explore how integrated approaches can be applied to real-world urban planning projects, particularly in addressing complex challenges such as circular economy implementation, climate adaptation, or equitable resource distribution.

By combining methods, future research can overcome the limitations of single method approaches and create a more nuanced understanding of urban metabolism. This multi-method integration would provide planners and policymakers with richer insights, enabling them to design more effective and sustainable strategies for urban development.

Enhancing the indicator selection process in strategic urban planning

While UM indicators are a focal point of this research, it is essential to broaden the scope to include indicators that address a wider array of urban challenges, such as social equity, economic resilience, and climate adaptation. This requires a more holistic approach to indicator selection, rooted in an in-depth understanding of the specific needs and priorities of stakeholders.

A critical step in this refinement process is the systematic assessment of stakeholder priorities. Urban planning projects often involve diverse groups—government agencies, businesses, communities, and academic institutions—each with unique perspectives and goals. Engaging stakeholders through participatory workshops, surveys, or focus groups can help planners identify the most pertinent indicators and ensure alignment with local and regional priorities. For example, while some stakeholders may prioritize economic growth, others may emphasize environmental conservation or social well-being, necessitating a balanced and context-sensitive set of indicators.

In addition to relevance, the selected indicators should be designed for continuous monitoring and evaluation. Mechanisms for iterative feedback, such as real-time data collection and periodic performance assessments, are essential for tracking progress and adapting strategies as urban conditions evolve. This dynamic approach ensures that the indicators remain responsive to emerging challenges and can inform timely decision-making.

By enhancing the indicator selection process, planners can develop more effective strategies that are inclusive, adaptable, and aligned with the multifaceted demands of modern urban environments. This improvement not only strengthens the planning process but also ensures that urban development efforts are sustainable and equitable across varying contexts.

Floriade, Almere (Photo by Yan Song 2022)

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Appendices

APPENDIX I

CIMO analysis of articles presenting urban metabolism mechanism and indicators

Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Al-Thani and Al-Ansari (2021)	This review article considers three popular concepts that support sustainable resource management in terms of potential areas for convergence and divergence.	Performance indicators to evaluate the different aspects of the industrial ecology and Energy-water-food nexus.	Life cycle assessment, material flow analysis	This review sets the premise for future work, which can help align the three guiding concepts into a combined holistic effort to manage resources depending on the problem considered, either through a single framework or a coordinated effort wherein all three concepts are deployed.
Arora et al. (2022)	This article brings together concepts of resource circularity and material flow analysis (MFA) to develop a demand- and discharge-driven water circularity assessment framework for cities.	Two key indicators of input and output circularity	Materials flow analysis (MFA)	It provides a quantitative tool to assess the scale of water circularity within engineered urban water infrastructure and its application to develop macro-level water systems planning and policy insights.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Athanassiadis et al. (2017)	This article proposes applying a production or urban metabolism (UM)-based approach to comprehensively assess the resource use and pollution emissions of Brussels Capital Region (BCR) over 40 years.	Energy, water input, materials input, greenhouse gas emissions, water output, materials output	Materials flow analysis (MFA)	This analysis brings forth a number of limitations that should be acknowledged in any attempt to comprehensively understand the metabolism of an urban system
Berigüete et al. (2023)	Urban metabolism is integrated as one of the three blocks to evaluate the impact of citizen initiatives.	11 indicators are applied to evaluate the metabolic efficiency in the theme of materials, energy, water, air quality, and waste.	Materials flow analysis (MFA)	The use of indicators also provides a standardized way of measuring progress or performance in different areas, allowing for more effective monitoring and evaluation.
Birgovan et al. (2022)	This article aims at outlining a framework for circular cities indicators based on their key characteristics, as well providing directions for fostering circularity at the city level.	Circular city indicators are selected and considered under seven pillars of the circular economy: materials are cycled at continuous high value; all energy is based on renewable sources; biodiversity is supported and enhanced through human activity; human society and culture are preserved; the health and well-being of humans and other species are structurally supported; human activities maximize the generation of societal value; and water resources are extracted and cycled sustainably	Materials flow analysis (MFA)	The need for a solid and realistic framework of indicators for a circular economy transition in cities emerges
Cárdenas-Mamani and Perrotti (2022)	This article proposed an integrated urban metabolism and ecosystem service framework to extend Economy-Wide Material Flow Analysis (EW-MFA).	A set of indicators was compiled from previous urban metabolism and ecosystem service studies to provide a shared and adaptable set of assessment categories	Economy-Wide Material Flow Analysis (EW-MFA).	This framework is an attempt to open methodological pathways into an in-depth examination of the role of natural capital in conventional approaches of resource demand assessments at the urban scale.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Chen and Chen (2014)	Find a way to balance economic development and ecosystem health within a workable framework.	1. Sets of material flow analysis, life cycle analysis, exergy- based analysis, and emergy analysis 2. Ecological network analysis sets	1. Element-based method 2. Structure-based method	An up-to-date inspection of integrating eco-indicators has both wide academic interest among interdisciplinary scientific board and realistic application meaning for a better urban management.
Chen and Wang (2014)	Learn from the insights of global cities, share best practices internationally, and discuss how cities and regions can play a leading role in creating a sustainable society	1. A new multi-layered indicator set for urban metabolism studies: definition information (spatial boundaries, constituent cities, population, economy), biophysical characteristics (climate, population density, building floor area), and metabolic flows (water, waste, materials, and all types of energy) of megacities. 2. Accounting scheme and its indicators from 13 flow elements and 9 fund elements.	1.Multi-layered urban metabolism 2. Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)	Probe into the regulation measures to optimize the configuration of water resources and realize the integration of the fundamental research innovation and the management practice, thus providing reasonable decision support for the nexus of water security, ecological security and sustainable socio-economic development of cities and regions.
Chifari et al. (2017)	To present a method useful for organizing a process of production and use of scientific information in which both scientists and the other social actors can have a bidirectional and constructive exchange of information.	Occupied land, power capacity electrical machineries, power capacity thermal machineries, process heat consumption, electricity consumption, fuel consumption, water consumption, fixed investments, running costs, cost of exports, electricity revenues, recyclables revenues, subsidies for electricity production.	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)	This approach provides a detailed characterization of the material balance of waste flows through the MSWMS.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Chrysoulakis et al. (2013)	Improve the communication of new bio-physical knowledge to end-users (such as urban planners, architects and engineers) with a focus on sustainable urban metabolism.	The indicators set used in BRIDGE evaluations: 1) Energy; 2) Thermal comfort; 3) Water; 4) Greenhouse gases; 5) Land use; 6) Mobility/ accessibility; 7) Social inclusion; 8) Human well-being; 9) Cost of proposed development; 10) Effects on local economy (employment and revenue)	Based on sustainability objectives and associated indicators addressing specific aspects of urban metabolism.	A tool like the BRIDGE DSS may not simplify the urban planning process, but it can help urban planners to deal more adequately with its complexity. Although implementation of the DSS during planning processes may be constrained by lack of resources and skills at municipalities, practitioners can gain significant insight for more informed decision making.
Feiferytė-Skirienė and Stasiškienė (2021)	This paper presents the concepts of circular economy, industrial symbiosis and circular urban system and how the new framework could improve cities transition to sustainability and circular economy, with detailed circular economy and industrial symbiosis indicators analysis.	Indicators in the areas of production and consumption, waste management, secondary raw materials, and competitiveness and innovation.	Material and energy flow analysis	This paper introduces the relations between industrial symbiosis, circular economy and urban metabolism concepts, how they can be used and monitored in the circular urban system framework.
Gao et al. (2021)	This study aims to establish a correlation via ecological network analysis and provides an analytical framework to explore the mechanism behind circular economy (CE) performance.	Resource productivity (RP), recycling rate (RR) and waste disposal amount (WDA)	Material flow analysis, ecological network analysis, ecological relationship analysis	This research provides policy decision support for understanding and improving urban CE performance and promoting CE development from the perspective of the material metabolism network of the socioeconomic system.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Goldstein et al. (2013)	Advances the ability to quantify environmental impacts of cities by modelling pressures embedded in the flows upstream (entering) and downstream (leaving) of the actual urban systems studied, and by introducing an advanced suite of indicators.	Indicators of environmental exchanges (material and energy inputs, air, soil, water emissions, etc.) For the modelled processes.	Urban metabolism and life cycle assessment (UM–LCA)	UM approach can be embedded within the process-based LCA framework, yielding a hybrid UM–LCA model that can provide a more complete measurement of the environmental pressures exerted by a city.
González et al. (2013)	Enable the formulation of planning and policy recommendations to promote efficient use of resources and enhance environmental quality in urban areas.	Water (i.e. Water balance, including evapotranspiration and run-off, and risk of flooding); air and climate (i.e. Air quality in terms of pollutant concentration and dispersion; as well as CO2 emissions, carbon sinks and energy balance); and material assets (i.e. Energy/ fuel consumption and associated heat fluxes, including heat island effects).	Analytical hierarchical process (AHP) multi-criteria assessment technique	The DSS can support impact assessment processes associated with the development and implementation of plans and projects, as well as contribute to monitoring and forecasting indicator performance in a planning context.
González-García et al. (2021)	A material flow accounting study combined with the Life Cycle Assessment approach is conducted for the municipality of Madrid	Indicators under 10 impact categories: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Human Toxicity - carcinogenic (HT), Fine Particulate Matter Formation (FPMF), Freshwater Ecotoxicity (FET), Land Use (LU), Water Consumption (WC) and Fossil Resource Scarcity (FRS)	Material flow analysis, life cycle analysis	Not only the development of precise estimation tools to quantify these flows, but also greater transparency of data sources, are fundamental elements in the study of the sustainability indicators proposed in this paper.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Gravagnuolo et al. (2019)	The analysis is carried out as a review of circular economy actions in the selected cities, and specifically aims to identify the key areas of implementation in which the investments in the circular economy are more oriented, as well as to analyze the spatial implications of the reuse of buildings and sites, proposing a set of criteria and indicators for ex-ante and ex-post evaluations and monitoring of circular cities.	Indicators in the sectors of built environment, energy and mobility, textile, waste, plastic, and agri-food	Material flow analysis	This article highlights a lack of indicators in some sectors and identifying a possible framework for "closed" urban metabolism evaluation from a life-cycle perspective, focuses on evaluation criteria and indicators in the (historic) built environment.
Hoekman and von Blottnitz (2017)	To contribute to the number of urban metabolism case studies using a standardized methodology.	Domestic extraction used, imports, exports, domestic processed output, direct material input, domestic material consumption, physical trade balance, direct material output.	Economy-wide material flow analysis (EW-MFA)	The study provides insights into the city's metabolism through various indicators including direct material input (DMI), domestic material consumption (DMC), and direct material output (DMO), among others.
Hong and Park (2023)	This article examined the effect of four circular water strategies on three water security goals for the city of Paju, South Korea.	Indicators of water efficiency, water self-sufficiency, and supply diversification. In addition the local water abstraction ratio, sourcing distribution, and diversity index	Materials flow analysis (MFA)	This study explored circular options to manage water as a resource from a metabolic perspective, but future studies are needed to evaluate other sustainability aspects, such as water quality, economic costs, environmental consequences, and/or water-related risks.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Hua et al. (2023)	This article investigates the solid waste metabolic characteristics of typical industrial metropolitan areas from the perspective of metabolic network relationships and provides suggestions for identifying management hotspots.	Network control analysis (NCA) and network utility analysis (NUA) on common industrial solid waste generation, hazardous waste generation	Input-output analysis, Ecological network analysis (ENA)	In this paper, a city-scale WIO model is constructed and the metabolic structure of solid waste at city and sectoral scales is studied based on ecological network analysis methods, providing new perspectives on urban solid waste management from the perspectives of direct and indirect solid waste generation, metabolic processes and structures and intersectoral metabolic relationships.
Huang et al. (2015)	This paper attempted to find the interrelations between land-use change and urban metabolism, by correlation analysis and regression analysis.	Emergy flex, emergy structure, emergy intensity, emergy efficiency, waste emission ratio	Emergy synthesis analysis	This paper solves the problem of conflicting measurement units, and avoid the disadvantages of subjective assignment.
Inostroza (2014)	A new indicator to measure this process of material accumulation is proposed, namely, the Technomass.	Technomass aspects (e.g. Buildings, roads, cars, furniture, clothes, machines, technological assets); Flows (e.g. Water, food, energy, supporting flow)	Materials flow analysis (MFA)	In metabolic terms, the indicator looks into the black box, providing the possibility to link metabolic behaviors with urban form and attempting to fill the gap between urban planning, UM and Material Flow Analysis (MFA). This new indicator offers a broad scope of applications. Further possibilities and links to urban research and policy making are explored in the discussion section.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Kennedy et al. (2014)	A new 'multi-layered' indicator set for UM studies in megacities.	Information on the definition (spatial boundaries, constituent cities, population, economy), biophysical characteristics (climate, population density, building floor area), and metabolic flows (water, waste, materials, and all types of energy) of megacities.	Multi-layered urban metabolism indicator set	Use of the standardized indicator set will ease inter-city comparisons of urban metabolism, whilst enhancing knowledge of megacities and their transformation into sustainable systems.
Kennedy et al. (2015)	To quantify the energy and material flows for the world's 27 megacities, based on 2010 population, and second to identify physical and economic characteristics that underlie these resource flows at multiple scales.	Resource flows of electricity consumption, heating and industrial fuel use, ground transportation energy use, water consumption, waste generation, and steel production in terms of heating-degree-days, urban form, economic activity, and population growth.	Materials flow analysis (MFA)	Overall energy and material flows vary considerably among megacities. It has provided previously unidentified insights into the relation between electricity consumption and urban form.
Lanau et al. (2021)	This article introduced a complementary indicator of carbon replacement value (CRV) to account for emissions embodied in the urban stocks.	Carbon replacement value (CRV)	Carbon accounting	CRV accounting is also valuable to benchmark the amount of emissions that would be needed for developing cities to reach the same level of services as industrialized cities.
Landa-Cansigno et al. (2020)	This paper evaluates the metabolism-based performance of a number of centralised and decentralised water reuse strategies and their impact on integrated urban water systems (UWS) based on the nexus of water-energy-pollution.	Reliability of water supply, potable water, total energy, GHG emissions, Eutrophication potential	Water-energy-pollution nexus	The results show metabolism performance assessment in a complex system such as integrated UWS can reveal the magnitude of the interactions between the nexus elements (i.e. water, energy, and pollution).

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Li et al. (2016)	Material flow analysis was applied in conjunction with specific socio-economic indicators to model urban metabolism and evaluate appropriate urban metabolism changes for the study case.	Four major component inputs and outputs of the city: metals and industrial minerals, energy consumption, construction materials and biomass (predominantly from the surrounding farming areas).	Materials flow analysis (MFA)	The study showed that MFA techniques can be used as valuable tools for understanding urban metabolism, evaluating urban sustainability, and suggesting strategies for the timely addressing of urban sustainability issues.
Liu et al. (2017)	a model framework of urban water metabolism was used as an example to analyze the natural hydrological processes and social water metabolism in an urban ecosystem. Water	Water supply, wastewater, evaporation, rainwater infiltration, runoff	Urban eco-metabolism model framework	The model has provided a tool for urban planners to improve landscape patterns and infrastructure layouts within urban ecosystem to build sustainable cities
Marcone et al. (2022)	This paper examines the composition, features, and topical coverage of national bioeconomy indicator sets with a threefold analysis: (1) assessment of the integration of circularity principles in the sets and their alignment with existing policy frameworks; (2) appraisal of quality and the fulfillment of the sets' functional purposes; (3) evaluation of the breadth and depth of tackled issues.	The indicator sets of four countries are assessed from 3 aspects, 6 categories and 36 components.	Materials flow analysis (MFA)	This paper proposes to include grounding the underlying indicator frameworks in both theory and policymaking practice, including indicator diversity for a more conclusive monitoring approach, aligning definitions of the Circular Bioeconomy with EU-wide policymaking

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Neves et al. (2023)	This paper describes the MetaExplorer, a GIS-platform, which gathers trustable energy-related datasets, at municipal level for Portugal, providing a user-friendly georeferenced visualisation tool that can be used to derive statistical models, and support policymaking.	28 indicators are applied in the platform in the categories of electricity, energy, emissions, mobility, buildings, waste management, social, economy, and socio-economic metabolism under both municipality and national scale.	Materials flow analysis (MFA)	This article presented demonstrate the capability to provide support to policymakers and develop customized cross-sectorial analyses on energy transition strategies, which is innovative when compared to other platform attempts, that focus only on data providence, or need developer's environment (such as python) to be assessed.
Pakina and Mukhamedina (2023)	Urban metabolism is applied to study urban sustainability, and to identify strengths and weaknesses of current state of city's development	Sustainable Development of Energy, Water, and Environment Systems (SDEWES) Index: 7 dimensions and 35 main indicators.	Materials flow analysis (MFA)	The SDEWES indicator framework can be used to evaluate and to compare cities strengths and weaknesses by multiple criteria.
Peponi et al. (2022)	This study couples Life Cycle Thinking (LCT) and Machine Learning (ML) adopting smart and regenerative urban metabolism to assess purchasing power per capita (IpC) changes driven by the multidimensional metabolic processes.	Indicator under urban process	Life cycle inventory, sensitivity analysis	An innovative and novel evidence-based methodology to manage the complexity of urban processes, that can enhance their resilience as part of the concept of smart and regenerative urban metabolism with the overarching intention to better achieve sustainability.
Rosado et al. (2016)	To contribute to the discourse on urban area typology as well as on identifying urban metabolism characteristics.	Eight urban metabolism characteristics: Needs; Accumulation; Dependency; Support; Efficiency; Diversity of Processes; Self-Sufficiency; and Pressure on the environment.	Materials flow analysis (MFA)	The extent of the imbalance between the types of materials extracted, consumed and stocked, which makes urban areas vulnerable to external changes in resource supplies.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Rufí-Salís et al. (2021)	The goal of our study is to analyze the environmental and circularity performance of applying circular strategies in urban agriculture systems.	Global Warming, Freshwater Eutrophication, Marine Eutrophication, Ecotoxicity, Cumulative Energy Demand, Linear Flow Index, Auxiliary Equipment, Rainwater Harvesting System	Life cycle assessment, material flow analysis	The use of these indicators provides a simple understanding of the circular and environmental performance of these systems while being fully adaptable. With these indicators, the uses of nutrient recirculation, struvite fertilizer or recycled materials were the best strategies to improve urban agriculture.
Shahrokni et al. (2015)	To analyze the implementation of the new-proposed smart urban metabolism framework and convey the potential short- and long-term implications of it,	Geospatial data, emission, electricity, water input, waste, biogas, renewable energy,	Smart urban metabolism framework	This article serves as a proof of concept of the SUM methodology and may provide a basis for other projects that aspire to advance this methodology. Most barriers identified revolved around trust to collect and integrate data from data owners.
Sun et al. (2016)	To develop an integrated MFA and emergy evaluation model to investigate the environmental and ecological benefits of urban industrial symbiosis implementation.	Urban statistics (urban level input and output flows), and micro level material and energy flow analysis (input and output flows within symbiotic network).	Integrated material flow analysis (MFA)	This paper provided useful modelling approach to understand the eco- logical benefits and trade-offs of local circular economy practices and fundamental insights on natural capital accounting.
Sun et al. (2023)	The research demonstrated a hypothesis that flows of primary resources, waste, and carbon emissions displayed a certain level of synchronicity in the past decades.	Indicators on resources use, carbon emissions, waste generation, and decoupling with GDP.	Material flow analysis, decomposition analysis	Increase in economic activities might drive up the material metabolism, but it was largely counteracted by a growing resource efficiency, which was probably the most significant driver to resource use and emissions.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Voukkali et al. (2023)	he objective of this paper was to identify the major challenges occurred due to the rapid urbanization in a coastal city though a qualitative and quantitative waste compositional analysis.	This article proposes the waste compositional analysis (WCA) as a new indicator n the literature for determination of the degree of metabolism in an island region.	Decomposition analysis	he most important outcome is related with the importance of WCA as an indicator for the determination of urban metabolism and the possibility for the future planning to meet the future needs.
Wang et al. (2018)	This study explores the driving forces in UM within a socioeconomic context.	Material input, construction industry, construction waste, urban use demand	Materials flow analysis (MFA)	This study provides a case that facilitated exploration of a relationship between material consumption, society and the economy.
D. Yang et al. (2014)	To create sustainable cities has led to increasing concern on achieving healthy spatial metabolic interactions and system sustainability.	Emergy-based indicators: renewable resources; non-renewable resources; local agriculture products; agricultural consumption; agricultural pollutants; residents' consumption; imports; exports.	Emergy synthesis analysis	It shows how emergy synthesis can effectively integrate economic, social and ecological dimensions and provide insights into cross-boundary metabolic interactions and system metabolic sustainability.
Zhai et al. (2018)	Combing input-output analysis with ecological network analysis help academics to shed light into the complicated system interactions and interior energy flows.	Embodied ecological energy element intensity, direct integral flow control intensity, average mutual information, residual uncertainty.	Energy Ecological Network model and Input-output analysis	The detailed study on the direction of energy flows uncovers the relationship between social production activities and energy circulation. A thorough insight into robustness creatively provides a reference for improving the system efficiency.
Zhai et al. (2019)	This paper investigated the impacts of different energies on the energy metabolism levels and the inter-departmental ecological relations of Guangdong.	Alternative indicators	Ecological network analysis, input-output analysis, Energy Metabolism Network (EMN)	It is expected that the results will provide scientific support to guide the reform of urban energy metabolic system in an attempt to coordinate the energy development strategy, improve the energy consumption structure and maintain energy security and stability.

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Authors	Context (C)	Indicators (I)	Mechanism (M)	Outcomes (O)
Zheng et al. (2019)	In this study, a wastewater metabolism input-output model is developed to achieve sustainable development through a novel perspective to depict the industrial wastewater flow among sectors.	Industrial waste water discharge	Wastewater metabolism input-output model	A wastewater metabolism input-output model is developed to achieve sustainable development through a novel perspective to depict the industrial wastewater flow among sectors.
Zucaro et al. (2014)	To identify the major drivers of change in the investigated period as well as future low-resource scenarios.	Renewable input, imported input, output, reference unit, emergy ratio, climate change, acidification,	Extended LCA approach and emergy	This paper proposed the application of decomposition analysis techniques to understand how specific drivers affect the selected extensive variables.

APPENDIX II

Urban metabolism indicators and their characteristics

Indicator	Analytical model[a]	Accounting method[b]	Indicator type[c]	Indicator level[d]
Air temperature	BB	MFA	D	M
Annual precipitation	BB	MFA	D	M
Anthropogenic heat	BB	MFA	D	F
Average household expenditure ratio	GB, NE	MFA	P	M
Bowen ratio	BB	MFA	P	M
Brownfields re-used	BB	MFA	D	M
Carbon sinks	BB	MFA	D	M
Concentrations (NO_x, PM10, PM2.5, O_3, CO, SO_2)	GB	MFA	D	F
Construction material import	GB	MFA,ESA	D	F
Cost of proposed development effects	BB	MFA	D	M
Density of development	GB	MFA	P	M
Effects on local economy (employment)	BB	MFA	P	M
Effects on local economy (revenue)	BB	MFA	P	M
Electricity	BB,GB,NE	MFA,ESA	D	M
ELR (environment load ratio)	NE	ESA	P	F
Embedded energy ratio	GB	MFA	P	M
Embedded mass ratio	GB	MFA	P	M
Emergy density	BB,NE	ESA	P	F
Emergy per capita	BB,NE	ESA	P	F
Emergy self-support ratio	BB	ESA	P	F
Emergy turnover ratio	BB	ESA	P	F
Emissions (CO_2, CH_4)	BB,GB,NE	MFA,ESA	D	F
Employee numbers	BB	MFA	D	M
Energy balance	GB,NE	MFA,ESA	P	M
Energy consumption by cooling/heating	GB	MFA,ESA	D	F
Energy consumption by transport	GB	MFA	D	F

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Indicator	Analytical model[a]	Accounting method[b]	Indicator type[c]	Indicator level[d]
Environmental pressure	BB,NE	MFA	P	M
ESI (emergy sustainable indices)	BB,NE	ESA	P	F
Evapotranspiration	GB	MFA	D	F
Exceedances (NO_x, PM10, O_3, SO_2)	GB	MFA	D	F
Exported emergy	BB	ESA	D	M
EYR (emergy yield ratio)	NE	ESA	P	F
Food import	BB	MFA,ESA	D	M
GDP	BB	MFA	D	M
GDP emergy ratio	BB	ESA	P	F
Heat island effects	BB	MFA	P	M
Imported emergy	BB	ESA	D	M
Incoming solar radiation	BB,GB	MFA,ESA	D	F
Infiltration	GB	MFA	D	M
Length of cycle-ways provided	GB	MFA	D	F
Length of new roads provided	GB	MFA	D	F
Metabolic efficiency	BB,NE	MFA	P	F
New urbanized areas	GB	MFA	D	M
Non-renewable emergy	BB,GB	ESA	D	F
Number of days above air temperature threshold	GB	MFA	D	F
Number of inhabitants affected by flash flooding	GB	MFA	D	F
Number of inhabitants affected by heat waves	GB	MFA	D	F
Number of inhabitants with access to public transport	GB	MFA	D	F
Number of inhabitants with access to services	GB	MFA	D	F
Number of inhabitants with access to social housing	GB	MFA	D	F
GWP (Gross World Product) per capita (tons CO_2 equivalents/person/year)	GB	MFA	P	F
Percentage of energy from renewable sources	GB	MFA	D	F
Percentage of use of public transport	GB	MFA	D	F
Potential flood risk	BB	MFA	P	M
Potential population exposure (NO_x, PM10, O_3, SO_2)	GB	MFA	P	F
Quality of pedestrian	GB	MFA	P	F
Ratio of population	BB	MFA	P	M
Renewable emergy	GB	ESA	D	F
Socio-economic efficiency	BB	ESA	P	M
Solid, liquid and gaseous fossil fuels	BB,GB	MFA,ESA	D	F
Surface run-off	BB	MFA	D	F
Thermal comfort	BB	MFA	D	M

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Indicator	Analytical model[a]	Accounting method[b]	Indicator type[c]	Indicator level[d]
Total emergy	BB	ESA	D	M
Waste emergy	GB	ESA	D	F
Waste water emission	BB,GB,NE	MFA,ESA	D	F
Water balance	BB	MFA	P	F
Water consumption	BB,GB,NE	MFA,ESA	D	M
Water import	BB,GB	MFA,ESA	D	M
Wood import	BB,GB	MFA,ESA	D	M

[a] *BB – black-box model, GB – grey-box model, NE – network model.*
[b] *MFA – material flow analysis, ESA – emergy synthesis analysis.*
[c] *D – descriptive, P – performative.*
[d] *M – material, F – functional.*

APPENDIX III

Questionnaire: A study of the designers' perspective on urban metabolism indicators

Assessing Urban Metabolism Indicators

A study of the designers' perspective on urban metabolism indicators

Introduction: *Urban metabolism is a multi-disciplinary approach which has been advanced for quantifying resource flows in the urban system. Its applications have been used in many domains. One of the most efficient application is indicator analysis, which is an efficient way to assess design performance. This study is part of an ongoing PhD that research focuses on applying urban metabolism in sustainable urban design. It is part of Horizon 2020 Research and Innovation Action project REPAiR (REsource Management in Peri-urban Areas: Going Beyond Urban Metabolism).*

Aims: *The major topic of this survey is to get to know the attitudes of designers towards urban metabolism indicators. It aims i) to acquire urban designers' awareness of urban metabolism indicators, ii) to develop feasible urban metabolism indicator framework as support for urban design, and hence iii)to help make urban design toward sustainability.*

Instructions: *Based on the indicator themes, the indicators are grouped into 3 parts: environment indicators, resource flow indicators, and city development indicators. Please evaluate each indicator separately. Responses will be anonymised.*

General information

0.1 Category of work
☐ Student ☐ Academic ☐ Practitioner

0.2 Level of education:
☐ PhD degree
☐ Master degree
☐ Bachelor degree

For the questions forthcoming:
Please read the description of each indicator. Then, evaluate each indicator in the aspects below, according to which you agree to disagree with each one.

The aspects are:
- *Understandable: Based on the short description, I can understand the meaning of the indicator and aware the limitation of it.*
- *Applicable: The indicator can be applied in spatial planning. It can be presented in my project.*
- *Available: The data for the indicator is available. I know how I can get data from related bureau/company/institution.*
- *Unique: The indicator is unique in the theme. It can not be replaced by other indicators.*

Part I: Environment Indicators

1.1 Water condition

a. **Precipitation**: the amount of rain, snow, sleet, or hail that falls to or condenses on the ground, it is is a major component of the water cycle.

b. **Evapotranspiration**: the amount of water which is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

c. **Infiltration rate**: velocity or speed at which water enters into the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour.

d. **Surface run-off**: the amount of water flow that occurs when excess stormwater, meltwater, or other sources flows over the Earth's surface.

Please list the indicator(s) in water condition theme that is(are):
Understandable:...
Applicable:
Available:
Unique:

1.2 Air quality

a**. Air temperature**: a measure of how hot or cold the air is.

b. **Air pollutant concentration**: concentration of air pollutants or toxins emitted from sources such as industrial plants, vehicular traffic or accidental chemical releases.

c. **Exceedance**: the concentration of air pollutants exceeds the limit values.

Please list the indicator(s) in air quality theme that is(are):
Understandable:
Applicable:...
Available:
Unique:

1.3 Carbon

a. **Carbon sinks**: an area that accumulates and stores some carbon-containing chemical compound for an indefinite period.

Please list the indicator in carbon theme that is:
Understandable:
Applicable:
Available:
Unique:

1.4 Thermal

a. **Heat island effect**: an urban area or metropolitan area that is significantly warmer than its surrounding rural areas due to human activities.

b. **Heat balance**: the distribution of the heat energy supplied to a thermomechanical system among the various drains upon it including both useful output and losses.

c. **Thermal comfort**: the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

Please list the indicator(s) in the thermal theme that is(are):
Understandable:
Applicable:
Available:
Unique:

Part II: Resource flow indicators

2.1 Resource input

a. **Biomass**: the gross of organic materials, such as food, wood, and agricultural crops.

b. **Minerals**: the gross of minerals, metals, rocks and hydrocarbons (solid and liquid) that are extracted from the earth by mining, quarrying and pumping.

c. **Water input**: the amount of water imported into the city.

d. **Fossil fuels**: the amount of a natural fuel, such as coal or gas.

e. **Renewable energy**: the amount of energy from a source that is not depleted when used, such as wind or solar power.

f. **Waste input**: the amount of unwanted or unusable materials imported into the city.

g. **Other input**: other materials imported into the city.

Please list the indicator(s) in resource input theme that is(are):
Understandable:
Applicable:
Available:
Unique:

2.2 Resource output

a. **Solid waste**: the amount of solid waste consisting of everyday items that are discarded by the public.

b. **Wastewater**: the amount of water that has been affected by human use and exported to nature.

c. **Gas emissions**: the gross of atmospheric gases that contribute to the greenhouse effect by absorbing infrared radiation produced by solar warming of the Earth’s surface.

d. **Electricity**: the amount of electric energy produced by transforming other forms of energy into electrical energy.

e. **Industrial products**: the amount of exported machinery, manufacturing plants, materials, and other goods or component parts for use or consumption by other industries or firms.

Please list the indicator(s) in resource output theme that is(are):
Understandable:
Applicable:
Available:
Unique:

2.3 Resource throughput

a. **Construction**: the amount of the materials used to build or make something.

b. **Water storage**: the amount of water stored within the city.

c. **Stored industrial products**: the amount of stored machinery, manufacturing plants, materials, and other goods or component parts for use or consumption by other industries or firms.

Please list the indicator(s) in resource throughput theme that is(are):
Understandable:
Applicable:
Available:
Unique:

Part III: City development indicators

3.1 Population growth

a. **Population characteristic change**: the change of qualities and characterization of various types of populations within a social or geographic group.

b. **Demographic composition change**: the change of human population composition over time.

Please list the indicator(s) in the population growth theme that is(are):
Understandable:
Applicable:
Available:
Unique:

3.2 Economy development

a. **GDP**: Gross domestic product

b. **Employee condition variation**: the change of employee condition.

c. **Effects on the local economy**: local economy development due to the city development

Please list the indicator(s) in economy development theme that is(are):
Understandable:
Applicable:
Available:
Unique:

3.3 Land-use transition

a. **New urbanised area**: the area that is developed into a density of human structures such as houses, commercial buildings, roads, bridges, and railways.

b. **Land-use transformation**: the area that the land-use is changed.

Please list the indicator(s) in land-use transition theme that is(are):
Understandable:
Applicable:
Available:
Unique:

3.4 Transportation changes

a. **Transportation construction growth**: the amount of construction for building new transportation.

b. **Public transportation accessibility**: the quality of transit serving a particular location and the ease with which people can access that service.

c. **Transportation method change**: the composition of different transportation method over time.

Please list the indicator(s) in transportation changes theme that is(are):
Understandable:
Applicable:
Available:
Unique:

3.5 Waste management

a. **Waste management accessibility**: the quality of waste management facilities and the ease with which people can access to them.

b. **Waste management organisation**: the numbers and efficiency of waste management organisations in a particular area.

Please list the indicator(s) in waste management theme that is(are):
Understandable:
Applicable:
Available:
Unique:

Others

4.1 This evaluation takes me ... minutes to finish.

4.2 Please add any additional comments to urban metabolism indicators:

4.3 Please indicate your interest in the following:

☐ I am available for follow-up questions if needed
☐ I would like a copy of the summary of findings from this evaluation

(Name:. / Email:)

Thank you very much for participating this evaluation!

APPENDIX IV

The urban metabolism indicators applied in the selected Dutch projects

(ordered by scales)

<table>
<tr><th>Metropolitan</th><th>City</th><th>Neighborhood</th></tr>
<tr><td>A Circular Economy in the Netherlands by 2050
[Based on five prioritized sectors]

– Biomass and food (including, efficiency in the use of biomass, sustainably produced biomass)
– Plastics (including, proportion of collected and recycled plastic packaging, recycled plastics, recycling of discarded plastic packaging, percentage of renewable plastics, CO_2 emissions from plastics)
– Manufacturing industry (including, upcycled critical metals, raw metals use efficiency, awareness of business on the risks and opportunities involved in metals)
– Construction (including, the reuse of construction and demolition waste, CO_2 reduction in the construction and operational phases, reuse of construction materials)
– Consumer goods (including, the annual volume of household residual waste, the volume of residual waste from companies, organizations, and governments)</td><td></td><td></td></tr>
<tr><td colspan="2">IABR Rotterdam (International Architecture Biennale Rotterdam) 2014
[Based on different resource flows]
– Goods (including, ship intensity, motorway intensity, industrial company number and locations)
– People flows (including, signal strength strong, education level, reachable jobs within 45 mins, problematic neighborhood)
– Waste (including, recyclation of household waste, organic waste per neighborhood, waste recycle points, wood waste, metal, residual household waste)
– Biota (including, animal migration, river gradient salt-sweet, park and forest)
– Energy flows (including, Hotspots heat surplus and demand, light pollution, CO_2 emission, global irradiation)
– Food (including, fertilizer input, chlorophyll concentration, nutrient sink, wastewater treatment, phosphate per neighborhood, nutrient loss in river)
– Fresh water (including, soil salinization, annual precipitation, river gradient salt-sweet)
– Sand and clay (including, land subsidence zones, sea depth)
– Air (including, NO_x emission, SO_2 emission, life expectancy, NO_2 emission, fine dust)</td><td></td></tr>
</table>

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TOC

<table>
<tr><th>Metropolitan</th><th>City</th><th>Neighborhood</th></tr>
<tr><td colspan="2">Circular Rotterdam
[Based on themes]

– Resource usage (including, total raw material productivity, primary raw material productivity, raw material demand per capita, primary raw material demand per capita, percentage of renewable material used, percentage of recycled material used, waste generated per capita, percentage of solid material applied to high-value reuse, solid material applied to low-value reuse, percentage of solid waste to landfill and incineration without energy recovery, percentage of scarce materials recovered at high value, percentage of high impact materials recovered at high value, potentially toxic material flows, energy requirement per capita, GDP per energy requirement, supply renewable energy)
– Environmental impact (including, CO_2 intensity, embedded water use, embedded land use, embedded energy use, embedded CO_2 emissions, raw materials with high risk for impact on biodiversity)
– Society, health and culture (including, social cohesion, health good/very good, population with middle or high education, annual average air quality particulate matter, percentage of population dying from diseases of the respiratory system)
– Economic performance (including unemployment, average household income, change in GDP through circular activities, share of circular jobs, change in circular jobs, population below poverty line)</td><td></td></tr>
</table>

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TOC

<table>
<tr><th>Metropolitan</th><th>City</th><th>Neighborhood</th></tr>
<tr><td colspan="2">H2020 REPAiR Project (Resource Management In Peri-Urban AReas: Going Beyond Urban Metabolism)
[Based on different impacts]

– Odor (Malodorous air)
– Visual impacts
– Accessibility /convenience of use (including, time-use for waste sorting, willingness to pay for others handling the sorting, percentage of doorways attending to the distance to the bin)
– Climate change (global warming potential)
– Acidification (terrestrial acidification potential)
– Particulate matter formation (particulate matter formation potential)
– Biodiversity (loss of species during a year)
– Human toxicity
– Occupational health
– Environmental human health (including disability-adjusted loss of life years, disability-adjusted loss of life years due to urban air pollution)
– Eutrophication potential (including fresh water eutrophication potential, marine eutrophication potential)
– Ecotoxicity (including ecotoxicity ecosystems, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity)
– Fossil resource depletion (including, Cumulative Exergy Extraction from the Natural Environment, Abiotic Depletion Potential fossil fuels, Cumulative Exergy Demand, CED, ReCiPe Midpoint indicator, Material Input Per Service unit)
– Water use (including, CEENE, CExD, water depletion, water footprint)
– Land use (including, ecological footprint, CEENE, land occupation, natural land transformation)
– Urban space consumption
– Capital productivity (capital expenditure)
– Labor productivity (operational expenditure)
– Revenues (projected revenues)
– Social costs (including, cost savings from waste diversion from landfill, cost savings from substituting energy by waste-based energy, cost savings from substituting materials and fertilizers by waste-based products, ReCiPe Endpoint indicator, LCC with externalities internalized)
– Public acceptance (including, willingness to pay for a project to be implemented, participation rate separate waste collection)
– Employment quantity (number of jobs created)
– Landscape fragmentation (the effective mesh size)
– Stakeholder involvement (stakeholder engagement and partnering)
– NIMBY syndrome (public perception of risk)
– Effectiveness in achieving behavior change (type of cooperation and/or participation in waste management programs and activities)
– Accessibility to green space (distance for accessing urban green spaces from home)
– Taxes (conventional life cycle costing LCC)
– Impact on resource productivity (resource productivity)</td><td></td></tr>
</table>

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Metropolitan	City	Neighborhood
	Circular Amsterdam – Value created – Job growth – Material savings – CO2 reduction – Raw material efficiency – Use of renewable resources – Gross value added – Circular services – Environmental costs – CO2 emissions	
	Urban Pulse Project – Imported resource (including biomass, minerals, fossil fuels, industry products, other imports) – Exported resources (including, biomass, minerals, fossil fuels, industry products, other exports) – Renewable energy – Recovered materials and energy from waste – Waste (including, municipal solid waste, industrial waste, construction and demolition waste) – Flows to nature (including, emissions into air, waste landfilled, emissions to water, dissipative flows) – Direct material input/GDP – Direct material input/capita – Domestic material consumption/GDP – Domestic material consumption/capita – Population – Land area – Population density – GDP – Annual precipitation	
	Circulair Den Haag – CO2 emission reduction – Value created – Job growth – Material savings	

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Metropolitan	City	Neighborhood
		Circulair Buiksloterham **[Based on different theme]** – Energy (including, total energy demand, renewable sources in remaining energy demand, local energy production, energy distribution system loss) – Products and materials (including household and office material demand, material recovery in new buildings, incinerated waste, reuse and recycling rate) – Water (including, domestic and commercial water demand, recovered nutrients and other resources from wastewater, micropollutants from wastewater, rainwater management) – Ecosystem and biodiversity (including, soil pollution, biodiversity through number of unique species in the area, zero-emission) – Infrastructure and mobility (including elimination of combustion engines, energy demand for vehicle-based transport, parking spots) – Socio-cultural (including, green surface, number of trees per 100m to enable hydraulic buffering and ecological corridors, crime rates, cost of living, housing and affordability) – Economy (including, the region’s general progress indicator, local unemployment, ecological footprint per euro) – Health and wellbeing (including, Gallup-Healthways well-being index, bi-annual Subjective Wellbeing Survey)
		De Ceuvel – Renewable heat and hot water supply – Electricity demand over conventional – Wastewater and organic waste treatment – Nutrient recovery – Water self-sufficiency – Vegetable and fruit production using locally recovered nutrients – Total phase 1 materials cost

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Metropolitan	City	Neighborhood
		Circulaire werklocaties **[Based on different themes]** – Energy (including building and usage-related energy demand, energy production, renewable and affordable resources) – Materials (including continuously recycled materials, use of secondary material, use of low impact materials, material management) – Water (including, water consumption, reuse of water for industrial processes, climate resilience) – Biodiversity (including, effect on existing ecosystem, habitat space) – Human activities and culture (including, connection to urban areas, accessibility, diverse system for different forms of ideas) – Resilient and adaptive economic system (including, long-term economic value, cost for space and functions) – Wellbeing (including, the mental and physical well-being of the users, WELL standard in the design of the buildings)

Curriculum Vitae

Yan SONG

1990
Born in Baotou, China

2008 - 2012
Bachelor of Science in Landscape Architecture at the department of Landscape Architecture, Tongji University, Shanghai, China

2012 - 2013
Volunteering teaching at Lizhuang Middle School, Yibin, China

2013 - 2016
Master of Engineering in Landscape Architecture at the department of Landscape Architecture, Tongji University, Shanghai, China

2014 - 2016
Master of Science in Transformation of Urban Landscapes at Faculty of Geosciences, Ruhr University, Bochum, Germany

2016 – present
PhD candidate at the chair of Environmental Technology and Design, Department of Urbanism, Delft University of Technology, Delft, the Netherlands.

2022 – present
Business analyst at Elsevier, Amsterdam, the Netherlands

Yan Song was born in Baotou, Inner Mongolia, China, in 1990. In 2008, he began studying Landscape Architecture at Tongji University (Shanghai, China), where he earned a Bachelor of Science in Landscape Architecture in 2012.

After graduation, he spent a year volunteering as a teacher at Lizhuang Middle School (Yibin, China). The following year, he pursued a Master of Landscape Architecture at Tongji University’s Department of Landscape Architecture. After completing his first year of graduate studies, he participated in a dual-degree program on Urban Landscape Transformation at Ruhr University (Bochum, Germany), where he was awarded a DAAD (German Academic Exchange Service) scholarship.

In 2016, he completed his master’s thesis, The Biodiversity Design Framework of High-Density Habitat in Cities, with distinction and obtained dual master’s degrees. That same year, he received a CSC (Chinese Scholarship Council) scholarship (No. 201606260044) and began his PhD at Delft University of Technology (Delft, the Netherlands), in the chair of Environmental Technology and Design within the Department of Urbanism.

During his PhD, he also contributed to the Horizon 2020 project REPAiR (No. 688920), participated in Master’s track course teaching, attended several international conferences, presented his research, and published in academic journals.

Since 2022, he has been working as a Business Analyst at Elsevier, an academic publishing company specializing in scientific, technical, and medical content, based in Amsterdam. Alongside his professional career, he continues to volunteer as a Chinese language teacher at Delft Chinese School. In 2024, he was elected as the president of Tongji University Alumni Association in Benelux. Additionally, he founded Museum Master, a company dedicated to spreading knowledge about art and museums.

Publications

Journal Articles

Teng, Y.,& Song, Y. (2022). Beyond legislation and technological design: The importance and implications of institutional trust for privacy issues of digital contact tracing. Frontiers in Digital Health, 4, [916809].

Song,Y., & Liu,M. (2021). Diversity and Connection: A Study of the Landscape Architecture (Post)graduate Training in Dutch Universities. Proceedings of China Landscape Architecture Education Conference, 374-380.

Kaika, M., Song, Y., & Chen, C. (2020). “Don’t Call Me Resilient Again!”: The UN Habitat New Urban Agenda as Immunology. Landscape Architecture Journal, 27(5): 52-58.

Song, Y., van Timmeren, A., & Wandl, A. (2019). A literature review and categorisation of sustainability-aimed urban metabolism indicators: a context, indicator, mechanism, outcome analysis. Regional Statistics, 9(1), 54-71.

Song, Y., Gil, J., Wandl, A. & van Timmeren, A. (2018). Evaluating sustainable urban development using urban metabolism indicators in urban design. Europa XXI, 34, 5-22.

Wang, M., Zhou, M., Song, Y., & Wang, Y. (2018). Study on Spatial Governance of Ecological Risk in Rural Tourism Development. Nanfang Jianzhu / South Architecture, 188(6), 66. (in Chinese)

Conference Articles

Song, Y., Gil, J., Wandl, A., & van Timmeren, A. (2017). Improving sustainable urban development using urban metabolism indicators. In Siłka, P. (Ed.), Books of Abstracts of Warsaw Regional Forum 2017: Space of Flows. (p.28). Warsaw, Poland.

Song, Y., van Timmeren, A., & Wandl, A. (2017). Defining sustainability-aimed urban metabolism indicators. In: Book of Abstracts of the International Conference on Changing Cities III: Spatial, Design, Landscape & Socio-Economic dimensions (p. 215). Thessaloniki, Greece: Grafima Publications.

Conference Presentation

September 2022, 14th ISIE SEM Conference, Vienna, An Integrative Framework for Selecting Urban Metabolism Indicators in a Strategic Urban Planning Process.

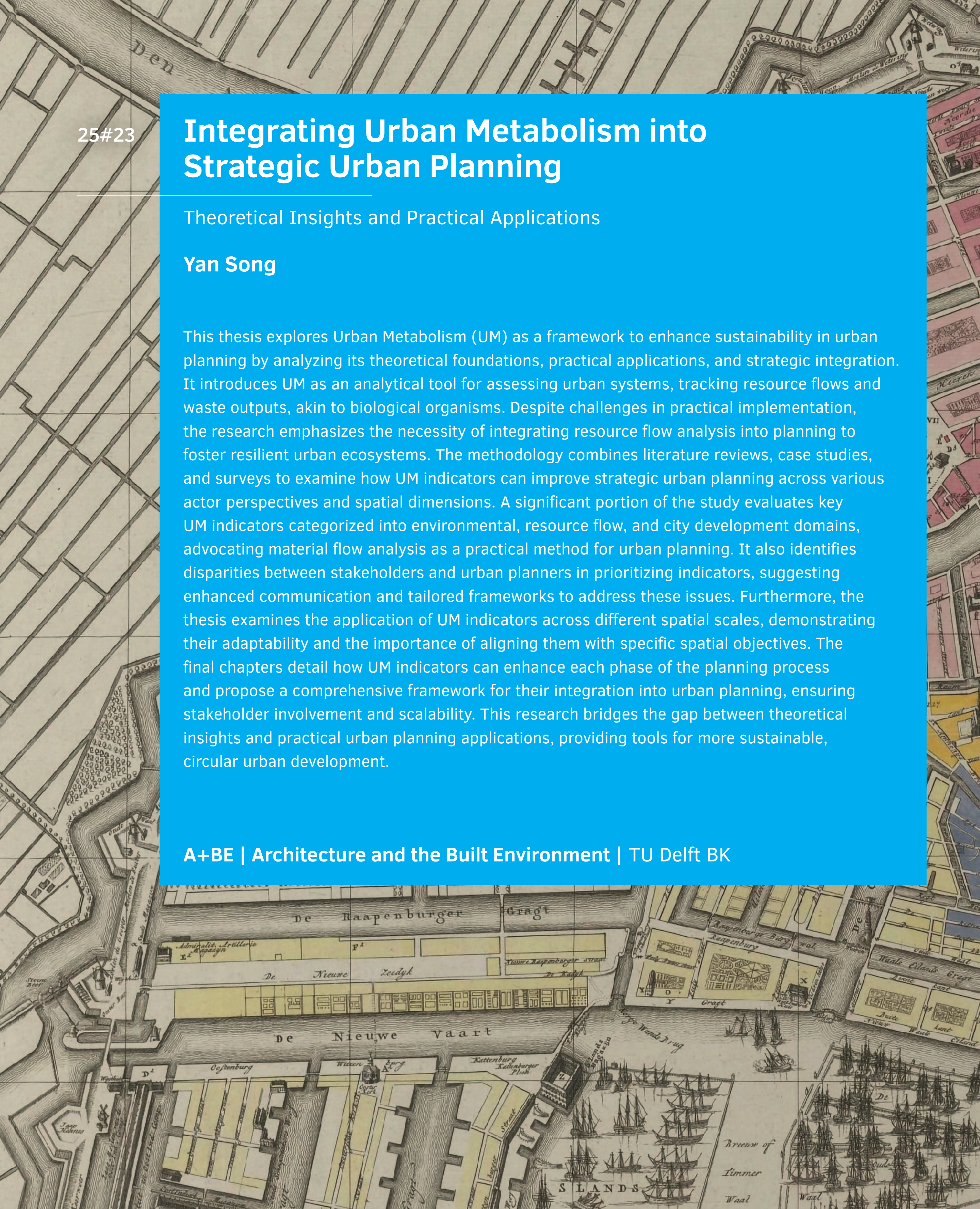
September 2019, IFLA world congress, Oslo, Urbanization impact on Biotope in Shanghai: A comparative study between Huangpu District and Pujin Block.

July 2019, 10th International Conference on Industrial Ecology, Beijing, A research on urban metabolism indicators from the standpoint of decision makers and urban designers.

April 2018, Social-economic, environmental and regional aspects of a circular economy international conference, Pécs, Exploring urban metabolism indicators for municipalities of metropolitan areas.

October 2017, Warsaw Regional Forum, Warsaw, Improving sustainable urban development using urban metabolism indicators in the design process.

June 2017, 3rd International Conference on "Changing Cities: Spatial, Design, Landscape and Socio-economic dimensions", Syros-Delos-Mykonos Islands, Improving urban sustainability in metropolitan areas using sustainability-aimed urban metabolism indicators.



25#23

Integrating Urban Metabolism into Strategic Urban Planning

Theoretical Insights and Practical Applications

Yan Song

This thesis explores Urban Metabolism (UM) as a framework to enhance sustainability in urban planning by analyzing its theoretical foundations, practical applications, and strategic integration. It introduces UM as an analytical tool for assessing urban systems, tracking resource flows and waste outputs, akin to biological organisms. Despite challenges in practical implementation, the research emphasizes the necessity of integrating resource flow analysis into planning to foster resilient urban ecosystems. The methodology combines literature reviews, case studies, and surveys to examine how UM indicators can improve strategic urban planning across various actor perspectives and spatial dimensions. A significant portion of the study evaluates key UM indicators categorized into environmental, resource flow, and city development domains, advocating material flow analysis as a practical method for urban planning. It also identifies disparities between stakeholders and urban planners in prioritizing indicators, suggesting enhanced communication and tailored frameworks to address these issues. Furthermore, the thesis examines the application of UM indicators across different spatial scales, demonstrating their adaptability and the importance of aligning them with specific spatial objectives. The final chapters detail how UM indicators can enhance each phase of the planning process and propose a comprehensive framework for their integration into urban planning, ensuring stakeholder involvement and scalability. This research bridges the gap between theoretical insights and practical urban planning applications, providing tools for more sustainable, circular urban development.

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